Multidimensional Analysis of Groundwater Pumping for Irrigation Purposes: Economic, Energy and Environmental Characterization for PV Power Plant Integration

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Abstract

Nowadays, the agriculture sector presents relevant opportunities to integrate renewable energy sources as an alternative solution to mitigate fossil-fuel dependence and decrease emissions. Moreover, this sector demands a detailed review of energy uses and other factors that are addressed as priority issues in most developed countries. In this framework, groundwater pumping energy requirements for agriculture irrigation emerge as a relevant topic to be improved in terms of power demand. Actually, this demand is currently supplied by diesel equipment solutions, with relevant drawbacks such as: (*i*) a large energy dependence on fossil fuels for the agricultural sector and (*ii*) a lack of participation in reducing CO_2 emissions.

This paper proposes a multidimensional characterization to evaluate photovoltaic (PV) solar energy integration into groundwater pumping requirements. Alternative solutions are compared under economic, energy and environmental aspects; thus providing an extensive scenario where the considerable influence of multiple factors such as water needs, irrigation area or aquifer depth are explicitly considered. Extensive results based on a real Spanish aquifer and discussion about the solutions are also included in the paper.

Keywords: PV systems, Solar pumping, Agricultural development, Optimization energy requirement, Characterization of energy alternatives, Economic-Energy-Environment (3E) Analysis.

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1. Introduction

Traditionally, the agriculture sector has depended heavily on fossil fuels in a similar way to other activities have, with a low Renewable Energy Source (RES) integration that can lead to suffering exhaustion [1]. This fact also affects final prices, which are highly dependent on energy cost fluctuations. The high fossil fuel dependence is especially remarkable in field crops, involving aquifer overexploitation problems [2]. In addition, this high energy dependence is one of the pollution sources responsible for emissions and the greenhouse effect [3]. Recently, Spanish energy initiatives [4], European policies [5, 6, 7], as well as environmental [8] and agricultural matters [9] have been aimed at raising awareness by promoting a rational use of energy and an optimal water management in the agriculture sector. These international policies involve sustainable development proposals for renewable energy sources and energy efficiency [10]. They also provide alternative solutions to mitigate the energy dependence on fossil fuels for the agriculture sector and environmental concerns [11].

During recent decades, irrigation techniques have progressively required greater and greater energy needs. For example, the energy demanded by this sector in Spain rose by 1800% from 1950 to 2007 [1], covering 20% of the total arable land and representing 60% of the final agricultural production [12]. The crop area irrigated with wells currently presents a major percentage, also in Spain, where most energy requirements are due to pumping extraction needs [14], see Figure 1. This situation is similar to that in other developed countries, where groundwater pumping energy demand was mainly covered with diesel equipment, and subsequently with a similar percentage of electricity-based solutions. PV solar energy for irrigation purposes has been proposed in the specific literature as an attempt to reduce both energy consumption as well as CO_2 emissions in agriculture [15, 16]. An evaluation of PV-based solutions was proposed by Purohit et al. [17], as an alternative to decrease fossil fuel dependence and reduce its influence on final prices. Other studies have focused on providing water as a basic resource in isolated rural areas, mainly to cover human needs in non-industrialised or under-developed countries [18, 19] such as Nepal, Kenya, Mauritania and Morocco [20, 21]. Rural communities of under-developed countries with solar pumping installa-

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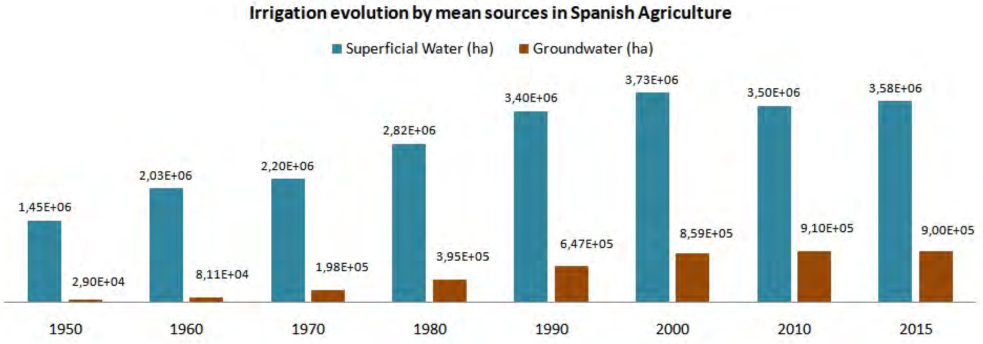
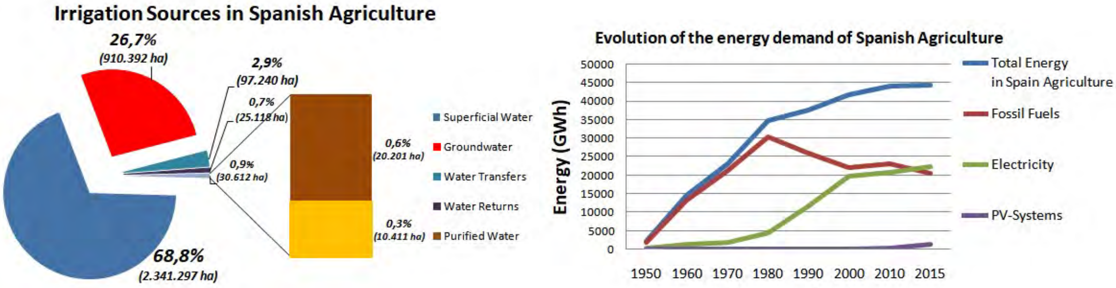


(a) Irrigation evolution in the Spanish agriculture



(b) Irrigation sources

(c) Energy requirement evolution

Figure 1: Main indicators on energy demand for groundwater pumping agriculture in Spanish case [12, 13].

tions lower than 2 kW have been also discussed in other works, such as Erbato et al. [22]. PV solar pumping solutions for agriculture purposes have been analysed from the technical and economic feasibility point of view [23, 24]. The economic viability of PV solutions applied to irrigation has been widely discussed by Foster et al. [25] and Odeh et al. [26]. Approaches to the solar-PV system design in line with specific technical studies on solar radiation, mostly applied to areas with severe water scarcity, are provided by Setiawan et al. [27]. According to Kelley et al. [28], PV systems are economically feasible for small systems (less than 4000 m^3 and less than 10 ha), whereas larger areas require a more detailed study. An extensive analysis is proposed by Cuadros et al. [29] to determine the viability of PV solutions for water pumping purposes for olive trees irrigation in a specific area, including the influence of additional factors such as water depth dependence, solar radiation or crop growing.

In line with the specific literature, a comprehensive review of alternatives is necessary to ensure that efficient irrigation systems are achieved from different points of view: water, energy, economy and environmental concerns; analysing the PV solar energy's integration under different configurations [30, 31]. Therefore, new methodologies must combine the optimisation, sizing and viability of irrigation systems based on solar technologies, including additional factors such as energy costs, water management and CO_2 emissions [32]. Moreover, recent contributions affirm that, before changing pumping diesel facilities into solar pumping equipment, the influence of other factors must be studied and characterized in detail. These include water depth, parcelling grouping, crops, connection to grid or PV technologies [25]. Global proposals are required to integrate renewable energies into agriculture from an extensive manner, optimising costs, reducing CO_2 emissions and minimising energy requirements [31]. Taking into account previous contributions, this paper addresses a multivariable extensive characterization for groundwater pumping irrigation purposes. The main contributions of this paper to RES integration into the agriculture sector are as follows:

- A proposal for characterizing a group of groundwater pumping alternatives that considers economic, energy and environmental points of view.
- An extensive visualization of dependences with relevant variables, such as aquifer depth, crop water requirements, irrigation area sizes and water storage options.
- A thorough comparison of the impacts of different resources for pumping groundwater requirements, in order to evaluate the suitability of each solution depending on different parameters.

Additionally, the proposed characterization is applied on a real Spanish aquifer and crops, providing a preliminary extended view to meet groundwater pumping requirements by introducing PV solar-based installations.

The rest of the paper is structured as follows: variables to be considered for detailed analysis in the pumping irrigation problem are discussed in Section 2. The method for the characterization and calculation of the alternatives taking complementary points of view to identify optimal and efficient alternatives is proposed in Section 3. The case study is described in detail in Section 4, as well as the alternatives and configurations that meet the constraints and requirements for the case study. The results are presented and discussed in Section 5. Finally, Section 6 details the conclusion and future works.

2. Multivariable Extensive Proposal: General Overview

Considering the contributions previously discussed in Section 1, a multidimensional group of variables is selected to characterize the pumping irrigation problem in a reliable and extensive framework. Indeed, multiple variables have a relevant influence on the power demanded by the groundwater pumping systems and thus, combinations of such variables provide an initial set of options to be considered as a general guideline for groundwater pumping purposes. Nevertheless, and due to the large number of possible combinations, this paper aims to filter the most relevant alternatives and practical solutions. Figure 2 shows the identified groups of variables as well as the variables to be considered as inputs of the problem: water needs, aquifer depth and parcelling grouping. Additionally, the figure depicts the relations among variables and the proposed characterization process to identify possible alternatives in a multidimensional scenario.

From the initial group of general variables, the proposed methodology to characterize pumping groundwater solutions involves the identification of alternatives and the configurations discussed in the following subsections.

2.1. Pumping water options

Firstly, a relevant issue considered in the proposed characterization process considers water storage options. Three configurations are taken into account by the authors to meet the different perspectives: annual water storage, seasonal water storage and direct pumping (without water storage). The first option usually requires large water reservoirs, with high costs and evaporation problems. However, it does ensure the water supply demand and uniform irrigation throughout the year, albeit with a low power/year ratio. The seasonal water storage option is based on pumping water during the months prior to the irrigation period and throughout that period. Therefore, this requires a smaller storage reservoir to meet water requirements, with lower evaporation problems. However, this option also demands high energy and initial investments, being used for a short period of time according to the hydraulic year. The third option to be considered is based on a direct pumping solution. Water storage is still needed as a pressure surge reservoir, although considerably lower than in the previous options. The crop water demand is then mostly directly provided by the aquifer. Consequently, the power demand presents a profile similar to the water needs. This configuration involves higher power needs than the other options, but significantly lower water storage and negligible evaporation problems.

2.2. Individual vs Cooperative facilities

In order to determine an optimal configuration for irrigation pumping systems, the proposed methodology considers both individual and cooperative energy alternatives. According to the irrigation requirements, different crop areas can be preliminarily defined. In the case study, from 1 to 2000 ha are estimated as initial solutions to be analysed, see Section 4. Nowadays, individual systems are very common in agriculture, since they provide the farmers with greater independence in terms of the method and amount of irrigation. Cooperative solutions usually offer significant size reduction in RES facilities, promoting RES integration scenarios.

2.3. Isolated or Connected installations

Isolated installations have some advantages in terms of versatility and easy implementation. However, these solutions must completely cover the energy needs (mostly oversized) required by the groundwater pumping. Installations connected to the grid allow us to reduce facilities, since additional power demand or deficiencies can be supplied by the grid. For crops on an annual scale (such as the case study), connected installations might inject any excess energy into the grid, thus being an economic profit for farmers in comparison to isolated installations. The costs of power lines and additional grid facilities are further investments that must be taken into account for these connected installations.

2.4. Energy Solutions

In relation to most of the usual solutions and renewable sources currently promoted, four main resources have been considered: diesel, isolated PV solar power plants, power directly provided by the grid, and PV solar installations connected to the grid under net balance conditions. Diesel is included due to its relevance in the current agricultural sector, being used as a mature and reliable technology for groundwater pumping actions and other agricultural applications in most countries. In fact, this solution is mostly used for groundwater irrigation purposes under individual diesel configurations. Isolated PV solar power plants emerge as a trending solution to supply power and reduce both energy dependence and emissions [33]. These present some relevant advantages, such as minor energy dependence, relevant energy efficiency and, in most countries, important subsidies. Indeed, some authors affirm that diesel equipment installations can be currently turned into

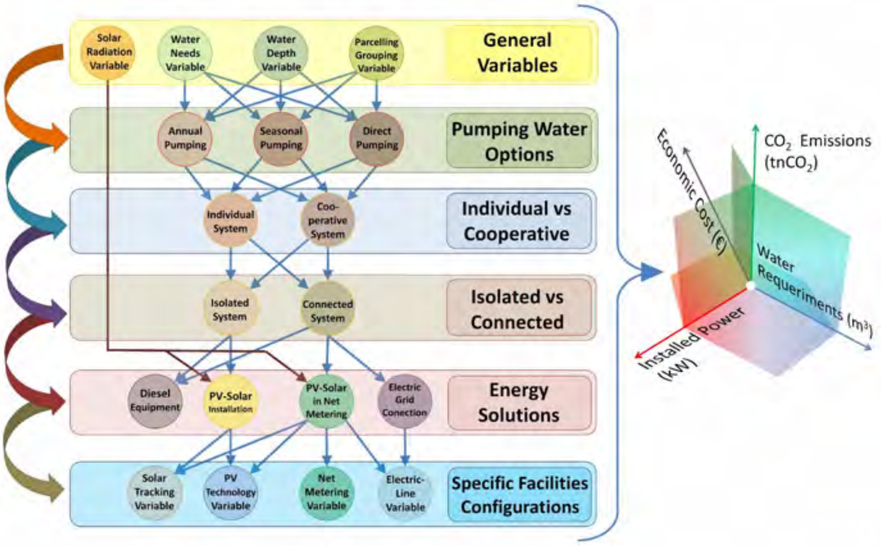


Figure 2: Groups of variables: identification and relations for characterization of initial alternatives.

individual-isolated PV installations [34]. Moreover, combinations of individual PV installations require less power capacity and offer different opportunities to the farmers to significantly reduce CO_2 emissions and optimise the integration of renewables into water pumping requirements. Its drawbacks include the large areas required for PV modules in comparison with diesel equipment, as well as power oscillations due to solar radiation fluctuations or partial shadings. For those reasons, PV solar installations connected to the grid are assumed as an alternative of distributed generation applied to the agriculture sector [35]. The power demanded by the pumps can be provided by both the PV installation and the grid. Subsequently, water can be used directly for irrigation purposes or stored in a reservoir. Actually, individual PV installations connected to the grid can be considered as a cooperative internal network with electricty suppliers and consumers [36]. Nevertheless, some countries differ in the laws and regulations regarding PV solar facilities and the power allowed to be injected into the grid. For example, Spain provides some requirements for PV power plant operations as well as taxes and fees currently applied on these installations [37]. With regard to cooperative irrigation systems, PV solar pumping is also considered as a trade-off between large-scale renewable integration and groundwater pumping requirement facilities. This approach must include additional costs for power line infrastructures and grid distributed system requirements [38]. Finally, power directly supplied by the grid and without additional renewables significantly reduces costs, although farmers depend on the grid in terms of prices and energy dependence. This alternative thus provides substantial reductions of CO_2 emissions in comparison with diesel approaches. However, it does not promote the integration of renewables with a consequent poor participation in the decreasing of fossil fuel dependence.

2.5. Specific Facilities Configurations

Finally, alternatives are also characterized and divided according to some facilities criteria. With regard to PV solar installations, we also distinguish: (*i*) different PV technologies, through a comparison of such technologies under economy, peak power requirements or emissions; this approach has also been discussed in the specific literature [39, 40]. In our case, the most common commercial solutions currently available are considered: Silicon Monocrystalline (Mono-Si), Polycrystalline Silicon (Poly-Si) and Thin-Film modules. (*ii*) different solar tracking technologies, such as fixed installations, one-axis and two-axes solar tracking solutions. (*iii*) PV installations in islanding-mode or connected to the grid. In reference to this last option, a relevant factor to be characterized is the energy pumping requirements and energy fed into the grid ratio. In fact, some contributions discuss investments and benefits when a percentage of the electricity is injected into the grid [35, 41, 37]. The proposed methodology then includes some scenarios depending on the percentage of participation with the grid: 25%, 50%, 75% and 100% of PV solar power injected into the grid. Finally, energy pumping requirements directly supplied by the grid is a very realistic situation which is also included among our alternatives. Different options are thus considered, depending on the distance between the crops and the power system. According to the case study describes in detail in Section 4, three different distances between the crops and the grid have been considered for simulation purposes: 1 km, 3 km and 5 km. In fact, they are the most common distances by considering the aquifer real location, the crop layout and the power distribution system. Such alternatives are discussed and characterized in detail in the following section.

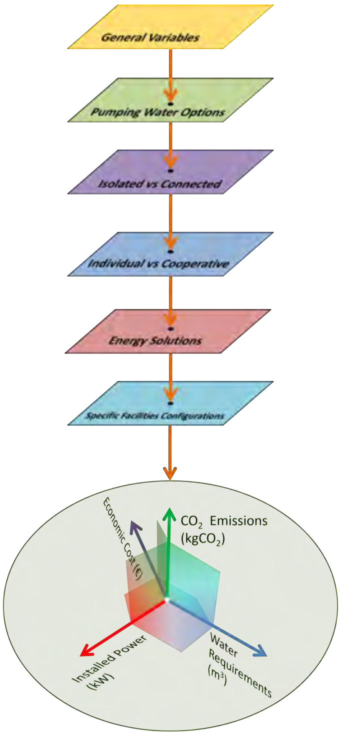


Figure 3: Analysis of variables and characterization of alternatives

3. Multidimensional Characterization of Alternatives

From the extensive group of variables described in Section 2, a characterization of alternatives is then proposed in the current section under different perspectives. A global assessment of such alternatives is thus given by the proposed methodology. An initial range of the variables to be characterized is selected from specific crop areas, aquifer depths and water requirements. Additional factors —such as energy resources, water storage options and cooperative levels, see Figure 2— are also considered under realistic scenarios [28][42].

The proposed methodology considers simultaneously four perspectives with the aim of characterizing the different alternatives: technical, economic, energy and environmental perspectives. From this complementary analysis, efficient and optimised alternatives can be identified. Subsequently, representative solutions of those combined factors are selected. Figure 3 summarises the proposed methodology to characterize the alternatives based on the extensive group of variables and perspectives considered in this work. A four-dimensional representation is proposed by the authors to visualise the different perspectives. Further information and examples of this visualisation proposal can be found in Section 5.

According to Figure 3, economic cost criteria are usually a relevant factor in the final decision. This is in fact a crucial parameter to be considered, as pointed out in [43, 44]. The costs of the initial investment depends on each alternative, considering different water reservoir solutions [45]. Annual benefits and costs of maintenance and operating expenses are also considered. In fact, costs of equipment are included in accordance with current prices [46, 47, 48, 49]. Power requirements are mainly based on facilities for groundwater pumping and water storage [50, 51, 52]. The energy perspective thus implies the comparison of different alternatives in terms of installed power and required energy according to the corresponding water requirements [53]. Additionally, water pumping for different depths under individual or cooperative approaches also has an important impact on the energy needs [28]. An estimation of the total required energy thus depends on the depth of the aquifer level and the crop water demand [54, 55, 56]. Other factors, such as hydraulic system pressure [31, 57] and hydraulic network are also considered [33]. For a comparison between alternatives, the power required by the pump is first estimated (P_p),

$$P_p = \frac{H_t \cdot Q_{mx} \cdot \rho \cdot g}{\eta_{MP}} \tag{1}$$

where H_t is the total hydraulic head (m), Q_{MX} the maximum volume flow rate (m^3/s), ρ the water density (kg/m^3), g the earth gravitational acceleration (m/s^2) and η_{MP} the pump efficiency (%). The rate power is then determined per hectare (kW/ha) depending on the source. For a diesel equipment (P_d),

$$P_d = \frac{P_p \cdot K_d}{\eta_d} \tag{2}$$

where K_d is the coefficient majority diesel equipment (usually 1.2) and η_d the diesel equipment efficiency (%). In a similar way, for solutions connected to the grid (P_g),

$$P_g = P_p \cdot K_g \tag{3}$$

where K_g is the coefficient majority electric contract (usually 1.1). Finally, for PV solar installations (P_{PV}),

$$P_{PV} = \frac{E_{con} \cdot G_{CEM}}{G_{dm(\alpha,\beta)} \cdot PR} \tag{4}$$

where E_{con} is the energy consumption (kWh/day), G_{CEM} is assumed as $1kW/m^2$, $G_{dm(\alpha,\beta)}$ is the average monthly value of the daily irradiation on the horizontal surface ($kWh/m^2 \cdot day$) and PR is the performance ratio of the PV installation.

Emissions of CO_2 for the different technologies are estimated according to previous contributions [58, 59]. The alternatives are the following: (i) technologies based on fossil fuels (diesel); (ii) alternative exclusively supplied by the grid; and (iii) isolated and connected to the grid PV power plants [60, 61, 39, 62]. Emissions are determined in terms of averaged life cycle energy consumption per hectare and considering a standard year ($TnCO_2/ha \cdot year$). According to the aim of this paper, initial CO_2 emissions for assembly and hydraulic network construction have been excluded from the analysis.

Figure 4: Situation of Case of Study. Aquifer 23. Castilla-La Mancha (Spain).

4. Case Study

The proposed methodology is a general-purpose solution which can be applied on different locations and crops. In order to evaluate the suitability of this characterization, an agricultural area located in the Region of La Mancha (Spain) has been selected. The irrigation of this area depends on Aquifer 23 [63], located in the center of this region and in charge of providing water for residential and irrigation purposes [64]. The case study covers an extensive area (over 5500 km^2) and subsequently, crops and water requirements on the land vary significantly. Nevertheless, different policies and actions have promoted a massive water extraction for decades. Figure 4 shows the location and shape of this aquifer.

With regard to the agricultural potential, there is a large concentration of vineyards, accounting for over 60% of the surface area. The rest of the crops are mainly based on different fruits and vegetables in small orchards. The kind of crops has a relevant influence on the amount of water to be extracted from the aquifer [51]. Therefore, it is assumed that the amount of water demanded by each agricultural sector varies from 1500 $m^3/year$ for vineyards up to 8000 $m^3/year$ for fruits, cereals and vegetables. In terms of climate, the region is considered to be semi-arid Mediterranean Continental [65], with high solar radiation levels and an average annual precipitation ranging between 320 mm/m^2 (dry years) and 460 mm/m^2 (wet year). In addition, the aquifer presents important depth variability between the different aquifer zones, which significantly modifies the energy requirements for each crop. Figure 5 summarises both the annual solar radiation values as well as the groundwater level for the selected aquifer.

As was discussed in Section 4, the proposed methodology includes both individual and cooperative alternatives to minimize costs and optimise facilities. An initial matrix combining water depth, agricultural cooperative areas and water requirements is proposed to characterize energy, economic and environmental criteria for each scenario. This multidimensional analysis allows us to visualize each solution in a very extensive way, depending on the specific characteristics of crops and the aquifer properties. In this case, and according to the aquifer characteristics —see Figure 5, four different depth values are considered: 10, 25, 40 and 55 metres. In terms of cooperative scenarios, agricultural areas from 1 to 2000 ha have been considered in this case study. Regarding water requirements (per averaged year), seven different values are selected: 1500, 3000, 4500, 6000, 7500, 9000 and 10500 m^3/ha. Ranges from these variables are selected to analyze real scenarios according to the aquifer and agricultural conditions. The methodology allows us to modifiy these ranges depending on the specfic case study.

5. Results

By considering the proposed multidimensional analysis described in Section 3 as well as the case study discussed in Section 4, different alternatives are characterised and compared in terms of economic, energy and environmental criteria. The characterization process only considers a reduced number of alternatives and configurations, which are the most representative and realistic scenarios according to the water crop requirements and the aquifer characteristics. In terms of PV power plants, only results for Mono-Si modules have been represented and 100% participation is considered for PV installations connected to the grid. For groundwater pumping solutions directly connected to the grid, different power line length scenarios have been estimated, including 1, 3 and 5 km of power lines. However, for the selected figures included in the paper, the 1 km power line length is considered as representative of the case study. Therefore, a complete characterisation of scenarios has then been carried out by the authors, showing the most representative alternatives in this section.

Figure 6 and 7 depicts the different alternatives, in terms of costs (in Euro), depending on seasonal pumping or direct pumping. Ranges previously selected for aquifer depths (1 to 55 m depth), water requirements (1.5 to 10.5 $m^3/Ha \cdot 10^3$) and cooperative agricultural areas (1 to 2000 Ha) have been considered, see Section 4. From the results, the larger agricultural area and water requirements, the higher costs required by all sources. For example, and considering net balance and direct pumping, 5.4 $\cdot 10^6$ Euro is the cost for 2000Ha, 1500 $m^3/Ha \cdot 10^3$ and 40 m depth; whereas 2.03 $\cdot 10^6$ Euro is the cost for 1000Ha, 1500 $m^3/Ha \cdot 10^3$ and 40 m depth. An installation direclty connected to the grid —without diesel solution neither PV power plant— gives the lowest costs. However, this solution can't be implemented on remote areas whithout grid

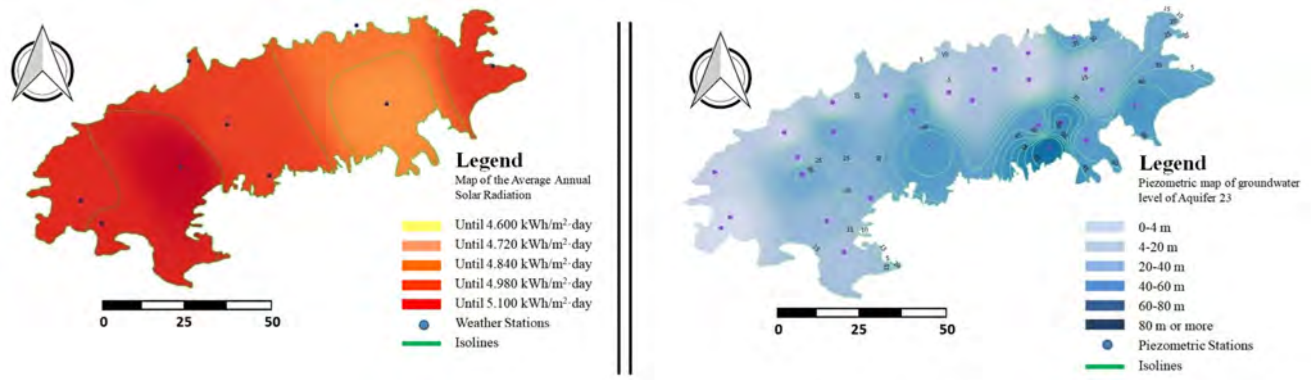
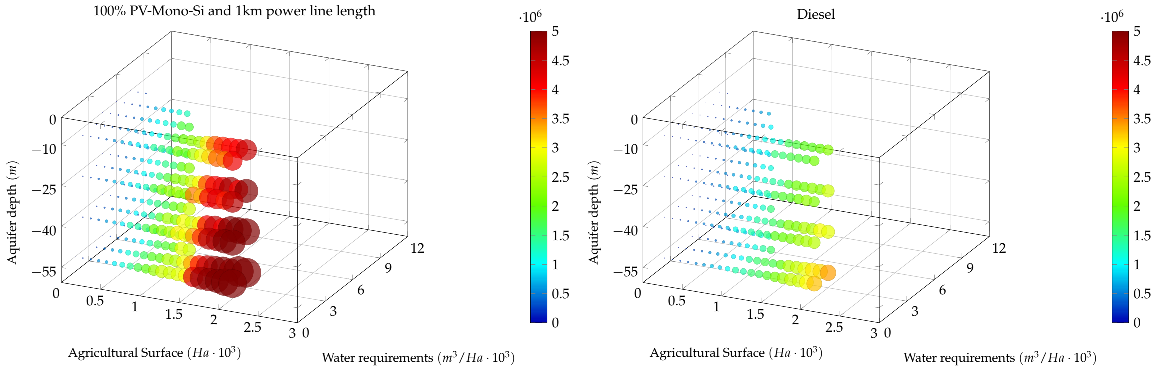
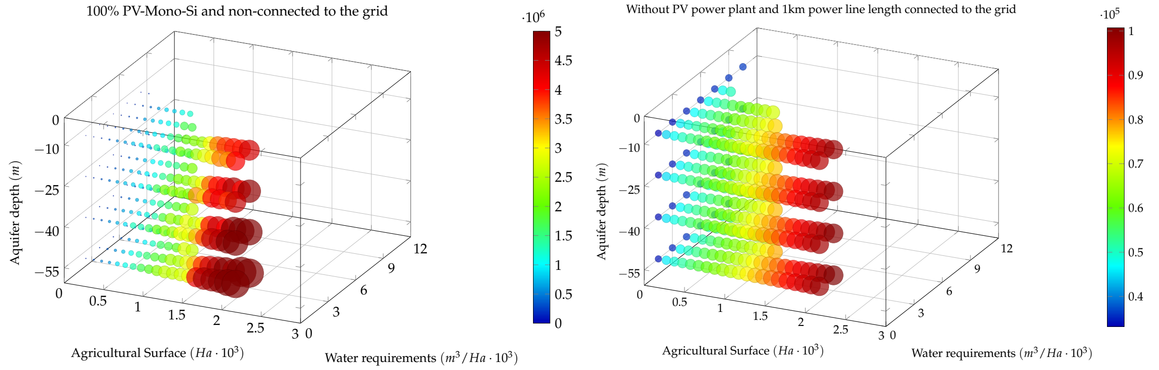


Figure 5: Average Annual Solar Radiation and Phreatic level of Aquifer 23. Castilla-La Mancha (Spain) [63].



(a) Net Balance

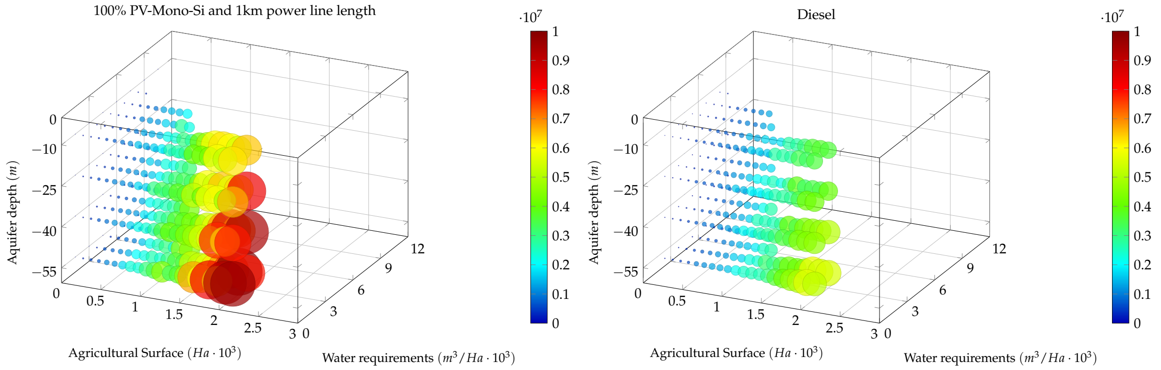
(b) Diesel



(c) Islanding PV solar installation

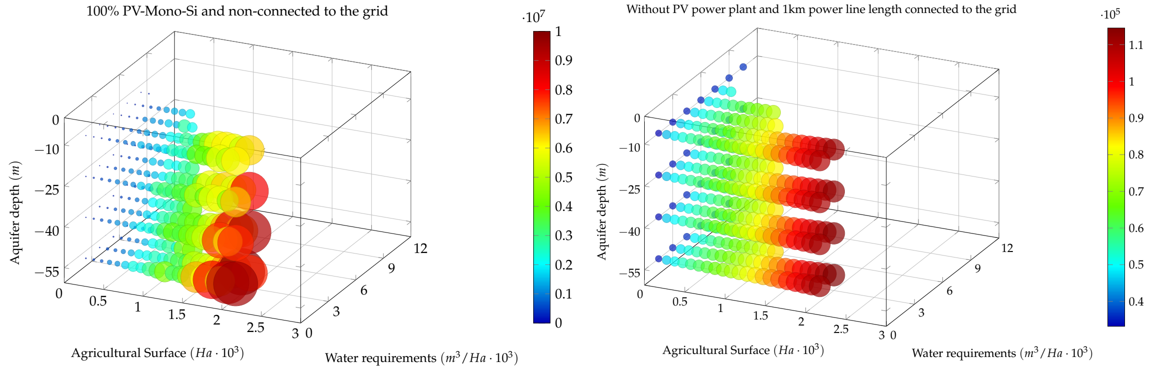
(d) Connected to the grid

Figure 6: Estimated Seasonal Pumping Cost (Euro). Comparison of sources



(a) Net Balance

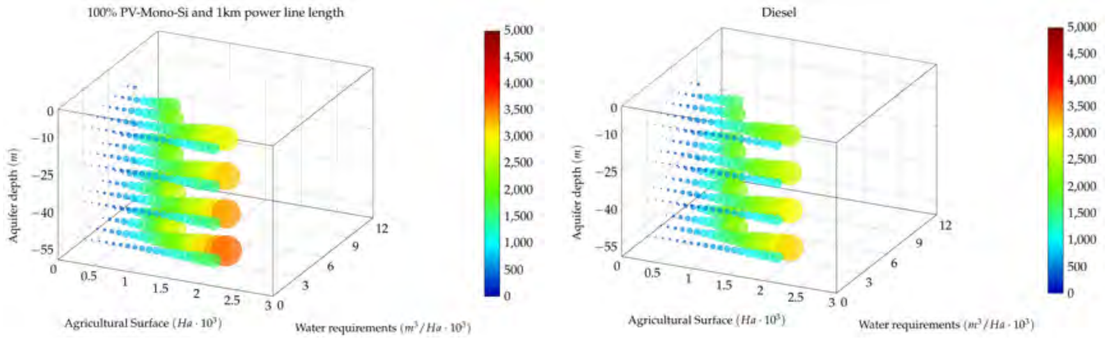
(b) Diesel



(c) Islanding PV solar installation

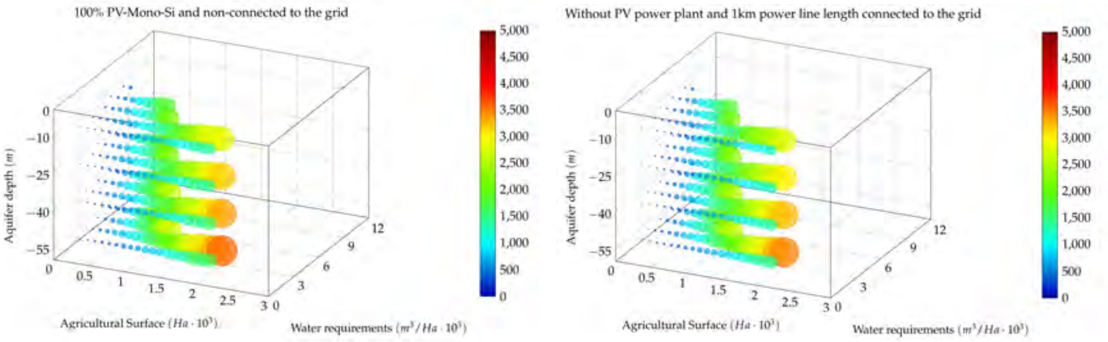
(d) Connected to the grid

Figure 7: Estimated Direct Pumping Cost (Euro). Comparison of sources



(a) Net Balance

(b) Diesel



(c) Islanding PV solar installation

(d) Connected to the grid

Figure 8: Estimated Required Seasonal Pumping Power (kW). Comparison of solutions

connection or when the power line length exceeds several km. The diesel equipment costs account for approximately half of the PV power plant costs, but the emissions are clearly higher as well as the energy dependence. Regarding seasonal and direct costs, the later are initially higher, though seasonal costs would be increased if additional installations related to reservoir purposes were included as well. Another relevant point for future works concerns the grid benefits and market potential generated through the sale of surplus electricity from the PV installations. This objective is beyond the scope of the present characterisation analysis and is currently under study by the authors.

Figure 8 and 9 show the power required for the different alternatives —seasonal pumping and direct pumping— in terms of aquifer depths (1 to 55 m depth), water requirements (1.5 to 10.5 $m^3/Ha \cdot 10^3$) and cooperative agricultural areas (1 to 2000 Ha). These alternatives are characterised and compared taking into account real scenarios from the Spanish aquifer and the crops currently available in this area. In both cases (seasonal and direct pumping), diesel equipment requires less power than the rest of sources. As an example, and considering a direct pumping scenario, $782.2kW$ is the diesel power for $1200Ha$, $1500m^3/Ha{\cdot}10^3$ and $25m$ depth; whereas $1006.2kW$ is the PV power plant required by the same conditions. Therefore, from an economic and power point of view, diesel solution would be initially the selected option. However, and as was previously discussed, relevant emissions and energy dependence should be also considered. In a similar way to the previous cost estimation analysis, no additional facilities are considered for the seasonal scenario and grid benefits generated through the sale of surplus electricity from the PV installations are not also considered.

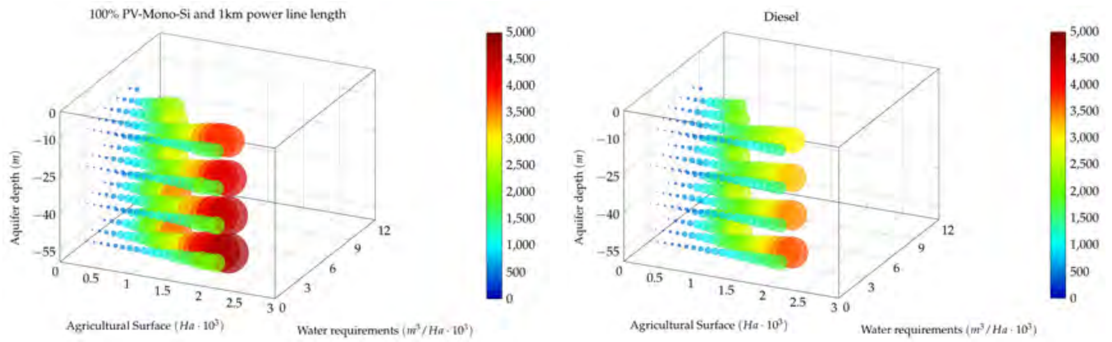
Figure 10 and 11 summarise the CO_2 emissions for the different alternatives. This environmental characterization allows us to visualise and compare how sustainable each solution is in terms of tonnes of CO_2. The diesel equipment obviously gives off the highest emissions, considerably greater than solutions based on PV installations or even for approaches which are connected to the grid. For example, for a seasonal pumping scenario, diesel equipment has 243.58 Tonnes of CO_2 for 1200 Ha, 1500 $m^3/Ha \cdot 10^3$ and 40 m depth; whereas the PV power plant has 9.0 Tonnes of CO_2 for the same conditions. Clearly, from the emissions and energy dependence, diesel equipment is not a suitable solution to be considered by the agricultural sector. However, from an economic analysis, the diesel solution is considerably cheaper than the other resources and, for this reason, an extensive and multidimensional characterisation is then necessary to be conducted before selecting an optimal solution. Consequently, the proposed framework provides an extensive characterisation of each alternative for each realistic scenario. As was previously pointed out, the proposed methodology can be applied to different locations and areas. Therefore, this alternative characterization aims to provide an extensive analysis of a more sustainable scenario with PV power plant integration.

As an additional example, the proposed methodology has been applied on the Saiss aquifer located in the region of Fez-Meknes (Morocco). This aquifer is mainly supported by rainwater infiltration contributions. Nowadays, the aquifer provides an annual irrigation demand between 275 and 400 million $m^3/year$, suffering an intesive agriculture demand and covering relevant drinking water necessities since the 1980s. Subsequently, the aquifer presents a water deficit situation, without pumping constraints and an average water demand between 3500 m^3/Ha and 5600 m^3/Ha. Further information can be found in [66, 67, 68]. Figure 12 summarizes the application of the proposed methodology on this aquifer. In this case, the results for PV installations are depicted and compared for different water requirements, aquifer depths and agricultural areas. The proposed characterization also allows us to compare and estimate solutions with specific agricultural areas; providing both scalability and flexibility properties. With this aim, PV installation costs are compared for 1300 Ha of crops. In this area, the aquifer depth is between 35 and 45 m. Figure 13 shows these costs for annual PV solar pumping requirements.

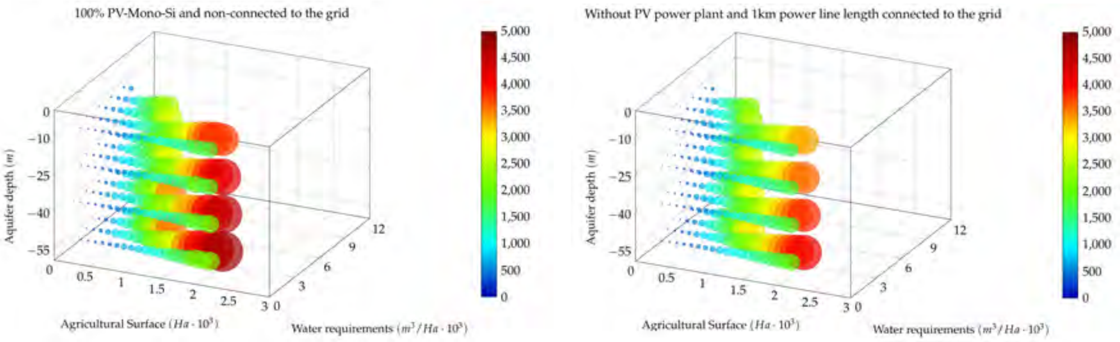
6. Conclusion

A multidimensional economic, energy and environmental analysis is proposed and assessed to characterise the groundwater pumping problem. Different alternatives can be compared, including conventional solutions based on diesel equipment, grid connection and renewable promotion focused on PV solar integration. A real Spanish aquifer mainly used for agricultural purposes has been used to assess the proposed characterisation methodology. By considering current crops, aquifer depths and agricultural water requirements the alternative resources are characterised and visualised from two scenarios: seasonal pumping requirements and direct pumping requirements.

From the results, including seasonal and direct pumping scenarios for the case of cooperative facilities, diesel equipment provides considerably lower investment costs in comparison to the net balance solution or islanding PV solar installation. In fact, the diesel approach is currently one of the most commonly selected solutions by the agriculture sector. However, diesel equipment presents very high CO_2 emissions in comparison to the power system solution or PV solar installations. Therefore, alternatives based on renewable energy sources should be promoted by governments to decrease CO_2 emissions and minimise fossil fuel dependence in the agriculture sector. This analysis can be extended by including other additional variables, such as investment costs in irrigation infrastructures (reservoir) and annual electricity or fuel costs (diesel). According to the results and the characterization of alternatives, this methodology presents a low computational time cost and it is suitable to be aaplied on different agricultural areas and scenarios. In addition, an estimation of the optimal

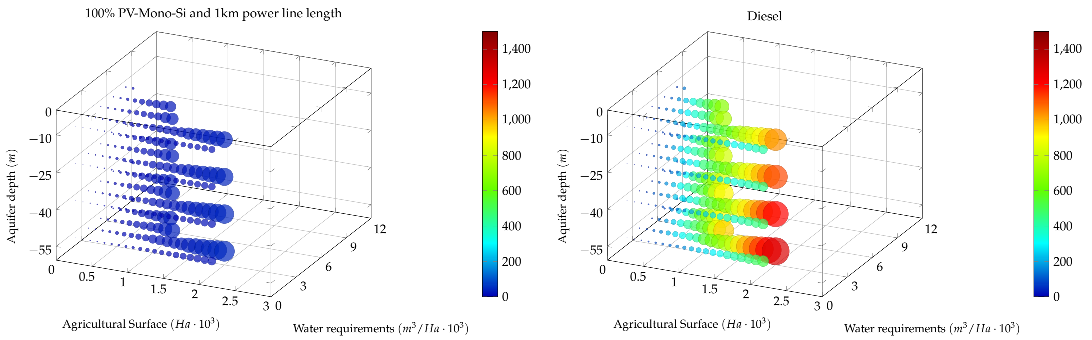


(a) Net Balance (b) Diesel

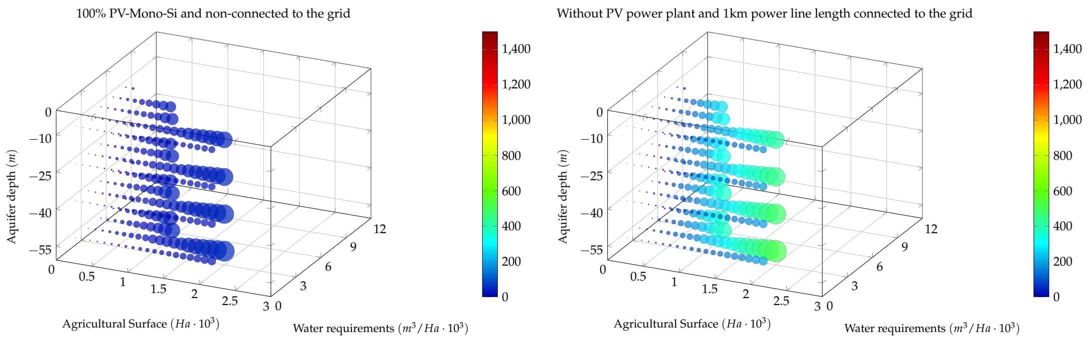


(c) Islanding PV solar installation (d) Connected to the grid

Figure 9: Estimated Required Direct Pumping Power (kW). Comparison of solutions

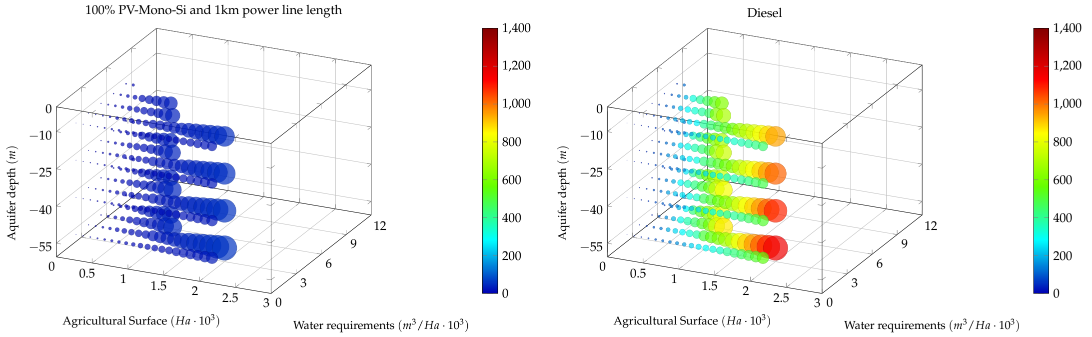


(a) Net Balance (b) Diesel

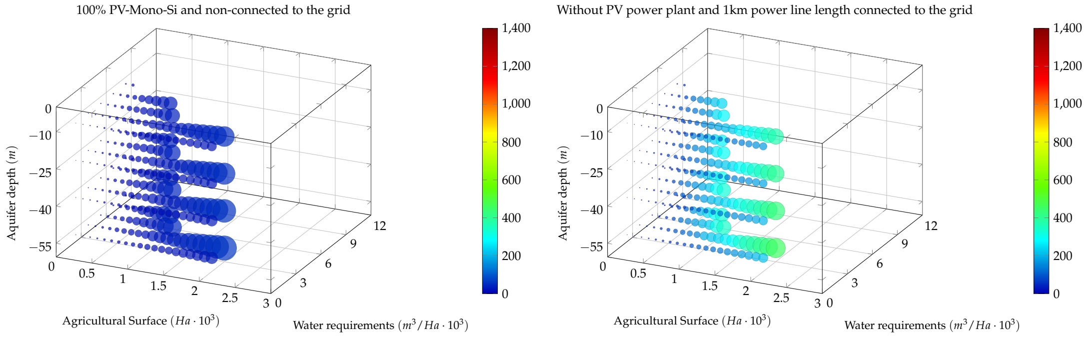


(c) Islanding PV solar installation (d) Connected to the grid

Figure 10: Estimated Seasonal Pumping Emissions (Tonnes of CO_2). Comparison of sources



(a) Net Balance (b) Diesel



(c) Islanding PV solar installation (d) Connected to the grid

Figure 11: Estimated Direct Pumping Emissions (Tonnes of CO_2). Comparison of sources

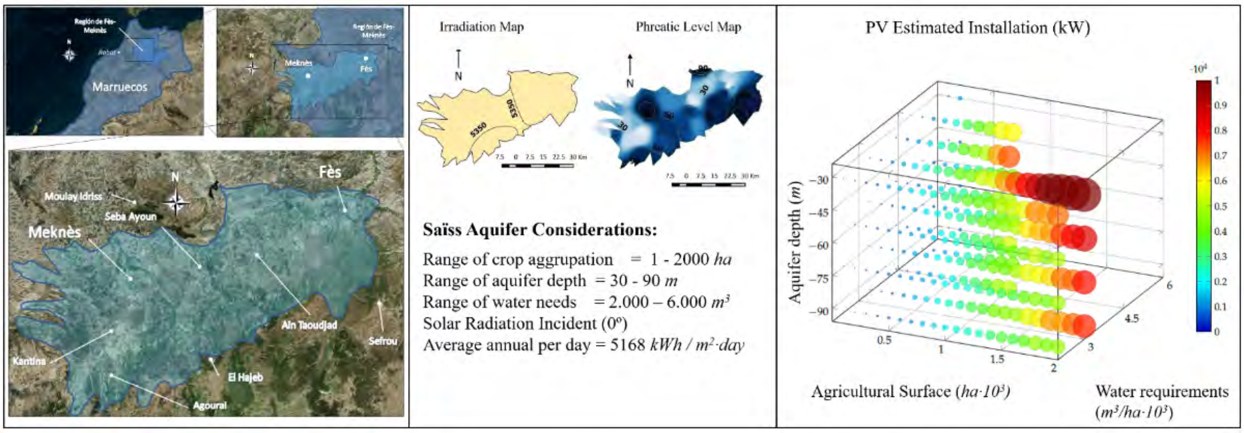


Figure 12: PV estimated installation: Saïss aquifer (Meknès, Morocco).

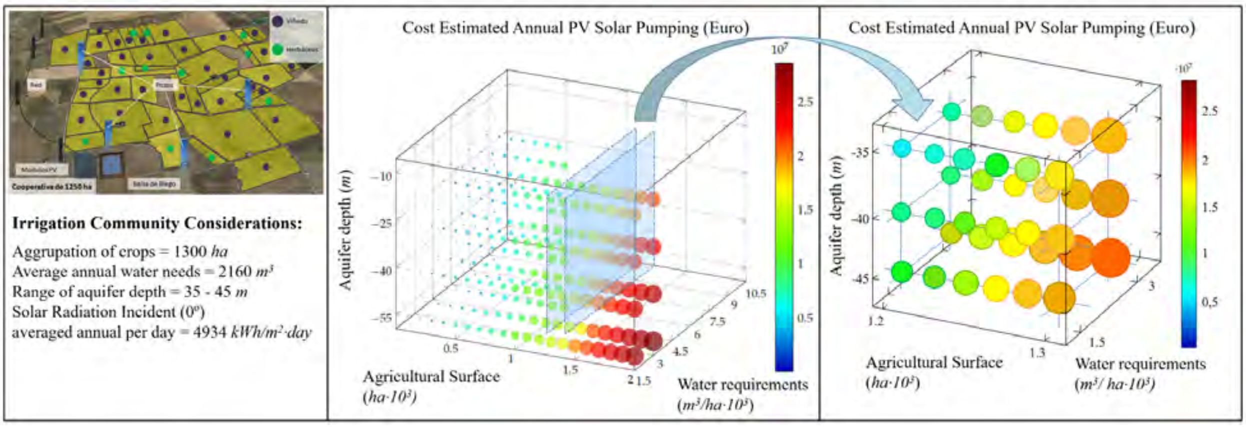


Figure 13: Cost estimated for annual PV installation (1300 ha): Saïss aquifer (Meknès, Morocco).

areas for agro-energy cooperatives are also provided by the proposed methodology based on different aquifer depths and crop water requirements.

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