Assessment of Groundwater Pumping Alternatives for Irrigation Purposes based on the SIMUS Method

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***Abstract*—The agricultural sector production in developing countries is highly dependent on rains, being affected by scarcity periods and important water resource reductions in summers. It is very common in countries of the Mediterranean basin that need to pump water for the irrigation of crops, mainly due to the problems of drought and shortage of surface water for irrigation. The water pumping from the subsoil can be then assumed as annual, seasonal or direct, identifying different types of energy sources such as fossil fuels —mainly diesel equipment—, direct supply from grid or PV power plants —isolated or connected to the grid through net-balance system—, which are required to be applied by the agricultural sector. It can be affirmed that the majority of the commercially available water pumps run with electricity generated by Diesel engines and renewables, more specifically photovoltaic (PV) solar technologies, which have become a competitive alternative to pump water with real advantages over traditional fuel-driven generators. However, PV Water Pumping (PVWP) solutions have been marginally implemented; being considered as an electric energy source mainly in remote locations or through hybrid solutions. This paper describes a multidimensional methodology assessment of the different types of groundwater pumping with their potential combinations of aggregated agricultural areas, aquifer depth, and irrigation crop requirements, to determine the optimum or suitable size for future implementation of the most advantageous system, according to the aquifer depth and the water endowment defined. For that, this paper uses the SIMUS method for the assessment of the different types of groundwater pumping, with their potential combinations, by considering specific water aspects of the Spanish studied area (Castilla La Mancha, Spain).**

Keywords—Multi-Criteria Decision Making (MCDM), SIMUS, Solar groundwater pumping

I. Introduction

The production of the agricultural sector in many countries is highly dependent on rains, and affected by scarcity periods and significant water resource reductions in summer time. Because of this, it is very common in countries of the Mediterranean Basin, to pump groundwater for the irrigation of crops, mainly due to drought and shortage of surface water for irrigation. Water is extracted from aquifers using a submersible water pump. The energy may be supplied by a diesel engine generator (Diesel), photovoltaic panels (PV) connected to grid (PV-grid Net-Balance) or isolated (Isolated PV) or taken from electric grid (Grid).

In this paper we work with 12 different alternatives, being the selection of the most adequate the aim of the paper. These 12 options are grouped in three modes, as follows [1, 2, 3]:

1- *Direct*: The water is extracted and immediately used,

2. *Seasonal*: The water is extracted during a season, and stored in dedicated reservoirs or ponds for their future use,

3. *Annual*: The water is extracted throughout the year and stored in dedicated reservoirs or pond, until its use.

Nowadays, most of the commercial water pumps equipment work with the supply of either electricity from the grid or from Diesel engines. However, PV Water Pumping (PVWP) [1-4] has been marginally implemented; being considered as an electric energy source mainly in remote locations or through hybrid solutions. There are four different ways for managing water pumping, with three options or alternatives each, as illustrated in Figure 1. To select the best mode, which is the objective of this paper, it is considered that the 12 options are subject to 9 criteria, as follows:

- C1 - Investment in installation,
- C2 - Investment in structures,
- C3 - Maintenance cost,
- C4 - Operating cost,
- C5 - Sale of surplus energy,
- C6 - Installed power,
- C7 - CO_2 emissions,
- C8 - Evaporation,
- C9 - Job generation.

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This paper describes a methodology for assessment using the Sequential Interactive Method for Urban Systems (SIMUS) method [5-7], where the previous 12 different alternatives are evaluated by a set of criteria; in this case, 5 main criteria with 9 sub-criteria in total, see Fig. 1.

The rest of the paper is organized as follows: Section II describes the study area; Section III discusses the methodology and the different alternatives to be subject to nine criteria for their evaluation; Section IV presents the mathematical tool used for estimating the most convenient alternatives; Section V provides results and their analysis; finally, conclusions are given in Section VI.

II. Description of tha study area

The Castilla-La Mancha autonomous region (Spain) has an area of about 79,409 km^2; its main wealth lies in agriculture, especially wheat as well as fruits such as oranges, almonds, melons, and saffron, as well as other crops, vegetables and fruits. Figure 2 shows its location within Spain, while Figure 3 depicts the profile of the aquifer with the levels of water or piezometric levels and the average annual solar radiation in the aquifer. It can be seen, and this is important for the study, that said level varies from 20 to 80 metres below the surface.

In this study it is considered an average level or depth of 50 metres, but of course, the same procedure may be applied to any other depth. The water is extracted by submersible water pumps, fed by AC from different sources, such as Diesel generators, solar dishes, photovoltaic and biomass, which can be used standalone or combined. The region is served by the Spanish National Electric Network, the Grid.

Considering the different sources there is no problem in getting enough water for irrigation, however, there exists, as explained, about 12 different modes on which this water can be pumped, and determining the most convenient one is the purpose of this paper.

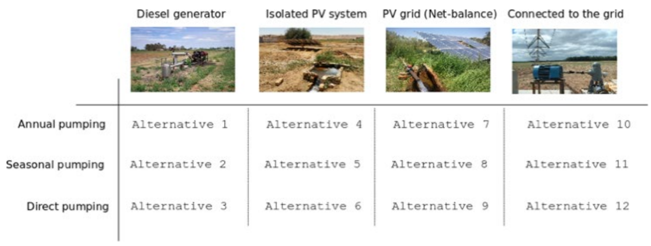

Fig. 1. Alternatives or options and pumping management modes [1,4].

Fig. 2. Location of Castilla La Mancha in Spain

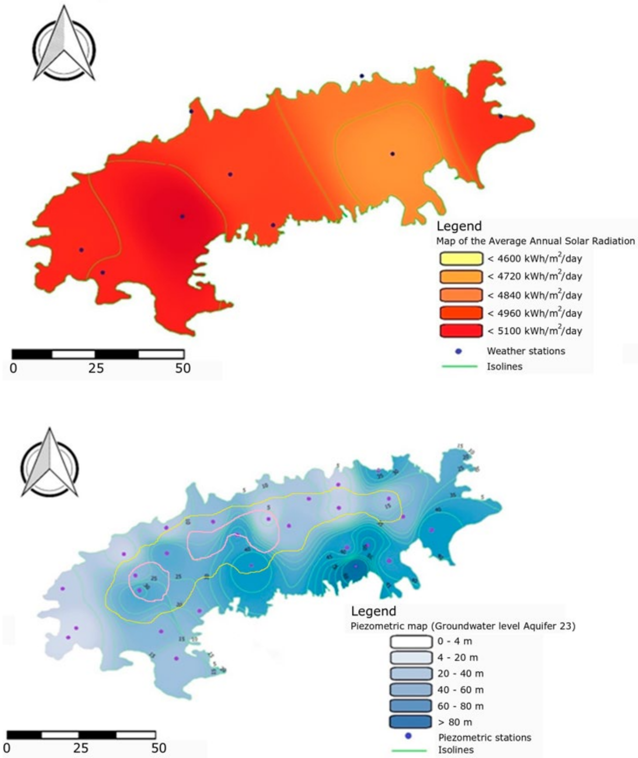

Fig. 3. Case study: Criteria and Alternatives identification [1,4].

III. Methodology and options description

Water extraction from the aquifer is standard and common for all modes of pumping, and the costs vary according to the depths of the wells and the amount of water needed in a year, which in turn depends on the total number of hectares and the type of production, since each one has different water requirements. However, an aspect is necessary to point out: the decision to extract water as needed, or extract water during certain periods and then store it in open ponds. Of course, there are advantages and disadvantages in both operation modes and, subsequently, it is very important the opinion of the farmers and different sectors to order the solutions in a more convenient way.

The advantage of the ponds is water immediate availability for utilization. However, there are some drawbacks to be considered, such as: *(i)* a fix and considerable investment is the lining of the bottom of the ponds with welded layers of strong plastic, to avoid losses due to filtration of the water back to the undergrow, and without guarantee that it goes back to the aquifer; *(ii)* evaporation in open ponds is another remarkable disadvantage. Indeed, Castilla -La Mancha is sunny country, where peaks of 35º C or more are common in summer time, with an average of 27ºC.

In this study, the different alternatives are evaluated by considering electric generation sources and water storage. With this aim, the corresponding alternatives are then identified by the combinations of solutions for pumping/storage and energy resources:

- *Alternative A1. Annual pumping supplied by a diesel generator*. In his option, water is raised throughout the year to a reservoir with a sufficient capacity to store the water needed at the time of irrigation, demanding a low amount of energy in comparison with the other alternatives.

- *Alternative A2. Seasonal pumping supplied with a diesel generator*. In the case of seasonal pumping, water is stored ahead of time of irrigation season, in the amount needed during the season. Due to that fact, size and cost of hydraulic infrastructures are lower; however, costs and sizes of the energy facilities are greater. In this case, the energy is also supplied by diesel generators.
- *Alternative A3. Direct pumping by a diesel generator.* This option lacks storage systems, since water is only pumped when needed. Therefore, cost of water infrastructure is considerably reduced, at the expense of increasing the energy installation. This system requires more pumping points to avoid depletion of the well when the water demand per unit of time is very high. This is the most common case, especially in small individual facilities.
- *Alternative A4. Annual pumping, with energy from and isolated PV system*. This option is similar to Alternative A1 with the difference of providing energy by an isolated PV solar facility instead of diesel generator.
- *Alternative A5. Seasonal pumping with energy from an isolated PV solar system*. In the same way, this configuration is similar to Alternative 2 with the exception of providing the energy through an isolated PV solar facility instead of diesel generator.
- *Alternative A6. Direct pumping by isolated PV solar system*. Once again, this option only varies with respect to Alternative 3 in the energy generation. The fluid is provided by an isolated PV facility instead of a diesel generator.
- *Alternative A7. Annual pumping by a PV power plant in net balance*. This configuration is quite similar to Alternative 4. The only difference is the configuration of the PV facility which is no longer isolated. In this case, this system is connected to the grid allowing not only supplying the energy demanded by the pumping, but also taking advantage of the energy that is not consumed.
- *Alternative A8. Seasonal pumping by photovoltaic PV system in net balance*. This configuration is quite similar to Alternative A5. Both alternatives differ in the configuration of the PV installation: isolated vs. connected to grid. In this case, the PV power plant is connected to the grid. A PV system with the support of grid is able to supply the necessary energy during the irrigation season. Due to that, this option offers the possibility of selling the excess energy.
- *Alternative A9. Direct pumping supplied by a PV system in net balance*. This option only varies with respect to Alternative 6 in the photovoltaic configuration (isolated vs. connected to grid). In this case, the PV system is connected to grid. Through this configuration, it is possible to match the energy demand by the pumping and take advantage of the energy that is not used in the months in which it is not required by the crops.
- *Alternative A10. Annual pumping supplied with grid connection*. In this configuration, as opposite to Alternative 1 the electrical grid provides the energy.
- *Alternative A11. Seasonal pumping supplied with grid connection*. In the same way, this configuration is similar to Alternative 2 with the exception of the way energy is delivered. That supply, in its totality, is provided via grid connection. Therefore, energy that requires pumping is supplied through electrical grid.
- *Alternative A12. Direct pumping by grid connection*. Again, this option is similar to Alternative 3. Its only difference is the way of energy provided (diesel generator vs. grid connection). A connection to the electricity grid allows to match the energy demand.

The purpose of this paper is to scientifically select the most convenient mode, subject to a series of constraints. These different alternatives or options to be evaluated are time-related regarding the different schemes of pumping to the crops, based on depth of the wells as well as volume of water needed. In this case, water extraction from 55 meters depth and a water irrigation volume of 3000 $m^3/year$, as well as their different alternatives are evaluated considering a variety of electric generation sources and water storage options.

IV. Description of the Mathematical Procedure Used for Selection

The SIMUS method is proposed by the authors to order the alternatives. With this aim, a hybrid method based on Linear Programming (LP) and Simple Additive Weighting (SAW) and on the Outranking procedure [4,5,6] is sequentially applied. SIMUS starts from an initial matrix. A set of alternatives are ordered in columns and criteria in rows accordingly. In the specific literature can be found others methods which, in general, use such matrix or the transpose as starting point. However, there is a difference in the sense that SIMUS works with inequalities. Because of that, the rows are inequalities with a left member (LHS or Left-Hand Side), and a right member (RHS or Right-Hand Side). Both members are linked by mathematic symbols, such as '≥' (Greater, or equal than), '≤' (Less, or equal than), and '=' or equality. That is, in lieu of working with lines as in equations or equalities, it works with spaces. This is the main advantage of LP since by working with spaces it gives a very large latitude for variation of criteria. For instance, it allows considering two limits: one minimum and one maximum for a same criterion, and then, the model can select an intermediate value as function of its relation with other criteria. Another advantage of LP is that it does not use weights for criteria or for the corresponding alternatives and thus, there is no room for subjectivities. However, it does not mean that relative importance of the different criteria is not considered. In fact, they are computed mathematically in each iteration of the model based on the inputted data. Consequently, no matter who carries out the calculation, a problem always gives the same result.

Another advantage is that if there is a solution to a problem, the LP methodology finds it, and if the problem is not feasible for whatever reasons, the model informs about it. SIMUS uses the LP Simplex algorithm for each row. The result is another initial decision matrix, which is Pareto efficient. From this matrix, SAW is applied and a first solution Efficient Results Matrix (ERM) found, which displays the scores for each alternative, the larger the better, and the ranking. It is thus applied outranking on the Pareto efficient matrix SIMUS, providing a second solution Project Dominant Matrix (PDM) with different scores, but with exactly the same best alternative and the same ranking than ERM.

This way, one solution checks the other, to make sure that there is perfect convergence and feasibility. Each problem is then solved with LP or SIMUS (which is called the Primal problem). It is simultaneously available the result of a transpose problem displayed, called the 'Dual' of the Primal. The primal gives the scores and ranking of the alternatives, while the dual provides the marginal values (costs or benefits) of criteria, and both of them give the same quantitative results. These marginal criteria values are not weights, and they indicate how much the objective varies when one unit is added or deducted from the RHS of a criterion. This is fundamental to determine the robustness of the solution found. The Decision Makers (DM) plays a paramount role in SIMUS, because, each of them selects the criteria to evaluate the alternatives, after receiving from the stakeholders and technical departments of a company or entity the corresponding potential alternatives. There are no limits for number of criteria, and they can even be in the thousands. The DM can follow the computation step-by-step, to observe partial results and even change data and, as a matter of fact, this is the system used for Group Decision Making, though the DM may prefer to get directly to the final result. Once it is known, it can be considered as the most appropriate order since it has been estimated excluding any subjectivity. Consequently, each DM can apply his/her knowledge, expertise, common sense and even preferences in analyzing the result and he/she may be satisfied or dissatisfied with it, and then criteria values can be changed, criteria can be added or deleted, or even the result can be rejected. The DM can make this operation as many times as he/she wishes, because changing values or adding new data takes only some minutes to get a new solution. Therefore, the DM executes a bottom-up approach, based on results mathematically obtained and on his/her judgement. For instance, using the criteria marginal values, as well as the range of validity (also given by SIMUS), the DM knows how much is able to increase/decrease the criteria, which are responsible for the solution. In some occasions, based in this analysis, the DM can suggest to disregard the best alternative determined by the model and choose instead other alternative. Figure 4 depicts the result produced by SIMUS. It can be seen that alternative *'Annual Grid'* is the best option, followed by *'Direct PV Net'*. It can also be seen the ranking for the other options.

V. Result and Its Analysis

This result has been obtained by a strictly mathematical procedure based on original data, with not subjective data inputted, and from this point of view this is unobjectionable. However, we need to analyze this result from the point of view of its stability and strength, that is, if this solution holds when there are variations in some parameters. From Figure 4 it can be ascertained that the intervening parameters are Z1, Z8 and Z9. These correspond to the criteria with the same sub index. Consequently, we need to determine how variations in these three parameters affect the result. Table I shows this analysis and conclusions for each one.

Which is the meaning for these conclusions?

1. It is obvious that drawing energy from the grid implies an infrastructure cost smaller than using any form of PV. However, the low value of allowed variation from using the grid (0.01), seems to indicate that a slightly decreasing of infrastructure cost of renewable energy, may provoke that taking energy from the grid might not be the best option, and possible yields its position to the second best which is *'Direct PV Net',* and this is probable to happen, because new advances in PV cells and its increasing utilization and production will reduce costs. In addition, this is confirmed when considering criterion C1, which is the cost of installation using the grid; its (0) value shows that it is not possible to reduce this cost without altering the ranking.
2. The option of annual pumping involves losses because evaporation, and this is inconvenience related to water storage, and, in addition, the construction of the pond or reservoir, which has to be bottom lined to avoid water filtration to the underground. Consequently, from the point of view of water saving it is better the direct extraction. It is true that the computation indicates that it is possible to decrease evaporation in 0.04 without altering the solution, however, this is not an easy and inexpensive task. With a value greater than that, that is, if it is possible to decrease evaporation, there is no guarantee that the solution holds. This can be understood because by decreasing evaporation for whatever means, can cause the solution reverse. Consequently, the Direct PV Net would possibly be the best option, since all water extracted is used.

Efficient Results Matrix (ERM) Normalized

	Annual Diesel	Seasonal Diesel	Direct Diesel	Annual PV	Seasonal PV	Direct PV	Annual PV Bal Net	Seasonal PV Bal Net	Direct PV Bal Net	Annual Grid	Seasonal Grid	Direct Grid
	Project 1	Project 2	Project 3	Project 4	Project 5	Project 6	Project 7	Project 8	Project 9	Project 10	Project 11	Project 12
Investment in installations Z1										0.97	0.03	
Investment in infrastructure Z2	1.00											
Maintenance cost Z3								1.00				
Operating costs Z4									1.00			
Surplus sale of energy Z5			1.00									
Installed power Z6				1.00								
CO_2 emissions Z7			0.04						0.96			
Evaporation Z8						0.01				0.75	0.24	
Jobs generated Z9										1.00		
Sum of Column (SC)	1.00	0.00	1.04	1.00	0.00	0.01	0.00	1.00	1.96	2.73	0.27	0.00
Participation Factor (PF)	1	0	2	1	0	1	0	1	2	3	2	0
Norm. Participation Factor (NPF)	0.11	0.00	0.22	0.11	0.00	0.11	0.00	0.11	0.22	0.33	0.22	0.00
Final Result (SC x NPF)	0.11		0.23	0.11				0.11	0.43	0.91	0.06	

ERM Ranking   Annual Grid -Direct PV Net – Direct Diesel – Annual Diesel – Annual Solar PV – -Seasonal PV Net – Seasonal Grid

Fig. 4. SIMUS screenshot with the best option and ranking

TABLE I. ANALYSIS OF THE SOLUTION FOR THE BEST ALTERNATIVE (GETTING ANNUAL ENERGY FROM THE GRID)

Objective	Criteria	Marginal values for criteria	Marginal values range		Conclusions	Action required
			↑	↓		
Z1	C2	0.01	0.18	0.01	It is possible to slightly decrease the infrastructure cost without altering the solution (1)	MIN
	C8	0.03	0.01	0.04	It is possible to decrease evaporation without altering the solution (2)	MIN
Z8	C1	0.31	0.05	0	It is not possible to decrease the installation cost without altering the solution (3)	MIN
	C2	0.10	0.13	0.03	It is possible to decrease the infrastructure cost without altering the solution (4)	MIN
	C7	0.48	0.11	0.12	It is possible to decrease the CO_2 emissions without altering the solution (5)	MIN
Z9	C5	4.69	∞	0.32	There id no limit for the retribution by energy sale, and also de ranking is not modified if this sales decreases in a certain extent (6)	MAX

3. By decreasing the installation cost, it is probable that the annual pumping from the grid will resign its position to the second place, since the Direct PV Net would be the best option. This appears to be contradictory since, by decreasing installation cost from the grid, gives more chances to this option. However, there is an aspect that has not been previously considered, and it is losses from filtration. To avoid this loss, it is necessary to line the bottom of the pond with a costly welded plastic liner, which involves extensive labor and costly liner.
4. Same considerations as in (3).
5. It is obvious that in getting power from the grid no CO_2 is generated in the field, therefore, this criterion is irrelevant here.
6. The sale of energy has very high marginal value (4.69). This value meaning that a unit increment in the power delivered from the PV produces large benefits, which shows that advantage in working with renewable energy in comparison with Diesel and the grid solution. In addition, the ranking does not change if the sale of energy decreases, since the allowed margin is 0.32.
7. The maximum value that can be obtained from the sale of energy, belongs to the *'Seasonal PV Net'* with a value of (0.41). The amount of 0.32 indicates that the sale of energy can decrease down to: $0.41–(0.11·0.32) = 0.37$; without any alteration of the ranking and being 0.11 the lower limit of such variation.

TABLE II. SCREENSHOT OF SIMUS (V.3.1.5) RESULT FOR DETERMINATION OF THE RELATIVE IMPORTANCE OF OBJECTIVES

	Max	*Normalization*	*Rank*
C1- Investment in installation	0.97	0.11	2
C2 - Investment in structure	1.00	0.12	1
C3 - Maintenance cost	1.00	0.12	1
C4 - Operating cost	1.00	0.12	1
C5 - Energy sale to grid	1.00	0.12	1
C6 - Installed capacity	1.00	0.12	1
C7 - CO_2 emissions	0.96	0.11	2
C8 - Evaporation	0.75	0.09	3
C9 -Jobs generation	1.00	0.12	1
TOTAL	8.68		

Additional information

There is another information available from the SIMUS method. It is related with the relative significance of the objectives as outputs that conform the solution, and then, indicating which are the most important objectives that have to be closely controlled during operation of the system.Table II shows them. It can be seen that there is little variation between importance since the values are very similar. The most important are Investment in structure, Maintenance cost, Operating cost, Energy sale, Installed capacity and Jobs generation. Therefore, it seems sensible to pay special attention to these objectives, during the operation stage of the system.

VI. CONCLUSIONS

A Spanish region is analyzed to determine the most convenient mode for managing pumping water extracted from aquifers. Because there is a large range of aquifers depths as well as different water needs, this study considered 55 m depth and 3000 $m^3/year$ of water needs to irrigate 2000 *ha*.

The result shows that for the time being, the most convenient mode is using electricity taken from the grid, followed by using a mode of direct extraction from electricity generated by PV, and linked to the grid to sell surplus energy. A sensitive analysis is performed to determine the strength or stability of such most convenient option, when examined regarding the effect that potential variations of some parameters (criteria) may have on the result. Even when the best alternative is considered stable by most parameters, there is a high possibility that foreseeable changes in them will reverse the selection. These changes are, for instance, the constant improvement of the efficiency of PV cells, the diminishing production cost as well as the increasing utilization, as well as the necessity to incur in additional expenses because the need to bottom-line ponds to avoid losses by filtration of the stored water to the underground. To this, it is necessary to add the losses for evaporation in a warm region and consequently the necessity to extract additional water in order to compensate evaporation losses.

A large advantage of the second selection (extracting water by using PV generated power, and using it immediately), is that excess energy can be fed into the grid, and then, with positive economic result to farmers due to energy selling.

These conclusions derive from examining the result using a mathematical approach, that is, selecting the parameters that have significance in the selection of the best solution and its ranking. Thus, out of the nine criteria considered for alternatives evaluation, only Z1 (Investment in installations), Z8 (Evaporation) and Z9 (Job generation), while the other are irrelevant. In addition, the relative importance of each objective has also been computed. As a conclusion, the best selected mode is taking annually enough energy from the grid to fill the ponds. However, even when this selection is robust, one cannot ignore that efficiency improvement of PV cells, their mass production, which has drastically reduced its price, and the losses due to water evaporation in ponds, suggest that a better selection is using the PV mode with direct utilization and net balance. It is believed that more complex scenarios can be examined in the same way, for instance. considering water demand for each type of crop, different depths, potential improvement in some technologies as in wind, bio and PV, potential cost decreases for these elements, etc.

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