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Net-Metering and Self-Consumption Analysis for Direct PV Groundwater Pumping in Agriculture: A Spanish Case Study

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Received: 28 February 2019; Accepted: 9 April 2019; Published: 20 April 2019

Abstract: International policies mainly that are focused on energy-dependence reduction and climate change objectives have been widely proposed by most developed countries over the last years. These actions aim to promote the integration of renewables and the reduction of emissions in all sectors. Among the different sectors, agriculture emerges as a remarkable opportunity to integrate these proposals. Indeed, this sector accounts for 10% of the total greenhouse gas (GHG) emissions in the EU, representing 1.5% of gross domestic product (GDP) in 2016. Within the agriculture sector, current solutions for groundwater pumping purposes are mainly based on diesel technologies, leading to a remarkable fossil fuel dependence and emissions that must be reduced to fulfill both energy and environmental requirements. Relevant actions must be proposed that are focused on sustainable strategies and initiatives. Under this scenario, the integration of photovoltaic (PV) power plants into groundwater pumping installations has recently been considered as a suitable solution. However, this approach requires a more extended analysis, including different risks and impacts related to sustainability from the economic and energy points of view, and by considering other relevant aspects such as environmental consequences. In addition, PV solar power systems connected to the grid for groundwater pumping purposes provide a relevant opportunity to optimize the power supplied by these installations in terms of self-consumption and net-metering advantages. Actually, the excess PV power might be injected to the grid, with potential profits and benefits for the agriculture sector. Under this scenario, the present paper gives a multidimensional analysis of PV solar power systems connected to the grid for groundwater pumping solutions, including net-metering conditions and benefit estimations that are focused on a Spanish case study. Extensive results based on a real aquifer (Aquifer 23) located in Castilla La Mancha (Spain) are included and discussed in detail.

Keywords: economic–energy–environment (3E) analysis; solar pumping; renewable energy source (RES) integration; net-metering; sustainable rural development

1. Introduction

Presently, the sustainability of the globalized society is at potential risk because of climate change, involving an important level of atmospheric pollution. These environmental effects have been evidenced in the climate and in the availability of natural resources, mainly water. With respect to this resource, the growing water demand requires government support to avoid undesired overexploitation. In addition, climate change can affect all sectors of society. In fact, certain effects are beginning to cause concern in the agricultural sector, such as minor rainfalls and increasing temperatures. These impacts also affect the sustainability of this sector as well as other dimensions, such as energy and productivity, and finally end up affecting the social and economic global structure, especially in rural areas and areas with water scarcity. To overcome these negative impacts, international organizations have promoted several agreements as global strategies, such as the Kyoto Protocol and the COP21 Conference of the Parties on Climate Change held in Paris in 2015 [1], aiming to reduce the impacts of those climate changes. At this last event, it was agreed to contain the increase in global average temperature below 2 °C at the end of the current century. To fulfill this objective, different actions were proposed, mainly focused on (*i*) reducing dependence on fossil fuels; (*ii*) increasing the integration of renewable energy sources [2]; and (*iii*) decreasing CO_2 emissions into the atmosphere. The change in the energy model toward a major use of renewable energy resources within a framework of sustainable development in all economic sectors of society implies the need for a firm Research and Development and Innovation (R+D+i) strategy. Although solutions to achieve these targets in the domestic, industrial, and transport sectors have been widely studied, there is a lack of contributions for the agriculture sector, which requires a more detailed and multidimensional analysis. Actually, from an agro-energy perspective, this issue must be studied widely in a global analysis on the environmental, hydrological, and socioeconomic effects that have certain influences on pumping irrigation. Therefore, the energy demand and proposals for renewable energy alternatives must be considered in all applications of agriculture, and specifically in pumping facilities. Villamayor-Tomas affirms that remaining institutional challenges must include an important water rights reform, including the promotion of a distributed energy network and irrigation modernization within Spain and at the European level [3]. The change in the energy model of pumping agriculture thus represents a strategy to reduce dependence on fossil fuels, creates wealth in rural areas, settles employment, and allows participation in the reduction of CO_2 emissions. Photovoltaic (PV) solutions for agriculture pumping present a viable and profitable alternative to replacing diesel generators in isolated and individual installations [4–6]. This has mainly been motivated by high fuel costs and easily amortized investment costs. In fact, Cuadros et al. defines 'photoirrigation' as a procedure to estimate PV installations for irrigation pumping purposes [7]. Some significant agriculture–energy synergy studies have been conducted by different authors [8–10]. However, most contributions in the agricultural sector are focused on standalone solutions without considering distributed generation purposes. In this way, battery and water tanks are proposed in [11] to store energy obtained from solar panels increasing the system stability. Mohana Rao et al evaluate PV-based water pumping system for agricultural sector under standalone conditions [12]. Similar analysis can be found in [13,14], where standalone PV water pumping systems described and evaluated. Binshad et al. investigates the operation and analysis of the photovoltaic water pumping system without considering grid connection requirements [15]. A grid-connected hybrid renewable energy system example is described in [16], consisting of PV and wind power technologies applied on rural township in the Mediterranean climate region of central Catalonia (Spain). Therefore, there is a lack of contributions focusing on grid-connected PV pumping systems for water supplies and human consumption where self-consumption and net-metering schemes are evaluated. This lack of contributions thus implies that (*i*) analysis of global irrigation pumping is not available in the specific literature; (*ii*) these solutions depend on different variables that must be evaluated accordingly; and (*iii*) PV pumping solutions need to be analyzed annually to include the problem of low use of these PV installations depending on the crops. In fact, optimal use and exploitation of the facility should be properly evaluated. Moreover, it is necessary to analyze energy generated in periods when irrigation is not demanded by crops and periods when an excess of PV generation power is provided by the installation. Some studies confirm that PV installations are usually oversized for individual PV solar pumping solutions [17], which are used for irrigation purposes only 180–200 h per year. In most cases, for the rest of the potential PV solar hours, when energy is available from their locations, PV power plants are disconnected from the grid and this additional energy is not used as a potential resource. For this reason, the use of this surplus energy, which in some cases could reach 80–90% of the annual potential energy generated by the PV system, must be analyzed in detail. In this way, Langarita et al. affirm that in irrigated agriculture, a producer-consumer can be systematically exposed to energy shortfalls and surpluses [18]. An example of hybrid power plant with wind turbines, photovoltaic panels, and compressed air energy storage is described in [19], where positive income due to sale of surplus energy to the national power grid is analyzed.

Presently, the idea of systems organized in agro-smart grids or rural smart grids, conceived as distributed generation in rural areas, has been widely studied [20–23]. This organizational structure represents an alternative way of carrying out energy development integration, energy storage, automation, measurement systems, information, and communication related to power generation/demand. In addition, it provides not only better and more efficient distribution/production energy management [24], but also an optimal localized use of resources [25,26]. This concept also includes efficient water management, automation, and precision agriculture, and generation/demand balance in rural areas. Figure 1 summarizes schematically the integration of the agricultural sector into a smart grid. However, one of the main limitations of these solutions is the power line construction cost and the auxiliary elements to inject the power from those PV power plants to the grid. Moreover, Bassi affirms that it is difficult to connect millions of scattered wells, fitted with solar pumps (earlier operating with diesel pumps), to the power grid [27]. Another important drawback of these systems in general—including other sectors such as the residential sector [28]—is the current legislation and requirements on distributed generation and net-metering policies. Christoforidis et al. affirm that there is a lack of a universal policy harmonizing the respective legislations of the EU member countries in terms of net-metering schemes [29]. Nevertheless, there is a favorable legislative framework for this type of facility in some countries such as Belgium and Denmark, in other countries, such as Spain, there is currently no advantageous regulation for net-metering implementation [30]. For the Spanish case, and after a long series of changes in the regulatory and legal framework of renewable energy installations in Spain (RD1699/2011, RDL 1/2012, L15/2012, OM1491/2013, RD413/2014), the regulation of self-consumption and net-metering facilities through RD900/2015 [31] implies a series of taxes that must be paid by the facilities connected to the grid when they inject power into the grid. Further information focused on self-supply and net-balance Spanish policies can be found in [32].

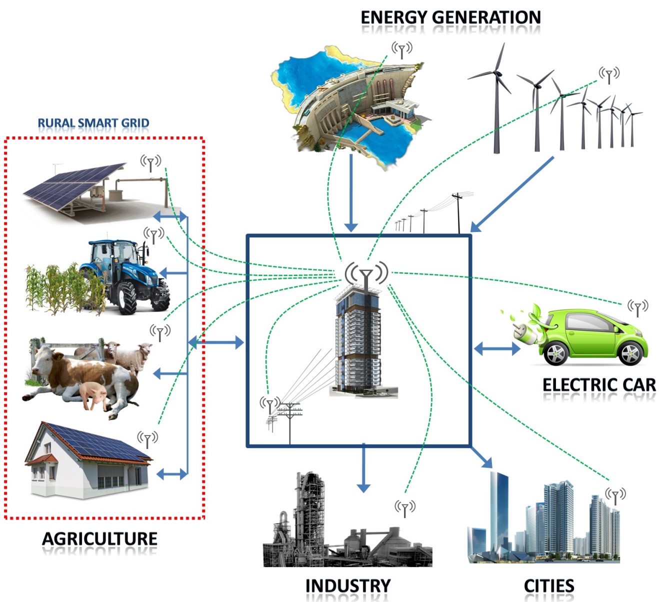

Figure 1. Integration of the agricultural sector into a smart grid: supply and demand-side active roles.

By considering previous contributions and the lack of analysis from a multidimensional perspective regarding PV power plants connected to the grid for groundwater pumping solutions, this paper aims to:

- Analyze and identify, from a socioeconomic, environmental, and energy perspective, the problems of current agriculture groundwater pumping systems based on fossil fuel technologies.
- Propose and analyze PV solar pumping alternatives connected to the grid by including surplus energy and its injection into the grid, evaluating the possible economic profits from the sector.
- Evaluate a case study based on including this alternative in a real environment and crops located in the southeast of Spain (Castilla La Mancha Region).

The rest of the paper is structured as follows: Section 2 discusses the methodology, focused on a global analysis of the problem in agriculture, describing the problems and their most important impacts, as well as the process of determining the surplus energy and the possible economic return from the sale of such additional energy. Section 3 describes the case study. Results are given in Section 4, including estimations of the surplus energy and the potential economic benefits of the sale of energy. In addition, benefits provided to the agriculture sector with the integration of this solar resource are also included. Finally, conclusions are given in Section 5.

2. Multifocused Analysis Methodology

The proposed methodology can be divided into two parts. The first part is a preliminary approach focused on analyzing, from a multidimensional perspective, the energy problem of groundwater pumping for agriculture. In this way, a study that considers a relevant number of specific factors, derived in part from the current use of fossil fuel–based solutions usually implemented for irrigation purposes, is conducted by the authors. We analyze how future changes related to an upcoming energy model, through the implementation of renewable resources (mainly PV technology as proposed this work), can address relevant positive impacts on the agriculture sector. The second part of the methodology describes a process for characterizing the energy alternative of PV pumping installations connected to the grid, identifying and quantifying the benefits provided by this solution [33]. Figure 2 schematically summarizes the proposed methodology.

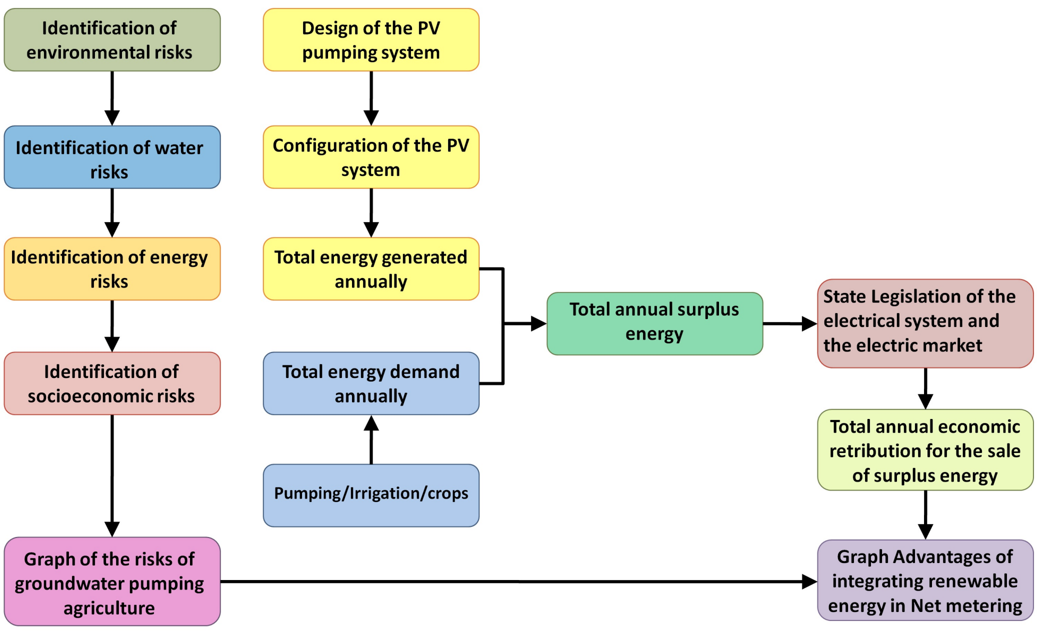

Figure 2. Description of the proposed methodology.

2.1. Groundwater Agriculture Problem: Multifocused Analysis

A multidimensional analysis is proposed by the authors to characterize groundwater pumping in agriculture. With this aim, the problem is analyzed considering: (*i*) an environmental problem (climate change, rainfall, temperature); (*ii*) a water scarcity problem (decreased aquifer phreatic level, among others); (*iii*) an energy problem; and (*iv*) a socioeconomic problem. Figure 3 shows this multidimensional analysis and the relationships among the different points of view. This methodology is in line with other contributions. Moreover, the proposed methodology considers some aspects that have been neglected or not considered in other works. Actually, the problem of sustainability related to water and aquifer resource exploitation as well as PV solar installation analysis has been previously considered in [34–37]. Figure 3 summarizes the dependencies and influences among the different approaches, which are discussed in detail below.

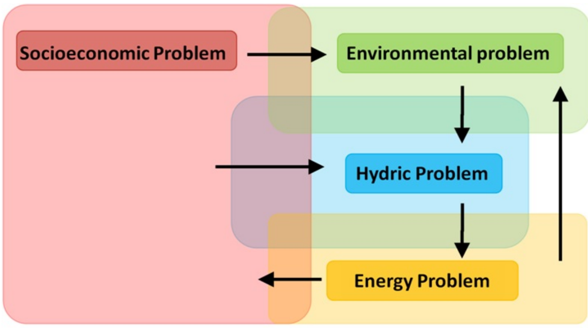

Figure 3. Multifocused analysis for agriculture groundwater pumping purposes.

2.1.1. Environmental Analysis

The environmental problem emerges as one of the most crucial impacts. In fact, this issue can involve important problems for the agricultural sector and its irrigation requirements, especially for groundwater irrigation proposals. In an arid climate, climate change can lead to a decrease in precipitation, consequently reducing the natural recharge of aquifers. These negative conditions are a limiting factor for agricultural development in those areas of the world [38]. Reduced rainfall as a result of climate change is not the only environmental impact, but also rising temperatures and other collateral effects. In fact, some analyses and studies focused on climate forecasting suggest a gradual temperature increase, with warmer and drier summer periods. Therefore, water reservoirs and lakes exposed to solar radiation can lose more water by evaporation, and crops will demand greater amounts of water. From a climate perspective, analysis of these data shows a clear tendency from semiarid areas to severely arid conditions, almost becoming desertified areas.

Water resource management in the agriculture sector emerges as a crucial and relevant factor, affecting irrigation and slightly increasing crop water requirements. Desertification and soil erosion are then collateral problems as a result of poor agricultural practices and inefficient use of irrigation strategies, leading to the loss of soil moisture in semiarid areas. Presently, the climate change problem is leading to unsustainability due to the overexploitation of some aquifers. Other physicochemical problems have also been identified as a consequence of such overexploitation. Leachates, pesticides, and inorganic fertilizers can come into contact with the aquifer and produce a contaminated environment. As an additional drawback to the overexploitation problem, groundwater salinization is becoming extreme. Consequently, water is unusable for either agriculture or human consumption unless highly expensive pretreatment is carried out. Finally, CO_2 emissions produced by pumping irrigation in agriculture must be also estimated and analyzed. Traditional agriculture has mostly been based on diesel equipment. Obviously, these systems do not contribute to mitigating climate change effects, but increase emissions. Therefore, alternative solutions based on clean and renewable energy technologies in the agriculture sector can promote the reduction of emissions.

2.1.2. Water Analysis

As previously discussed, climate change has an important impact on pumping solutions and it must be considered for irrigation groundwater purposes. In fact, well-irrigated areas have increased rapidly over the last century thanks to a large investment in pumping technology. Thanks to advances in irrigation technology, farmers have changed their agricultural models from rainfed lands (with a low agricultural productivity ratio) to high-yield irrigated crops. Indeed, some of these crops have a very high water demand, such as maize, beets, and rice. Therefore, these advances have given farmers a remarkable opportunity to diversify their crops for greater economic value but also higher water demand value, by increasing pressure on aquifers [39].

Concerns about groundwater sustainability became relevant when many aquifers reached overexploitation and encountered emergency situations [40]. Overexploitation of aquifers also involves direct environmental impacts on discharges or sources [41,42]. Indeed, sources and rivers dependent on aquifers have considerably reduced their flows, generating problems downstream of the aquifers, for both irrigation and human consumption purposes. At the same time, lake and fluvial aquatic ecosystems have been degraded, depending on maintenance of the phreatic level. Examples of these situations can be found in the Tables of Daimiel (Spain), the Saiss plain (Morocco), the flow losses of the Mikkes River, and other sources [43]. Overexploitation and other water problems are transformed into greater energy demands. Irrigation methods present different efficiency values, with significant discrepancies among them. For example, methods based on gravity, furrows, or flooding are the most inefficient irrigation solutions (50%). Apart from water inefficiency, their use can bring serious consequences to underground aquifers [44]. To achieve suitable crop maintenance, a more efficient use of water resources should be proposed, such as localized irrigation (90% efficiency) or irrigation by spraying (70–80%) [45]. In addition to the previous problems, which are easily discernible by their immediate impact on the agricultural economy, other problems associated with the continuous depletion of aquifer resources can be identified, such as the problematic subsidence of the terrain due to different pressures of water storage inside [46].

2.1.3. Energy Analysis

The environmental issues not only affect the water balance of the river basins, but are also involved in one of the main water problems in agriculture: aquifer overexploitation with high energy consumption [47]. Once a well is built, the energy required to raise water to the surface is the most relevant annual cost for these systems. This cost depends mainly on: (*i*) the unit price of energy, (*ii*) the depth of the phreatic level, (*iii*) the generator-pump system efficiency, and (*iv*) the hydrogeological characteristics of the aquifer. The high energy dependence of fossil fuels poses an international problem for any sector, and it usually involves high costs. The agriculture sector also suffers from these consequences, as it is a demanding sector of fossil fuels. To solve this, geopolitical and economic factors must be considered to find a suitable solution. For a specific crop, a decreasing phreatic level is closely related to the corresponding energy requirements. Indeed, proper hydric maintenance requires pumping from a deeper source of water and thus more energy is required in the process. Reducing the phreatic level requires a large amount of energy to raise, transport, and distribute water to crops. Increased energy demand involves major production costs for farmers, regardless of their country. This is a difficult problem to be borne by farmers, since it implies more economic effort to pay for fuel for pumping. Different contributions have been devoted to solving this energy problem [48]. The different solutions depend on proper water management to meet high energy demands at low cost [49]. Other inefficiencies, such as poorly performing irrigation methods, a lack of maintenance, or oversized facilities, can mean an excess of energy demand and high economic costs. To solve these problems, some countries have developed different energy policies for agriculture, aiming to reduce the cost of energy production. In some cases, national policies advocate the subsidization of fossil fuels for any sector or exclusively focused on agricultural use. Other policies are based on fiscal subsidies of hydrocarbon taxes on farmers and ranchers, whereas in other countries, the price of fuel is totally regulated by the government.

2.1.4. Socioeconomic Analysis

The problems mentioned above usually imply an increasing price of fuels to meet the relevant energy demand. Because of this, small plots with wells are disappearing and the current tendency is to aggregate larger areas able to decrease the costs associated with pumping maintenance at very deep groundwater levels. This effect is the complete opposite of maintaining traditional agriculture and land democratization [50]. The typical way of dealing with this problem is to raise food prices by farmers; usually prices at the farmer level are then increased to improve their profit margin. This option reduces the competitiveness of their products compared to similar and cheaper products from other countries where the costs of production are considerably lower [50]. A more drastic option is to give up crops or plots, which results in poor economic benefits and does not allow this solution to continue over time. This last option generates depopulation in agricultural and rural areas, where the opportunities and jobs could decrease drastically [50]. Both options have a great impact on the agricultural sector, involving a loss of economic value in the sector, a loss of competitiveness for national products, a reduction in investment, and a subsequent loss of plot value in rural areas. In addition, there is a loss of social value, such as loss of employment in the countryside, loss of traditional agriculture, and depopulation of rural areas. These situations mean that governments, including international associations such as the European Union and the United Nations Organization, must offer alternative actions, strategies, and energy policies to provide solutions to these problems. These strategies are intended to help or subsidize the agricultural sector, such as the Community Agricultural Policy (CAP), which subsidizes, with nuances, such loss of competitiveness of European products directly to farmers. In other cases, there is protectionism toward national agriculture, such as an agrarian policy.

2.2. PV System Configuration and Surplus Energy Estimation

Presently, customers of electricity that have installed energy sources at their households are transformed into 'prosumers' [51]. As was previously discussed, different countries use diverse schemes of support for 'prosumers' [52]. In fact, diverse mechanisms supporting the self-consumption of electricity in key countries all over the world and to highlight the challenges and opportunities associated with their developments have been recently discussed by the IEA [53]. Under this framework, the present section characterizes the sale of energy from PV installations, which supplies energy for agricultural irrigation by groundwater. This characterization process starts with an initial database, where the energy demanded by the irrigated area and the energy-demanding facilities are estimated. Subsequently, a preliminary configuration of the PV facility is determined by including the type of technology (Mono-Si, Te-Cd. . .), solar tracking options, connection to the grid, and injection of surplus energy to the grid. Other parameters such as depth of the aquifer, plot grouping, and water needs of crops are also taken into account [9]. It is then possible to estimate the rate power of the PV installation under different groundwater pumping scenarios, which depend on the depth of the aquifer level, the averaged crop water demand, and the hydraulic system pressure. For the purpose of comparing different alternatives, the rate power required by the pump is first estimated (P_p) [54]:

$$P_p = \frac{H_t \cdot Q_{mx} \cdot \rho \cdot g}{\nu_{MP}} \rightarrow P_d = \frac{P_p \cdot K_d}{\nu_d} \rightarrow P_g = P_d \cdot K_g \tag{1}$$

where H_t is the total dynamic head (m), Q_{mx} is the maximum flow rate (m^3/s), r is the water density (kg/m^3), g is the earth's gravitational acceleration (m/s^2), and ν_{MP} is the pump efficiency (%). For PV solar power estimations (P_{PV}), the following expression is proposed [55]:

$$P_{PV} = \frac{E_{dem}}{E_{(\alpha,\beta)} \cdot PR} \tag{2}$$

where E_{dem} is the expected averaged energy consumption (kWh/day) by considering the crop water need, $E_{(\alpha,\beta)}$ is the expected averaged energy production of a PV power plant from an average monthly value of a typical daily irradiation on the horizontal surface (kWh/m^2·day) and PR is the performance ratio of the PV installation. The surplus energy from the PV pumping system can be then determined from the global PV-generated power and the global crop water need:

$$Se_{(x,y,z)} = \sum_{k=1}^{k=8760} \frac{E_{gen}(k) - E_{dem}(k)}{1000} \tag{3}$$

where $Se_{(x,y,z)}$ is the surplus annual energy (MWh/year), x is the aggregated areas (ha), y is the phreatic level of groundwater depth (m), z the global crop water need (m^3), k is hours in a year, E_{gen} is the energy produced in a specific k-hour (kWh), and E_{dem} is the energy demanded in a specific k-hour (kWh).

The next step is to apply the rules and requirements to enable pouring surplus energy into the electricity grid, determining the economic values to consider possible economic retribution. At this point, as discussed in the introduction, the net-metering is differentiated by applying the prices of the electricity market and self-consumption defined and regulated by the corresponding national authorities. The following section describes the case study, which focuses on current Spanish legislation. Nevertheless, the proposed methodology can also be applied to other legislative frameworks under different national authority requirements.

3. Case Study

3.1. Preliminaries

Recently, Barbel affirms that in Spain, irrigated agriculture accounts for 20% of the total agricultural area, consumes 75% of total water resources, and generates 60% of the total agricultural production and 80% of agricultural exports [56]. Under these circumstances, Aquifer 23 located in Castilla La Mancha, Spain, is considered for the case study. Figure 4 shows the location of this aquifer and the agricultural area that depends on this water resource. The area is basically a sedimentary basin immersed in a karstic system. This aquifer varies in depth between 10 and 70 m, occupying an area of 5500 km^2. Recently, it has been declared an overexploited aquifer as a consequence of not only poor management and a lack of environmental and water control, but also a lack of planning of water resources. Indeed, it has reached drops of 2.3 m/year over several years of severe extraction. Over the last decade, it has been considered as a remarkable resource recovery example, increasing the groundwater level of the aquifer, as depicted in Figure 5. Presently, this aquifer is still considered overexploited, mainly due to high influence of recent periods of low rainfall. The recovery process is a consequence of the awareness of this situation and farmers' economic dependence on the aquifer [57]. Irrigation is one of the main economic drivers and sources of sustenance of the rural society in this area [58]. Regarding the climate in the area, it can be classified as continental Mediterranean with dry and hot summers with high solar irradiance levels, and cold winters with certain frost periods. Spring and autumn are characterized by soft and humid periods. Annual rainfall is a determining factor, which in the study area presents relevant oscillations between wetter periods and drier periods, accounting for 350–400 mm per year. However, with the conditions imposed by climate change in recent decades, average annual temperatures are slightly rising while rainfall is being partially reduced, posing a serious risk of desertification. Solar resource has high average potential during sunshine hours, with more than 4900 sunshine hours per year. Figure 6 depicts solar irradiance levels and aquifer depth for the case study.

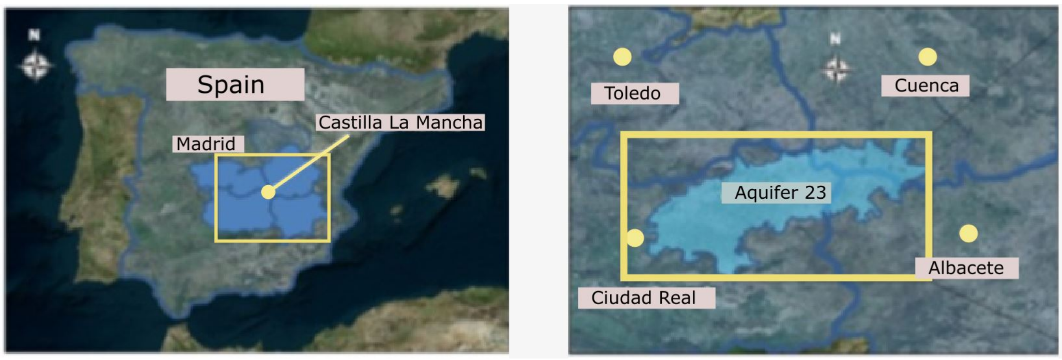

Figure 4. Location of study area and aquifer.

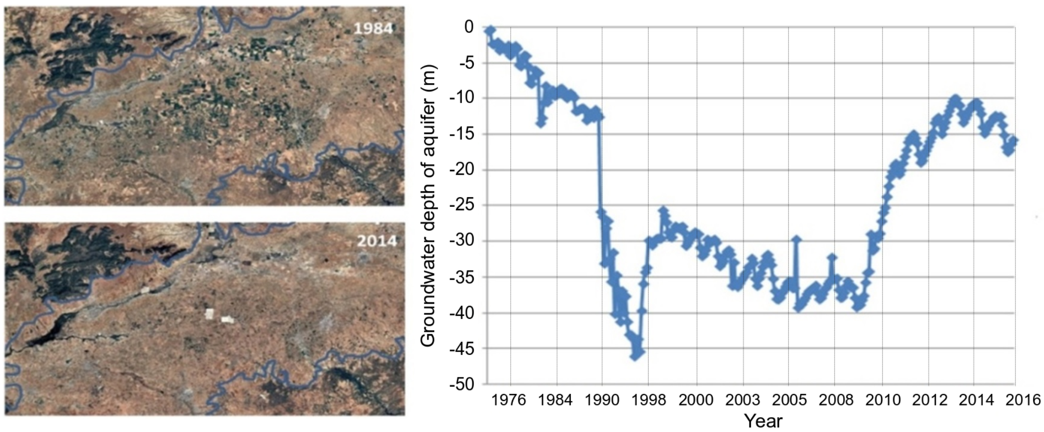

Figure 5. Satellite image of regime of exploitation of water resources and chronological graph of groundwater aquifer level. Source: Authors' elaboration through Google Earth images and CHG data.

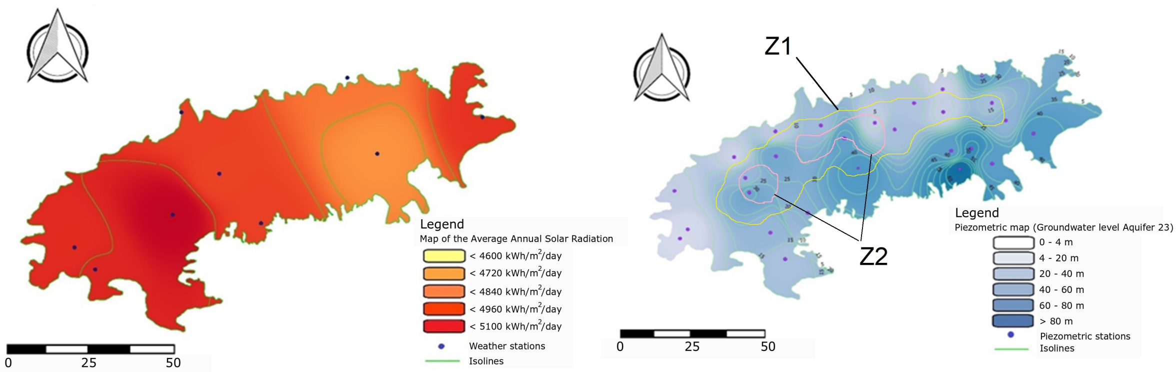

Figure 6. Irradiance solar resource and groundwater depth level: case study. Description of Z1 and Z2.

3.2. Crop Water Need

According to Figure 6, the central band of the aquifer (labelled as Z1) has the highest concentration of irrigation plots: 79% of the irrigation surface of the entire aquifer. This part accounts for 257,456 ha and 58% of this surface (149,647 ha) has irrigated crops. In other areas, labelled as Z2, groups of plots have an irrigated vs. unirrigated ratio of around 75%, accounting for around 15% of the agricultural surface on the global aquifer. In addition, the average depth of the aquifer estimated in 2016 was 29.41 m, according to reference piezometers used by the Guadiana Hydrographic Confederation (Spain) and data from the SIG maps. Due to the initial conditions related to the present case study, two levels of crop water need are considered: 1500 m^3/ha per year and 3000 m ^{3}/ha per year. Both values are the result of water constraints on crop irrigation with the aim of preserving the aquifer. Although there are crops that have higher water requirements, most crops in the study area (mainly vineyards) currently have an average water requirement within the selected range, by considering usual and real grouping plots. Subsequently, both crop water need values (1500 m^3/ha and 3000 m^3/ha per year) are representative of averaged crop irrigation necessities.

3.3. PV Power Plant Configuration

As was previously described in Section 2.2, the rate power of the PV installation can be estimated by considering the depth of the aquifer level, the averaged crop water demand and the aggregated crop area. Under these requirements, the specific PV power plant configuration is not in line with usual individual installations, mainly promoted in the agricultural sector and based on isolated pumping systems. In our case, we propose an aggregated PV pumping solution without accumulation, directly connected to the grid and excluding any water reservoir facility. The proposed pumping solution thus requires more power, but lower annual maintenance. Therefore, PV power plant solutions with PV modules based on mono-silicon PV technology in fixed installations is considered for the analysis, being the rate PV power estimated to cover the average daily demand according to a specific crop water need. From the aquifer characteristics, ranges to be considered for the study can be then summarized as follows: groups from 1 to 2000 ha, groundwater pumping levels between 10 and 55 m of aquifer depth; and two representative crop water need: 1500 m^3/ha and 3000 m^3/ha—discussed in Section 3.2. Different PV power plant solutions are determined based on the different configurations assumed in the case study. In this way, Figure 7 summarizes the PV solutions (in kWp power capacity) for the different scenarios. In all cases, PV power plant is determined to supply the averaged power demand according to the crop water need, the aggregated area (ha) and groundwater pumping level (m). Therefore, the PV power plants to be installed (in kWp) would provide power enough to supply the corresponding pumping groundwater requirements.

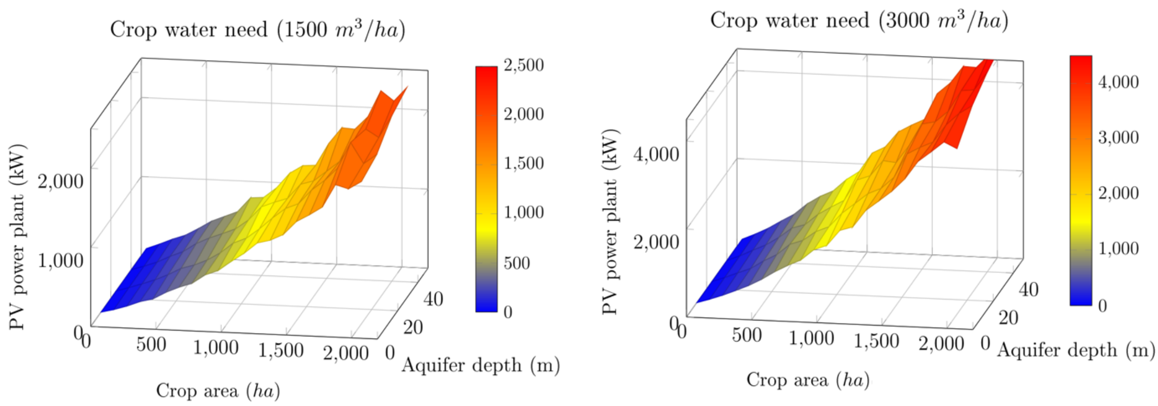

Figure 7. PV power plant capacities for self-consumption scenarios: 1500 m^3/ha and 3000 m^3/ha.

3.4. Self-Consumption: Spanish Legislative Framework

As previously discussed, the proposed methodology can be applied to any legislative framework and according to the corresponding different national authority requirements. In our case, the aquifer is in Spain (Aquifer 23), and thus, the Spanish legislation based on RD 900/2015 is applied [31]. Through this directive, two types of self-consumption are defined: (i) `Type 1`, lower than 100 kW of rate power; most individual pumping irrigation facilities can be classified as `Type 1`; and (ii) `Type 2`, self-consumption with more than 100 kW rate power, injected into the grid at a price established by the electricity market pool. In line with the PV power plant capacities estimated and summarized in Figure 7, most communities of solar pumping irrigators would be considered as `Type 2`. In the case of Spain, taxes and fees that would reduce the final remuneration for the sale of energy must be imposed. These conditions represent a burden at a time of encouraging the implementation of solar solutions—mainly in this case that PV power plants connected to the grid cannot be amortized in a relatively short period of time. Indeed, the costs include a variable charges component associated with the system costs and determined from the variable terms, and a capacity payment component to compensate for system support, compensation to the market and system operators, and interrupted service and adjusted service. It is also necessary to add the recent 7% tax on electricity generation (in September 2018 this was removed by the Spanish government) and the value added tax (VAT) of 21%. Tables 1–3 summarize the representative Spanish fixed, variable, and additional costs to be currently considered for the sale of energy.

Table 1. Spanish fixed fees and taxes applied to the sale of surplus energy through self-consumption: requirements according to RD900/2015 [31].

Access Cost	Annual Fixed Tax (Euro/kWh)					
	Period 1 P1	Period 2 P2	Period 3 P3	Period 4 P4	Period 5 P5	Period 6 P6
2.0 ($P \leq 10$ kW)	8.682019					
2.1 ($10 \leq P \leq 15$ kW)	15.083303					
3.0 A ($P > 15$ kW)	32.083923	6.212601	14.245468			
3.1 A (1 kV to 36 kV)	35.952537	6.717794	4.985851			
6.1 A (1 kV to 30 kV)	22.169359	7.844864	9.790954	11.926548	14.278122	4.882162
6.1 B (30 kV to 36 kV)	14.050921	3.782129	6.817708	8.953302	11.304876	3.525577
6.2 (36 kV to 72.5 kV)	9.082012	1.409534	4.372144	6.352856	8.073738	2.442188
6.3 (72.5 kV to 145 kV)	9.279523	2.525841	3.909548	5.479569	6.893947	1.911493
6.4 ($\geq$145 kV)	2.815509	0.000000	1.718359	3.457606	4.990376	0.970612

Table 2. Spanish variable fees and taxes applied to the sale of surplus energy through self-consumption: requirements according to RD900/2015 [31].

Access Cost	Annual Variable Tax (Euro/kWh)					
	Period 1 P1	Period 2 P2	Period 3 P3	Period 4 P4	Period 5 P5	Period 6 P6
2.0 A ($P \leq 10$ kW)	0.043187					
2.0 DHA ($P \leq 10$ kW)	0.057144	0.006148				
2.0 DHS ($P \leq 10$ kW)	0.057938	0.006430	0.006112			
2.1 A ($10 \leq P \leq 15$ kW)	0.054883					
2.1 DHA ($10 \leq P \leq 15$ kW)	0.068081	0.015450				
2.1 DHS ($10 \leq P \leq 15$ kW)	0.068875	0.018220	0.011370			
3.0 A ($P > 15$ kW)	0.020568	0.013696	0.008951			
3.1 A (1 kV to 36 kV)	0.015301	0.009998	0.012035			
6.1 A (1 kV to 30 kV)	0.011775	0.011336	0.007602	0.009164	0.009986	0.006720
6.1 B (30 kV to 36 kV)	0.011775	0.008312	0.007322	0.008260	0.009403	0.006349
6.2 (36 kV to 72.5 kV)	0.012669	0.011554	0.007881	0.008377	0.008716	0.006245
6.3 (72.5 kV to 145 kV)	0.015106	0.012816	0.008530	0.008510	0.008673	0.006278
6.4 ($\geq$145 kV)	0.011775	0.008531	0.007322	0.007788	0.008257	0.006104

Table 3. Spanish additional fees and taxes applied to the sale of surplus energy through self-consumption: requirements according to RD900/2015 [31].

Annual Additional Tax (Euro/kWh)	
Electricity market operation	0.000025
Power system operation	0.000109
Interruptibility service	0.002000
Provision of adjustment services	0.003210

In Spain, the times of reduced power are usually distributed in three periods. However, for power higher than 450 kW, the Spanish electricity market offer six time periods (P1, P2, P3, P4, P5, P6). Figure 8 shows the electricity rates for the different time periods under the Spanish electricity system legislation. As an example, and for the systems described in this case study (direct PV solar pumping installations) and the selected crop water-need values—1500 m^3/ha and 3000 m^3/ha, the typical periods for this type of facility are the following: P5 in May, P3 and P4 in June, P1 in the rest of June and July, and P6 in August. Irrigation is not usual in September for the considered crops, but it would be framed in periods P3 and P4. To clarify the Spanish electricity market, in terms of selling the excess energy to the grid at a price determined by such electricity market, Figure 9 shows an example for an 870 kWp PV installation, 1000 ha aggregated crop area, 40 m aquifer depth and 1500 m^3/ha crop water need. Energy demanded by the crop, surplus of energy and estimated benefits—excluding and including Spanish taxes—are determined by the different months. Time periods to be applied according to the Spanish electricity market, see Figure 8, are also included.

Hours	0-8	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
February	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2
March	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
April	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
May	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
June (1-15)	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
June (15-30)	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
July	P6	P2	P2	P2	P1	P1	P1	P1	P1	P1	P1	P1	P2	P2	P2	P2	P2
Augost	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6	P6
September	P6	P4	P3	P3	P3	P3	P3	P3	P4	P4	P4	P4	P4	P4	P4	P4	P4
October	P6	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5	P5
November	P6	P4	P4	P4	P4	P4	P4	P4	P4	P3	P3	P3	P3	P3	P3	P4	P4
December	P6	P2	P2	P1	P1	P1	P2	P2	P2	P2	P2	P1	P1	P1	P2	P2	P2

Figure 8. Description of electricity rates for different time periods in the Spanish electricity system.

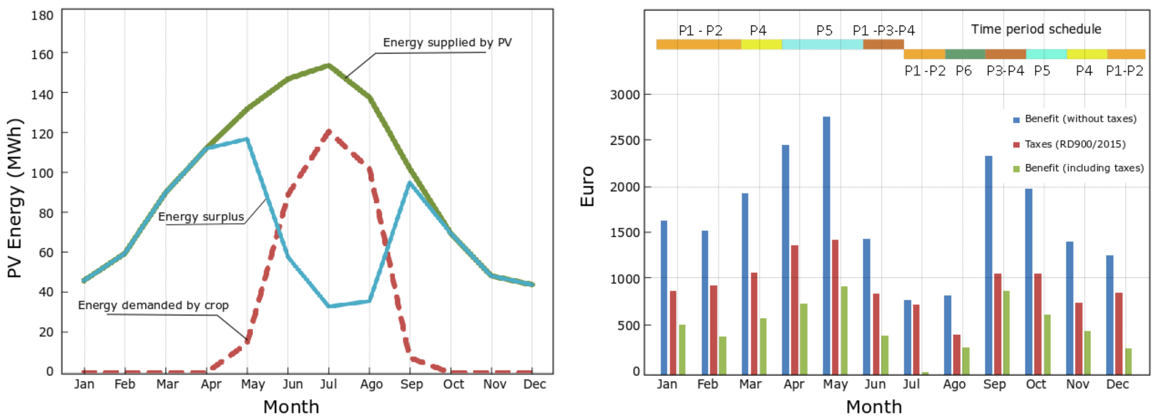

Figure 9. Example of PV generation and surplus of energy. Costs and benefits for the Spanish electricity system.

4. Results and Discussion

According to the proposed methodology described in Section 2, the case study is analyzed from a multidimensional perspective with the goals of reducing the intense dependence on fossil fuels, increasing the integration of solar solutions and preserving the aquifer to avoid future lower phreatic levels that would require more energy resources and thus relevant economic efforts. Furthermore, PV power plants connected to the grid can give farmers additional benefits through net-metering scenarios and annual energy surpluses.

4.1. PV Installations Connected to the Grid: Surplus of Annual Energy

Depending on the agronomic management of irrigation, the amount of water demanded by certain crops, the climatic conditions, and the state of the soil, the energy required by crops can vary considerably. As previously discussed, most crops require irrigation during specific periods of the year and their demand can be considered as seasonal. For example, for the case study, the months are limited to May, June, July, August, and September. Therefore, an important part of the potentially generated annual power is initially wasted. Under this hypothesis, the energy generated for the case study has been quantified-based on the selected PV configuration and the corresponding 1500 and 3000 m^3/ha crop water needs, which represents vineyard crops and a mosaic of vegetation and vineyard for typical areas of the case study. Figure 10 shows the surplus energy gradient based on the surface in hectares and the aquifer depth for the different PV configurations summarized in Figure 7. As shown in these results, greater depth aquifer and greater crop water need would imply more power required by the system, and consequently, the potential annual generated energy will be higher. This is due to the fact that both parameters have a relevant influence on the preliminary estimation of the PV solar pumping installation. Nevertheless, the investments are related to size of the PV power plant, and subsequently, the higher the PV system the higher the annual profits. A more detailed economic analysis, including investments, should be conducted to estimate the best solution. A recent detailed economic analysis carried out by the authors can be found in [59].

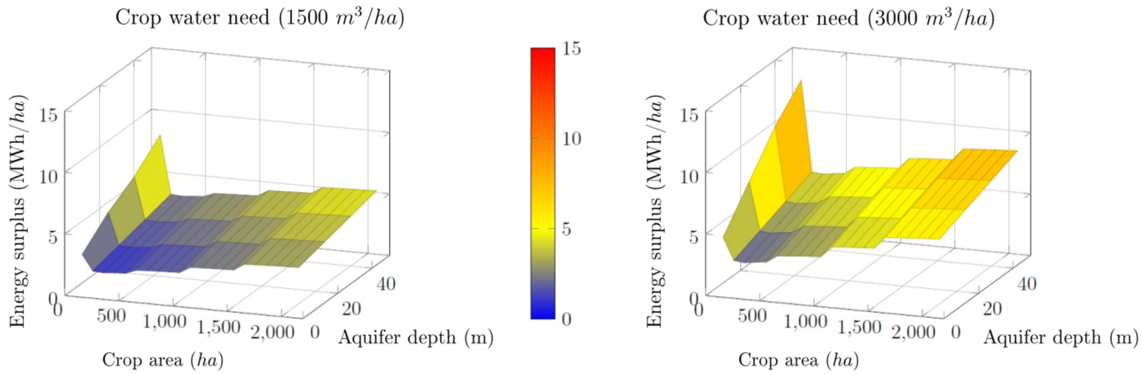

Figure 10. PV installation connected to the grid: annual surplus energy estimation examples (1500 m^3/ha and 3000 m^3/ha).

4.2. Grid Injection from PV Systems into the Grid: Net-Metering Schemes

Firstly, and from the annual surplus energy estimation examples depicted in Figure 10, a preliminary estimation of annual benefits can be determined by considering the current Spanish legislation—aimed at promoting net-metering policies—but excluding current taxes on electrical generation summarized in Tables 1–3. With this aim, Figure 11 shows annual estimated economic returns provided by the corresponding PV installations previously determined and summarized in Figure 7. It is important to point out that these benefits are highly dependent on the irrigation profiles required by the crops, and subsequently, they could be different when considering other crops and water needs. Nevertheless, the proposed can be applied to other legislative scenarios.

From these preliminary analyses, the following results estimate the economic compensation of PV facilities under the current Spanish legislation. Figure 12 gives the benefits under the legislation defined in RD900/2015 and the application of the corresponding taxes and charges. The final economic compensation, compared to Figure 11, is reduced for both 1500 m^3/ha and 3000 m^3/ha cases. The analysis of the results and the comparison between economic return on surplus energy for 1500 m^3/ha and 3000 m^3/ha, with a law aimed at developing renewable energy and Spanish legislation defined by RD 900/2015, means that only between 40% and 60% of economic compensation for the sale of energy is obtained with application of this legislation regarding a net-metering scheme excluding taxes and fees. Subsequently, a PV solar configuration for 3000 m^3/ha allows us to provide between 1.6 and 1.8 times more surplus energy than the 1500 m^3/ha-based solution. For example, an area of 1000 hectares with an aquifer depth of 30 m and a vineyard crop of 1500 m^3/ha of annual water requirements is estimated to cost 180 Euro/ha (per year) for the sale of energy. The same solution under current Spanish self-consumption legislation would be significantly reduced by up to 81 Euro/ha (per year).

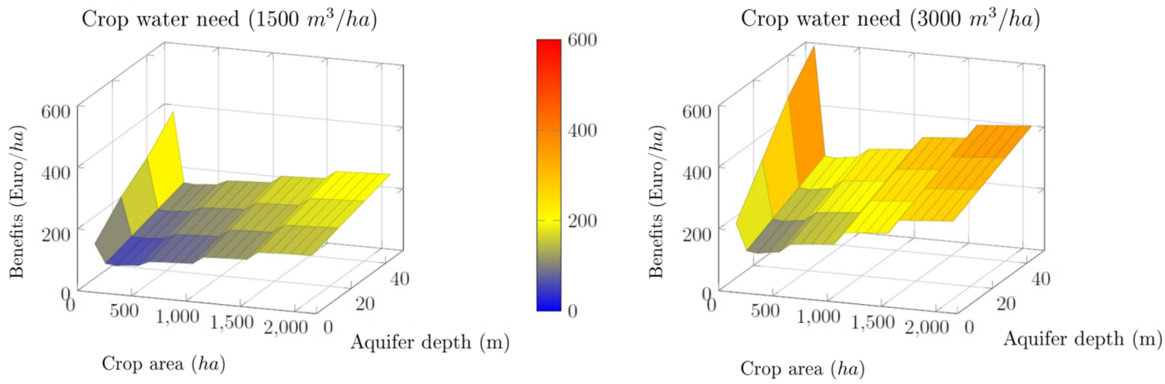

Figure 11. PV installation connected to the grid: annual benefit estimation examples excluding taxes and fees (1500 m^3/ha and 3000 m^3/ha).

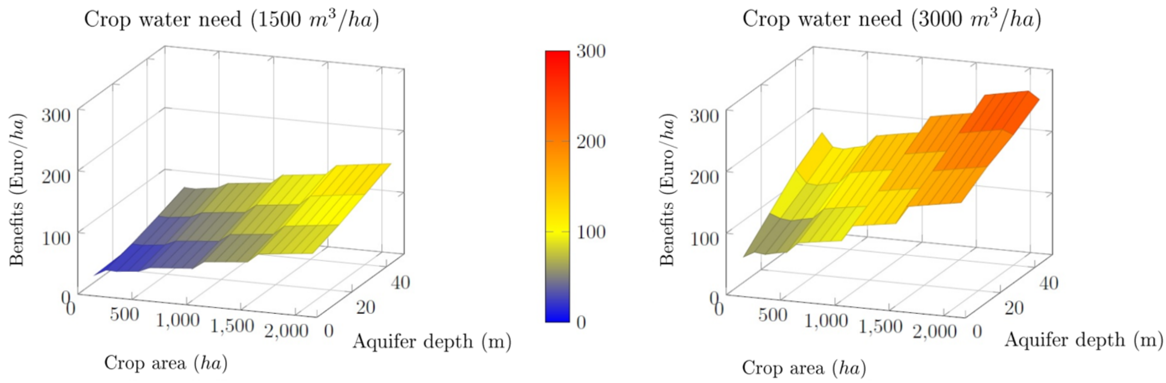

Figure 12. PV installation connected to the grid: annual benefit estimation examples including taxes and fees (1500 m^3/ha and 3000 m^3/ha).

4.3. PV Integration into Net-Metering Schemes: Aquifer 23 Discussion

By considering that PV solar installations for pumping groundwater purposes can be used more efficiently under net-metering schemes, significant economic benefits and environmental profits can be provided by these facilities. The proposed PV configurations allow reduction in the energy costs and subsequently the production costs, becoming more competitive without changing the profit margin. In addition, these solutions give rural areas an opportunity to maintain their population and, at the same time, reduce their economic dependency mainly based on subsidies. A remarkable reduction of emissions in the agricultural sector can also be achieved. According to the annual benefit estimation for the self-consumption and net-metering schemes previously described are summarized in Figure 12, it is possible to extrapolate the data to the rest of the aquifer (Aquifer 23). In this way, we consider the point where the concentration of wells is larger: within zones Z1 and Z2, accounting for 58% of the wells. If communities of irrigators of 800 ha, such as an existing one of this size, were connected to the grid, considering the average aquifer depth in those zones, emissions would be reduced in a more than relevant way. As previously discussed, after implementing a PV power plant connected to the grid in a community of irrigators, the economic benefits are highly dependent on the specific crop water need and the aquifer depth, which corresponds to 50,000 to 90,000 Euro in Z1 and 100,000 to 140,000 Euro in Z2, based on a net-metering scheme excluding taxes and fees; and from 28,000 to 50,000 euros in Z1 and 40,000 to 90,000 euros in Z2 according to current legislation in Spain (RD900/2015). Extrapolating the economic benefits for the entire aquifer, direct benefits to farmers of between 8 and 13 million Euro could be achieved in Z1, and between 3 and 4 million Euro in Z2, in accordance with a preliminary net-metering scheme without taxes and fees. However, with the current legislation in Spain regarding self-consumption and net-metering, between 4 and 8 million Euro in Z1 and between 1 and 2.5 million

Euro in Z2 would be estimated annually. Tables 4 and 5 summarizes the economic benefits from the corresponding net-metering schemes by Z1 and Z2 zones, respectively.

Finally, Figure 13 summarizes the analyzed approaches considered in this work and the corresponding advantages from these different perspectives. Presently, to undertake projects and design aid for the promotion of new renewable technologies and energy efficiency in agriculture, the European Union promotes several programs along this line under the European Agricultural Fund for Rural Development (EAFRD), to which is added the Green Fund for Climate [60] for other countries.

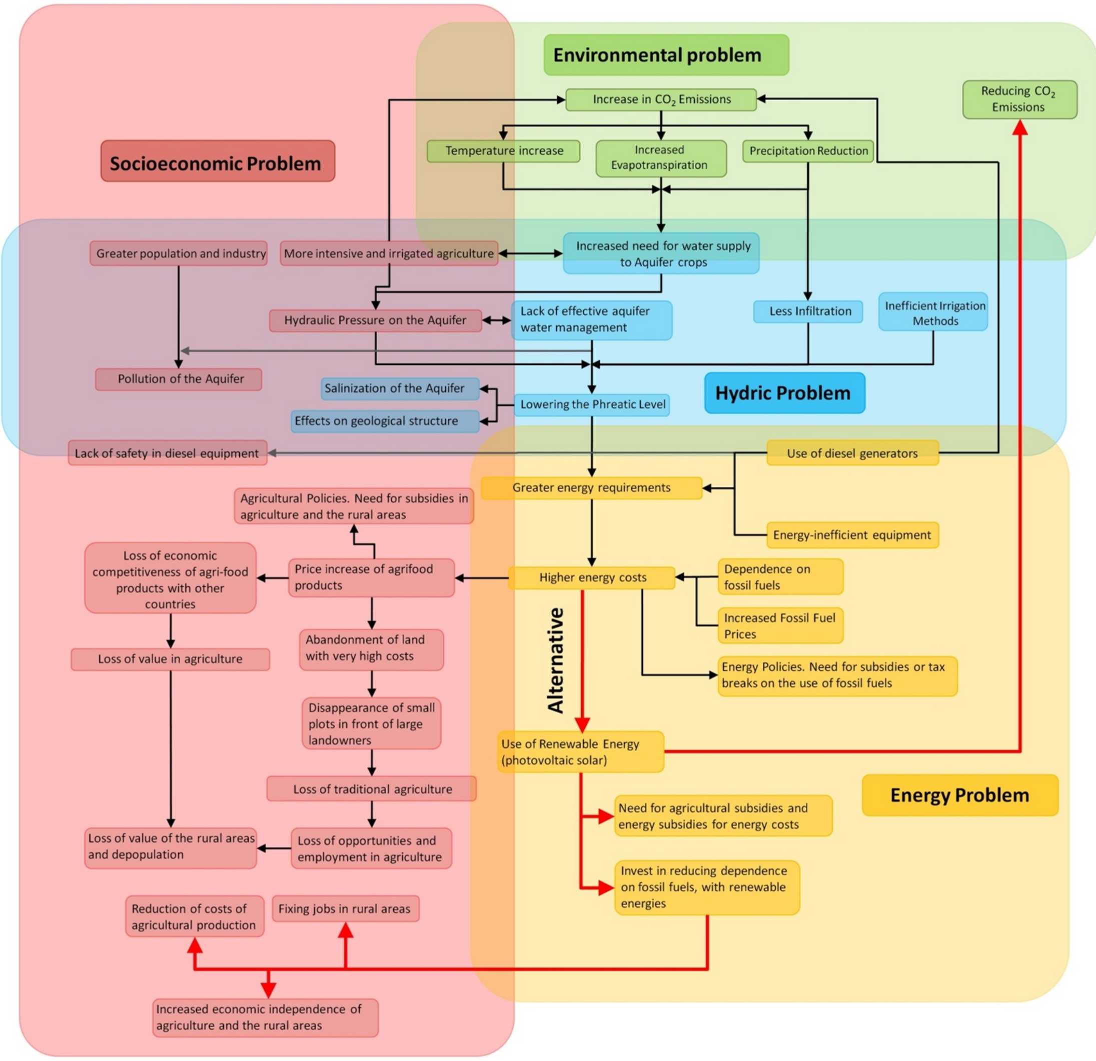

Figure 13. Integrating renewables into net-metering: advantages and multifocused approach.

Table 4. Economic benefits: Z1 zone (159 communities, 800 ha/community).

Crop Water Need (m^3/ha)	Area (ha)	Economic Benefit Excluding Taxes (Euro)	Economic Benefit Including Taxes (Euro)
1500	440 (Aggregated Area)	52,800	26,800
	127,200 (Global Area)	8,395,134	4,547,364
3000	440 (Aggregated Area)	88,000	50,600
	127,200 (Global Area)	13,991,890	8,045,337

Table 5. Economic benefits: Z2 zone (28 communities, 800 ha/community).

Crop Water Need (m^3/ha)	Area (ha)	Economic Benefit Excluding Taxes (Euro)	Economic Benefit Including Taxes (Euro)
1500	Community Area (616)	105,336	47,432
	Global Area (27,400)	2,955,596	1,330,883
3000	Community Area (616)	142,912	94,248
	Global Area (27,400)	4,009,932	2,644,481

5. Conclusions

The integration of PV solar installations connected to the grid into the agriculture sector is proposed and evaluated under net-metering and self-consumption scenarios. This solar resource allows us to decrease emissions and fossil fuel dependence and improve economic benefits from a surplus energy sale standpoint. This multifocused analysis is an exportable and scalable solution that can be applied in different locations depending on different parameters, such as crop water need, aquifer depth, and grouped crop areas. A Spanish aquifer highly overexploited over the decades is used to evaluate the proposed methodology. Different surplus energy sale scenarios are analyzed according to the typical crops in this location and the corresponding annual water requirements and common grouping areas. In this way, relevant annual benefits are estimated in grouped areas of 800 ha, accounting for 50,000 to 140,000 euros/year in a net-metering situation excluding taxes and fees; and 28,000 to 90,000 euros under current Spanish regulations. Regardless of the level of grouped areas, PV power plants interconnected with the grid for the use of surplus energy could generate nonnegligible global revenues: between 10 and 18 million euros/year with a legislation prone to net-metering and between 5 and 10 million euros/year under the current Spanish legislation framework. Therefore, global policies focused on water management and efficient agricultural objectives should be promoted for massive integration of such renewables into the agriculture sector. More specifically, energy policies in terms of net-metering and/or self-consumption schemes that provide regulatory stability to this energy model in agriculture are required by the sector.

Author Contributions: Conceptualization, A. M.-G.; Formal analysis, J.M.S.-L.; Funding acquisition, M.S.G.-C.; Investigation, A.R.-A.; Project administration, A.R.-A.; Validation, M.S.G.-C.; Writing—original draft, A.M.-G. and J.M.S.-L.; Writing—review and editing, A.M.-G.

Funding: This research was funded by the research project TIN2017-86647-P from the Spanish Ministry of Science and Innovation (including FEDER funds), and the Seneca Foundation 19882-GERM-15.

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

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