MCDM-based Multidimensional Approach for Selection of Optimal Groundwater Pumping Systems: Design and Case Example

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Abstract

Herein, optimal groundwater pumping solutions based on a variety of energy resources and water storage options are estimated and classified. Each energy source and water storage option is first characterized considering energy, economic, and environmental criteria. A multi-criteria decision making (MCDM) process based on the analytic hierarchy process (AHP) and the technique for order performance by similarity to ideal solution (TOPSIS) is subsequently applied to identify and classify the optimal groundwater pumping solutions under such a multidimensional framework. An aquifer located in the southeast of Spain is analyzed in a case study to assess the proposed optimal MCDM-based approach. Conventional diesel-based equipment, solar PV power plants, and direct grid connection, as well as three water storage systems—direct pumping, seasonal storage, and annual storage—are identified as potential energy sources and water storage options, respectively. Characterization and visualization of these energy and water storage systems, as well as prioritized option results, are also discussed herein.

Keywords: Groundwater pumping, Economic-Energy-Environment analysis, Multi-Criteria Decision Making (MCDM), AHP/TOPSIS Method.

Nomenclature

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CI	Consistency Index
CR	Consistency Ratio
GIS	Geographic Information System
ELECTRE	ELimination and Choice Expressing Reality
MCDM	Multi-Criteria Decision Making
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
RES	Renewable Energy Sources
RI	Random Index
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
PV	PhotoVoltaic
PVWP	PV water pumping

1. Introduction

With the relevant integration of renewable energy sources (RES) into most of the sector, renewables currently represent an energy transition opportunity in agriculture [1]. Considerable efforts are being made to improve the efficiency of irrigated agriculture [2], where current commercially available water pumps mostly run on electricity or diesel-powered equipment [3]. Among the different solutions, solar photovoltaic (PV) water pumping systems can be used efficiently for water pumping in agriculture [4]. Moreover, they play a vital role in reducing the consumption of conventional energy sources and their environmental impact for water pumping applications [5]. Examples of different PV water pumping systems are provided in various studies, mainly as an alternative to traditional diesel pumps [6]. Ouoba *et al.* describe the sizing and optimizing of PVWP solutions applied in the tertiary sector at the Faculty of Science and Technology of Mohammedia (Morocco) [7]. The optimal size of PV water pumping systems to replace diesel-fueled generators for an existing farm in Oman is determined in [8]. Recently, PVWP technology has been proposed to fulfill the domestic water requirements of five isolated houses located in a remote Moroccan area [9]. An analysis of the prevailing conditions for irrigating cassava based on PV solar technology is described in [10], where solar energy resource availability is also studied. However, PVWP solutions have rarely been implemented, and they are considered as electric energy sources only in remote locations [11, 12], as a part of hybrid solutions —i.e. integrating fuel cells and solar panels [13], or as standalone solar PV with groundwater pumped-hydro-storage systems [14]. In addition, and according to the authors in [15], the 'cost per watt' is a relevant drawback to considering PV installations as a major solution for water pumping purposes. Moreover, Sampedro *et al.* recently affirmed that fossil fuel subsidies are one of the most prominent barriers to tackling climate change, encouraging inefficient energy consumption, and diverting investment

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away from clean energy sources [16]. Closas and Rap show that most policies and projects promoting PV solar-based groundwater pumping for irrigation through subsidies and other incentives overlook the real financial and economic costs [17]. PVWP can thus be considered as a promising alternative to conventional pumping systems and a cost-effective application [18]; mainly in remote off-grid areas of developing countries —such as Algeria [19]— and due to the ongoing inflation of fuel costs leading to a consistent increase in operational and maintenance costs [20].

Under this scenario of different possible combinations of resource usage and water storage options for groundwater pumping solutions, the application of Multi-Criteria Decision Making (MCDM) methodologies constitutes a useful tool to prioritize these combinations and estimate the most appropriate solutions under a multidimensional framework. An MCDM approach is defined as a selection process from among different alternative courses of action, based on a set of criteria, to achieve one or more objectives [21, 22, 23]. During the last decade, a large number of MCDM methodologies have been proposed under different hypotheses. Some examples include the preference ranking organization method for enrichment of evaluations (the PROMETHEE methodology [24]) developed by Brans *et al.* [25]; the ELimination and Choice Expressing Reality (ELimination Et Choix Traduisant la REalité –ELECTRE) from the French school [26]; the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) both of which were proposed by Tomas Saaty [27]; and the technique for order performance by similarity to ideal solution (TOPSIS) developed by Hwang and Yoon [28]. Several studies based on an individual or combined application of MCDM techniques have been carried out in the field of groundwater management. The combination of AHP/ANP methodologies was proposed by Agarwal *et al* to determine the corresponding weights or coefficients of relevance for each criterion, which influence the evaluation of potential groundwater zones. The AHP/ANP methodologies were used to delimit the area of potential groundwater in a region of India [29]. Recently, An *et al.* designed a sustainability assessment methodology to prioritize groundwater decontamination technologies based on a combined fuzzy logic process from both the AHP and ELECTRE methodologies [30, 31]. Water management strategies have also been analyzed, not only by using the TOPSIS methodology alone [32], but also in combination with the AHP methodology [33]. Other work focused on groundwater pumping solutions has been described in the literature. For example, Liu *et al.* optimized a pumping well design located in northwestern China by using the TOPSIS method [34]. The potential for groundwater in a semi-arid region of India was also evaluated by combining remote sensing techniques, a Geographical Information System (GIS) computer tool and the AHP methodology [35]. Indeed, GIS has been recently used to analyze different resources such as solar, wind, biomass, geothermal, and hydro-power, to determine potential sites within the

Fukushima Prefecture (Japan) based on geographic, topographic, and land use constraints [36]. Therefore, by considering the field of management and groundwater pumping, the scientific literature affirms that MCDM is a well-known branch of decision making. Indeed, it is a branch of a general class of operations research models that are used to solve decision problems considering several decision criteria. However, there is a lack of contributions to evaluate and prioritize different groundwater pumping alternatives. Moreover, the results in [37] affirm that renewable energy sources (RES) contribute to achieving the '3E' objectives: energy, economic, and environmental goals. These objectives have been studied and proposed in other areas, such as waste management [33], or in the role of wind energy in China [38] and Japan [39]; but they have not been taken into account in the field of agriculture to date. Subsequently, and from the perspective of the 3E objectives and the evaluation and prioritization of groundwater pumping solutions for irrigation purposes, the main contributions of this paper can be summarized as follows:

- A multidimensional characterization of different energy resources and water storage options based on energy, economic and environmental criteria.

- An MCDM application based on AHP/TOPSIS techniques to prioritize such resources and water storages within a multi-objective framework.

The rest of this paper is structured as follows: Section 2 describes the proposed methodology; the case study is described in detail in Section 3; the results are discussed in detail in Section 4; and, finally, the conclusions are given in Section 5.

2. Proposed Methodology

2.1. *Overall process*

The proposed methodology is firstly based on the identification of the groundwater pumping systems based on different energy resources and water storage options. These systems are then characterized through a multidimensional criteria scenario to consider energy, economic, and environmental aspects. This characterization is in line with recent approaches addressed by the authors to discuss the application of renewables for underground water resource purposes [40]. From this preliminary characterization in a multidimensional framework, an MCDM approach is used to provide a classification of groundwater pumping systems, with the aim of making the identification of optimal solutions easier. Different applications under some disciplines can be found in the literature, such as energy, supply chains, tourism management, construction, risk management, distribution [41]. Therefore, a combination of the AHP and TOPSIS solutions is applied according to the previous contributions discussed in Section 1. In general, a literature review indicates that AHP is a popular approach to cope with MCDM problems [42]. The Analytic
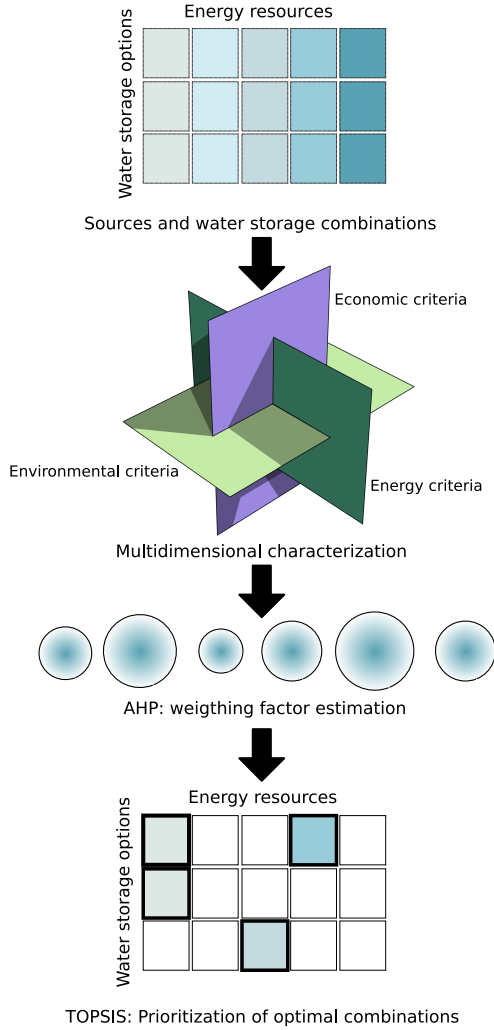
Figure 1: Proposed methodology: general overview.

Hierarchy Process (AHP) is used for criteria weight calculation purposes. Subsequently, the Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS) allows us to identify and prioritize the optimal alternatives. The following advantages justify the application of the TOPSIS approach [43]: (*i*) TOPSIS logic is rational and understandable; (*ii*) the computation processes of TOPSIS are straightforward; (*iii*) the concept of TOPSIS pursues the best alternatives for each criterion from an easy-to-understand mathematical viewpoint; and (*iv*) the relevance weights are incorporated into the comparison procedures. Figure 1 shows the proposed methodology schematically.

2.2. Criteria selection: multidimensional characterization

In line with the aim of the paper, the criteria selection involves a multidimensional characterization of the resources and water storage combinations including economic, energy and environmental (3E) aspects, as well as additional hydrological and social criteria (see Table 1). It must be noted that all criteria and sub-criteria are char-

Table 1: Criteria selection: multidimensional characterization of solutions.

Criterion	Sub-criterion	Label	Units
	Energy facility investment	C1.1.1	$Euro/ha$
	Water infrastructure investment	C1.1.2	$Euro/ha$
Economic	Maintenance costs	C1.2.1	$Euro/ha$
	Operation costs	C1.2.2	$Euro/ha$
	Sale of surplus energy (retribution)	C1.2.3	$Euro/ha$
Energy	Nominal power value of the facility	C2	kW/ha
Environmental	CO_2 emissions of the groundwater pumping systems	C3	kCO_2/ha
Water	Evaporation from the water storage solutions	C4	m^3/ha
Social	Jobs created in the rural area	C5	$Jobs/ha$

acterized in quantitative terms according to [44]. This previous work gives the corresponding initial quantitative values for each criterion and sub-criterion. A detailed description of the main criteria is provided as follows:

2.2.1. Economic (Euro/ha)

This criterion includes economic aspects that decisively influence the viability of the different groundwater pumping systems. The economic criterion has been divided into five sub-criteria:

- Energy facility investment ($Euro/ha$). This sub-criterion analyses investment data, mainly the energy installation costs, i.e., diesel generator sets, power line connections, and PV modules and their connectors, inverters, etc.

- Water infrastructure investment ($Euro/ha$). This sub-criterion includes the investment costs of all components for irrigation and pumping facilities (rafts or irrigation reservoirs, pipelines, pumps, drilling, drains, filters, sensors, and irrigation meters, etc.).

- Maintenance costs ($Euro/ha$): These expenses refer to the maintenance of both water storage and energy resource facilities, such as the cleaning of filters, the lubrication of moving parts, installation safety, etc.

- Operations costs ($Euro/ha$). This sub-criterion refers to the expenses derived from the operational costs of the facilities. Fuel costs for diesel equipment and electricity supply costs for systems connected to the grid, are the most relevant costs.

- Reimbursement for sale of surplus electric energy ($Euro/ha$): some combinations can be connected to the grid via a net metering system. Consequently, the sub-criterion of reimbursement for the sale of surplus electric energy must be considered.

With the exception of the reimbursement for sale of surplus electric energy sub-criterion, which should be maximized, the rest of the economic sub-criteria are cost criteria and should thus be minimized.

2.2.2. Energy (kW/ha)

This criterion mainly focuses on analyzing the value of the nominal power of the electrical energy facility. This criterion should be minimized —as some energy alternatives

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require a greater installed power, even under a similar energy demand— to ensure that the electrical supply meets the system requirements.

2.2.3. Environmental (kgCO$_2$/ha)

This environmental criterion refers to the CO$_2$ emissions of the different combinations of groundwater pumping systems. This criterion should be minimized to ensure lower emissions and environmental impact.

2.2.4. Water or hydrological (m^3/ha)

Water is a scarce resource in many areas and represents a limiting factor for agriculture. Therefore, the reduction of water losses is a priority issue in irrigation system design. The water or hydrological criterion analyzes the evaporation of water that occurs on the surface of the reservoir due to solar radiation. It should be minimized.

2.2.5. Social (Jobs/ha)

This criterion analyzes the impact of the combinations on the social level. The number of jobs created in the rural area for each combination is determined. Therefore, this criterion should be maximized.

2.3. Analytic Hierarchy Process (AHP): weighting factor estimation

The Analytic Hierarchy Process (AHP) [45] is accepted by the research community as a robust and flexible MCDM model to address complex decision problems [46, 47]. Furthermore, AHP/fuzzy AHP and integrated methods were ranked first in their number of contributions relevant to sustainable and renewable energies [48]. The AHP consists of three main tasks: (i) structuring a complex decision as a hierarchy of goals, criteria, and alternatives; (ii) conducting a pairwise comparison of all the elements in each level of the hierarchy with respect to each of the criteria involved in the previous levels; and (iii) vertically synthesizing judgements on the different levels of the hierarchy. Therefore, the AHP attempts to estimate the impact of each alternative on the overall hierarchy's objective. The multi-objective index evaluates several impacts, and is a weighted-sum of the technical impacts [49]. In this study, we apply this methodology for criteria weight estimation, assuming that the quantified judgements provided by the decision maker for any criteria pair (C_i, C_j) are the entries in the following n–order matrix:

$$C = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_n \end{array} \begin{pmatrix} C_1 & C_2 & C_3 & \dots & C_n \\ c_{11} & c_{12} & c_{13} & \dots & c_{1n} \\ c_{21} & c_{22} & c_{23} & \dots & c_{2n} \\ c_{31} & c_{32} & c_{33} & \dots & c_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & c_{n3} & \dots & c_{nn} \end{pmatrix} \quad (1)$$

Note that the input c_{ij} refers to the relative significance of C_i with respect to C_j, i.e., $c_{ij} \approx (w_i/w_j)$. This concept can be further extended and expressed as follows:

Table 2: Valuation scale in the pairwise comparison process.

Labels	Preference verbal judgments (i vs j criteria)	Saaty's scale
(EI)	C_i and C_j are equally important	1
(S+I)	C_i is slightly more/less important than C_j	3 - 1/3
(St+I)	C_i is strongly more/less important than C_j	5 - 1 /5
(VSt+I)	C_i is very strongly more/less important than C_j	7 - 1/7
(Ex+I)	C_i is extremely more/less important than C_j	9 - 1/9

- $c_{ij} \approx (w_i/w_j); \forall i, j = 1, 2, \dots, n$

- $c_{ii} = 1, \forall i = 1, 2, \dots, n$

- If $c_{ij} = \alpha \neq 0$, then $c_{ji} = 1 \neq \alpha; \forall i = 1, 2, \dots, n$

- If the criterion C_i becomes more relevant than C_j, then $c_{ij} \approx (w_i/w_j) > 1$

A positive and symmetric matrix (C) is then determined, with its main diagonal containing ones. Accordingly, the decision maker provides value judgments to fill in an upper triangular matrix. Moreover, as the Saaty scale indicates [45], the values assigned to each entry c_{ij} usually lie within an interval of $[1, 9]$, or its reciprocal. Table 2 summarizes the decision maker's verbal judgements and the pairwise comparison process considered in our case study.

The weight vector is given by the eigen-vector corresponding to the maximum eigen-value λ_{max} of the C-matrix. The Consistency Index (CI) is then calculated as $CI = (\lambda_{max} - n)/(n-1); \lambda_{max} > n$ if the expert shows a minor inconsistency. The Saaty scale provides the next indicator for the Consistency Ratio (CR), determined by $CR = CI/RI$, where RI is the Random Index estimated as the average value of CI for random matrices [50, 51]. Table 3 summarizes the Random Index (RI) for matrix orders from 1 to 15, where n represents the number of compared criteria. The CI value is subsequently used to quantify the probability that the judgement matrix was randomly estimated [52].

2.4. TOPSIS Method: prioritization of optimal combinations

The TOPSIS method, was developed by Ching-Lai Hwang and Kwangsun Yoon [53] and is classified as one of the classical MCDM methods [54]. This approach selects an optimal combination according to the farthest distance from the negative ideal solution (NIS) and the shortest distance from the positive ideal solution (PIS). The optimal solution provided by TOPSIS constitutes a trade-off between both ideal solutions, as shown in Fig. 2. It remains closest to the PIS (labeled as C) and farthest from the NIS (labeled as B and D respectively). TOPSIS thus considers the distances to both the PIS and the NIS simultaneously. The method structure is discussed in the following subsections.

2.4.1. Decision matrix: definition and normalization

$A_i(i = 1, 2, \dots, m)$ constitutes the alternatives/solutions to be prioritized and ordered by the

Table 3: Random Index (`RI`) for matrix orders (1–15) [51].

n	1–2	3	4	5	6	7	8	9	10	11	12	13	14	15
(RI)	0.00	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854	1.5140	1.5365	1.5551	1.5713	1.5838

Figure 2: The concepts of PIS and NIS in a TOPSIS approach.

Table 4: Decision matrix for the TOPSIS approach.

	w_1	w_2	$\ldots$	w_j	$\ldots$	w_n
	C_1	C_2	$\ldots$	C_j	$\ldots$	C_n
A_1	x_{11}	x_{12}	$\ldots$	x_{1j}	$\ldots$	x_{1n}
A_2	x_{21}	x_{22}	$\ldots$	x_{2j}	$\ldots$	x_{2n}
$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$	$\ldots$
A_m	x_{m1}	x_{m2}	$\ldots$	x_{mj}	$\ldots$	x_{mn}

series of criteria $C_j = (j = 1, 2, \ldots, n)$. A decision matrix is defined as summarized in Table 4, where x_{ij} refers to the performance score of alternative A_i with respect to criteria C_j, and $W = [w_1, w_2, \ldots, w_n]$ denotes the weighting vector associated with such criteria. The value of each criterion is then normalized through the Euclidean norm in order to homogenize each criterion with the same scale.

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad (2)$$

The normalized weighted decision matrix (V) is determined through the following expression:

$$v_{ij} = w_j \otimes n_{ij} \qquad (3)$$

where $j = 1, 2, \ldots, n$; $i = 1, 2, \ldots, m$; and $\sum_{j=1}^{m} w_j = 1$; corresponding to the weighting vector obtained by the AHP methodology (see Section 2.3).

2.4.2. Priorization of solutions

The positive ideal solution (PIS) is referred to as A^+, and the negative ideal solution (NIS) is represented as A^-.

These expressions can be determined as follows ($i = 1, 2, \ldots, m$):

$$A^+ = \{v_1^+, v_2^+, \ldots, v_n^+\} = \left\{ \begin{array}{l} (max_i\, v_{ij}, j \in J) \ for\ maximization\ criterion \\ (min_i\, v_{ij}, j \in J') \ for\ minimization\ criterion \end{array} \right\}$$

$$A^- = \{v_1^-, v_2^-, \ldots, v_n^-\} = \left\{ \begin{array}{l} (min_i\, v_{ij}, j \in J) \ for\ maximization\ criterion \\ (max_i\, v_{ij}, j \in J') \ for\ minimization\ criterion \end{array} \right\},$$

where the J-index is associated with the criteria that represent benefits, and the J'-index is associated with the criteria indicating losses. The separation of each alternative (PIS and NIS) is obtained through the following expressions:

$$\text{PIS} \rightarrow d_i^+ = \left[\sum_{j=1}^{m} \left(v_{ij} - v_j^+ \right)^2 \right]^{1/2}; \ i = 1, 2, \ldots, m. \qquad (4)$$

$$\text{NIS} \rightarrow d_i^- = \left[\sum_{j=1}^{m} \left(v_{ij} - v_j^- \right)^2 \right]^{1/2}; \ i = 1, 2, \ldots, m. \qquad (5)$$

The ranking score R_i is first calculated as follows:

$$R_i = \frac{d_i^-}{d_i^+ + d_i^-}; \ i = 1, 2, \ldots, m. \qquad (6)$$

Subsequently, if $R_i = 1$ then $A_i = A^+$, and, if $R_i = 0$, then $A_i = A^-$. Nevertheless, if the R_i values are close to one, then the priority for the ith alternative will be higher. The best alternatives according to the ranking score R_i are ordered and classified in descending order. These results correspond to the case study described in detail in Section 3.

2.5. Additional analysis: homogeneous weighting vector

In MCDM approaches based on the TOPSIS technique, it is very common to include an additional analysis considering a homogeneous weighting vector. The TOPSIS methodological process is then executed assuming this homogeneous weighting vector, and not based on the AHP results. Therefore, all criteria take the same relevance as well as their corresponding sub–criteria. The aim of this process is to compare the subsequent classification from both analyses: (i) the expert decision and (ii) the homogeneous weight vector decision. Consequently, variations in the list of prioritized alternatives and percentage differences between both classifications provide relevant information on the suitability of the expert evaluation with respect to a homogeneous analysis.

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3. Case Study

3.1. Description of the study area

The case study focuses on Aquifer 23, in the Castilla La Mancha Region (eastern part of Spain). The climate characteristics of this zone are labeled as `Bsk`, a typical continental Mediterranean climate (14.4^oC, 416 mm) consisting of cold winters with periods of frost and significantly hot summers. In terms of energy, due to the widespread use of diesel equipment for water extraction, a strong dependence on fossil fuels can be identified, not only in this area, but also in agricultural areas that depend on pumping groundwater solutions in the Mediterranean region. For solar resources, this Spanish area offers a representative annual average value of around 4900 kWh/m^2 per day, with a uniform territorial distribution and variation of less than 5%. Therefore, the availability of this renewable resource on the agricultural land surface provides a remarkable opportunity to supply energy requirements for groundwater pumping.

Three variables represent the main features of the aquifer study area: the aggregated agricultural area, the aquifer depth, and the water requirements. The estimated depth of the aquifer ranges from 10 to 55 m, encompassing the depth ranges of most of the plots irrigated by the aquifer. A range from 1500 to 10500 $m^3/year$ is considered for water requirements, according to the mosaic of Mediterranean crops involving mostly vines. The aggregation of agricultural areas is estimated to be between 1 and 2000 ha, which is in line with current crops depending on the aquifer and considering that larger areas would cause excessive pressure losses throughout the grid.

3.2. Energy resources and water storage combinations: identification of alternatives

As can be seen in Figure 1, alternatives are identified through a combination of different energy resources and water storage options. Following Section 1, diesel generator, isolated PV power plant, net energy metering schemes for PV installations and direct connection to the grid are selected as potential energy resources. These sources represent the most common solutions currently implemented in most groundwater pumping systems as well as the most promising renewable solutions to be integrated into the agriculture sector. With regard to the water storage options, three different possibilities are considered for the case example, according to the irrigation crop requirements: direct pumping without any water tank storage, seasonal water storage, and annual water storage. Four different energy resources and three water storage options are thus identified, giving a total of twelve different groundwater pumping systems to be characterized and prioritized from a multidimensional framework according to Table 1 and Section 2.2. Table 5 summarizes the alternatives and the corresponding energy resources and water storage options. In addition, Figure 3 shows graphically

Table 5: Energy resources and water storage combinations: identification of alternatives.

Alternative	Label	Energy resource	Water storage option
Alternative 1	A1	Diesel generator	Annual water tank storage
Alternative 2	A2	Diesel generator	Seasonal water tank storage
Alternative 3	A3	Diesel generator	Direct pumping
Alternative 4	A4	Isolated PV power plant	Annual water tank storage
Alternative 5	A5	Isolated PV power plant	Seasonal water tank storage
Alternative 6	A6	Isolated PV power plant	Direct pumping
Alternative 7	A7	Net energy metering – PV	Annual water tank storage
Alternative 8	A8	Net energy metering – PV	Seasonal water tank storage
Alternative 9	A9	Net energy metering – PV	Direct pumping
Alternative 10	A10	Direct connected to the grid	Annual water tank storage
Alternative 11	A11	Direct connected to the grid	Seasonal water tank storage
Alternative 12	A12	Direct connected to the grid	Direct pumping

the different groundwater pumping systems to be considered in line with the overall process general scheme provided in Figure 1.

With regard to the water storage options, the annual storage systems include a reservoir with a sufficient capacity to store the water required at the time of irrigation for a year; thus, they require a low amount of energy in comparison with the other alternatives but have significant water requirements due to their water evaporation losses. In the case of seasonal water storage facilities, such reservoirs only store, ahead of the irrigation season, the amount of water demanded during the irrigation season. The size and cost of hydraulic infrastructure is considerably lower than that of annual water storage solutions, but more energy facilities are required. The direct pumping option lacks storage systems since water is pumped only when required. Therefore, the cost of water infrastructure is considerably reduced at the expense of increasing energy installation costs. These alternatives require 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.

Based on the proposed methodology described in Section 2, as well as the different energy resource and water storage options summarized in Table 5 —where the alternatives are labeled as A_i, $i = 1, 2, \ldots, n$; with $n = 12$—, Figure 4 graphically represents a multiobjective framework based on the proposed methodology described in Section 2, as well as the different energy resource and water storage options summarized in Table 5, where the alternatives are labeled as A_i, $i = 1, 2, \ldots, n$; with $n = 12$. It is based on the different criteria defined in Section 2.2, and the application of such criteria on each alternative/solution in a multidimensional analysis. The total number of criteria is consequently considered for the decision making process, as C_j, $j = 1, 2, \ldots, m$, with $m = 9$ according to Table 1. Finally, in order to carry out the weight estimations and criteria based on the expert survey and AHP methodology, a questionnaire is prepared and provided to the experts. This is a pseudo–Delphi technique, as the members take part in the decision process but do not interact with each other at any time. This questionnaire is based on Saaty's scale (Table 2), and is intended to perform a pairwise comparison. Comparisons between pairs of criteria at the same

	Diesel generator	Isolated PV system	PV grid (Net-balance)	Connected to the grid
Annual pumping	Alternative 1	Alternative 4	Alternative 7	Alternative 10
Seasonal pumping	Alternative 2	Alternative 5	Alternative 8	Alternative 11
Direct pumping	Alternative 3	Alternative 6	Alternative 9	Alternative 12

Figure 3: Case study: identification of alternatives.

level in the hierarchy, determined via the AHP methodology, are also conducted.

4. Results

4.1. AHP: weighting factor estimation

In order to verify the consistency of the AHP method, the consistency ratio (CR) is determined by each expert. This value was lower than 0.1, which demonstrates the consistency of the method. Therefore, it is not necessary to revise the judgments of the experts. A comparison between the expert ranking (priorization of expert alternatives) and the homogeneous decision ranking is also included in this work. Table 6 shows the weight vector for both the homogeneous and expert approaches, according to the hierarchy of criteria described in Figure 4 and the criteria selection defined in Table 1. From the weighting vector data given in Table 6, it can be initially deduced that economic aspects are mostly relevant for the experts in comparison to the rest of the criteria. The TOPSIS methodology is then applied with the homogeneous weight vector to determine a different ranking of alternatives, which is subsequently compared to the expert ranking results.

4.2. Priorization of optimal combinations: expert results

From the participation of experts previously discussed, the TOPSIS application gives a prioritization of the alternatives described in Section 3.2. Consequently, an identification of the most efficient and optimal groundwater pumping systems in a multidimensional analysis is then provided by the expert results. With this aim, a total of six experts were selected, who were completely consistent in their opinions. These experts included PhD engineers with relevant backgrounds in renewable energy technologies and agriculture and hydrology experience, as well as post-graduates focused on renewable energy sources.

By considering the vector $[X =$ aggregated agricultural areas, $Y =$ aquifer depth, $Z =$ irrigation crop requirements], the optimal energy resource and water storage alternatives selected by the experts for each value of aquifer depth (m), aggregated agricultural surface $(ha \cdot 10^3)$ and crop water requirements $(m^3/ha \cdot 10^3)$ are then estimated. With the resulting data, a 4D graphic of the optimal alternatives for each $[X, Y, Z]$ value is given. Figure

5 shows the corresponding optimal alternatives selected by the experts depending on the aquifer depth (m), the aggregated agricultural surface $(ha \cdot 10^3)$ and the crop water requirements $(m^3/ha \cdot 10^3)$. Using a color legend for each different alternative (A_i), this 4D-graph offers information on recommended groundwater pumping systems in terms of optimal energy resource and water storage options depending on the aquifer depth (m), the aggregated agricultural surface $(ha \cdot 10^3)$ and the water requirements $(m^3/ha \cdot 10^3)$. By considering these results, it can be affirmed that direct water pumping connected to the grid (labeled as A_{12} in Section 3.2) is the most likely alternative selected by the experts. Moreover, this selection is almost independent of the aquifer depth, aggregated agricultural area, and water requirements, as can be seen in Figure 5 where the A_{12} alternative is marked in bold in the legend.

In addition, Figures 6 and 7 summarize the second and third most preferable and efficient alternatives selected by the experts. Both the direct PV net energy metering and isolated PV power plant solutions (labeled as A_9 and A_6 respectively in Section 3.2) are considered to be the next most valuable alternatives. Therefore, alternatives based on diesel installations are excluded by the experts from the most preferred solutions. In addition, these three optimal alternatives avoid water storage requirements; thus, direct water pumping options were selected by the experts as the most preferable choices. It can then be concluded that water storage options are less attractive in terms of energy, economic, and environmental factors. However, when we considered the same energy solution but included water storage requirements, this option was ranked lower by most of the experts. Therefore, the consideration of any water storage solution entails a lower value for such alternatives.

With regard to conventional diesel solutions, which are currently some of the most commonly used solutions in the agricultural sector, it is noted that, by considering the expert results, the diesel direct pumping solution is exclusively preferred under conditions of low aquifer depth and small agricultural area, independent of the water requirement range (between 0 and 12 $m^3/(ha \cdot 10^3)$). Therefore, despite its negative environmental impact and energy dependence, the diesel solution is considered the most prefer-
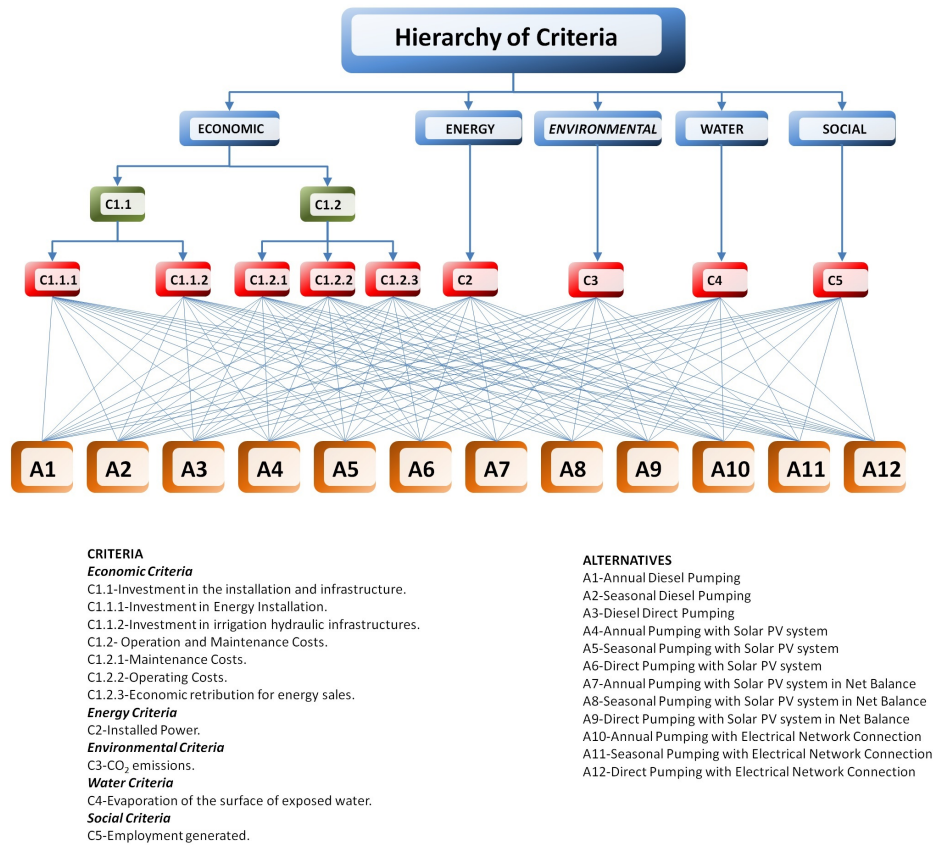
CRITERIA
Economic Criteria
C1.1-Investment in the installation and infrastructure.
C1.1.1-Investment in Energy Installation.
C1.1.2-Investment in irrigation hydraulic infrastructures.
C1.2- Operation and Maintenance Costs.
C1.2.1-Maintenance Costs.
C1.2.2-Operating Costs.
C1.2.3-Economic retribution for energy sales.
Energy Criteria
C2-Installed Power.
Environmental Criteria
C3-CO_2 emissions.
Water Criteria
C4-Evaporation of the surface of exposed water.
Social Criteria
C5-Employment generated.

ALTERNATIVES
A1-Annual Diesel Pumping
A2-Seasonal Diesel Pumping
A3-Diesel Direct Pumping
A4-Annual Pumping with Solar PV system
A5-Seasonal Pumping with Solar PV system
A6-Direct Pumping with Solar PV system
A7-Annual Pumping with Solar PV system in Net Balance
A8-Seasonal Pumping with Solar PV system in Net Balance
A9-Direct Pumping with Solar PV system in Net Balance
A10-Annual Pumping with Electrical Network Connection
A11-Seasonal Pumping with Electrical Network Connection
A12-Direct Pumping with Electrical Network Connection

Figure 4: Hierarchy of Criteria: energy resources and water storage option alternatives (A_i).

Table 6: Weight vector comparison: homogeneous and expert approaches.

| | Economic | | | | | Energy | Environmental | Water | Social | |
	C.1.1.1	C.1.1.2	C.1.2.1	C.1.2.2	C.1.2.3	C.2	C.3	C.4	C.5	TOTAL
Homogeneous	0.0500	0.0500	0.0333	0.0333	0.0334	0.2000	0.2000	0.2000	0.2000	1
Experts	0.1262	0.1218	0.0169	0.0328	0.0381	0.2372	0.1605	0.1794	0.0867	1
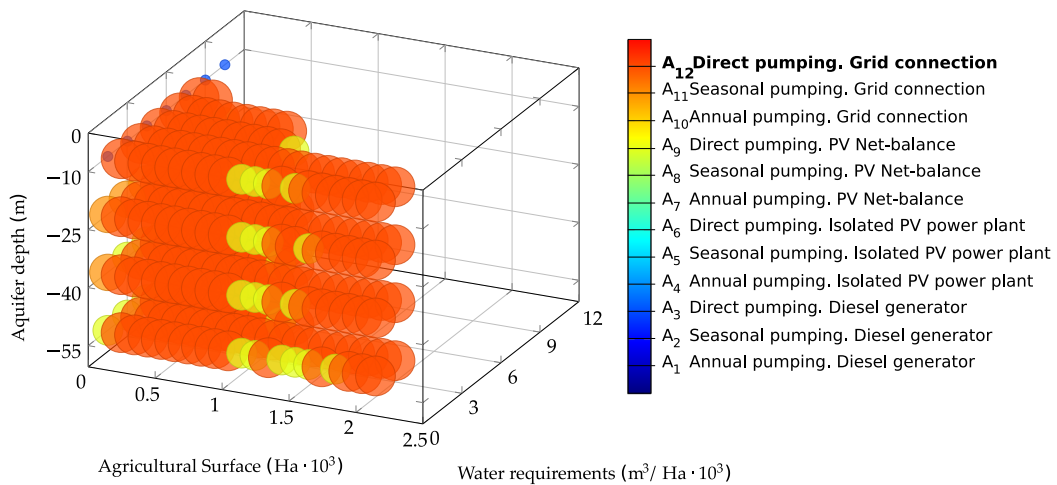
Figure 5: First optimal alternatives selected by the experts.

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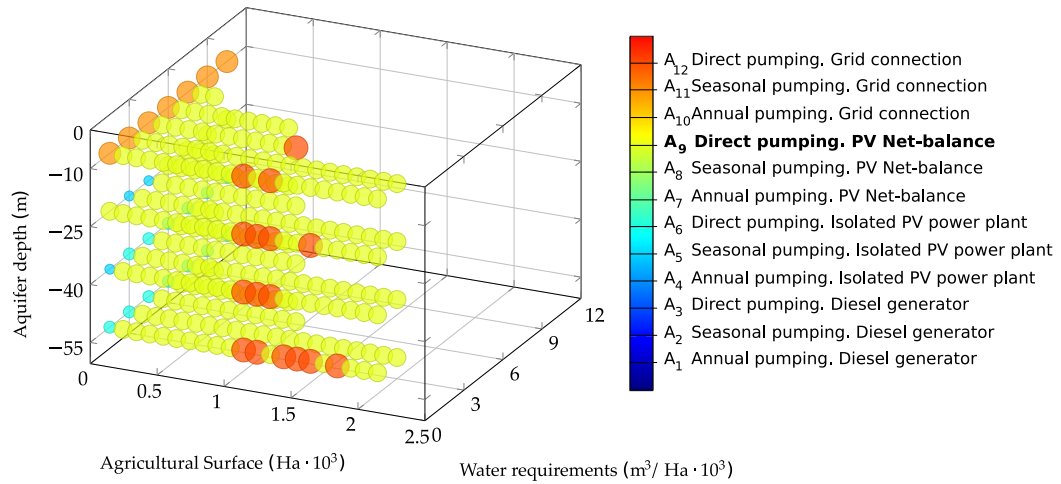
Figure 6: Second optimal alternatives selected by the experts.
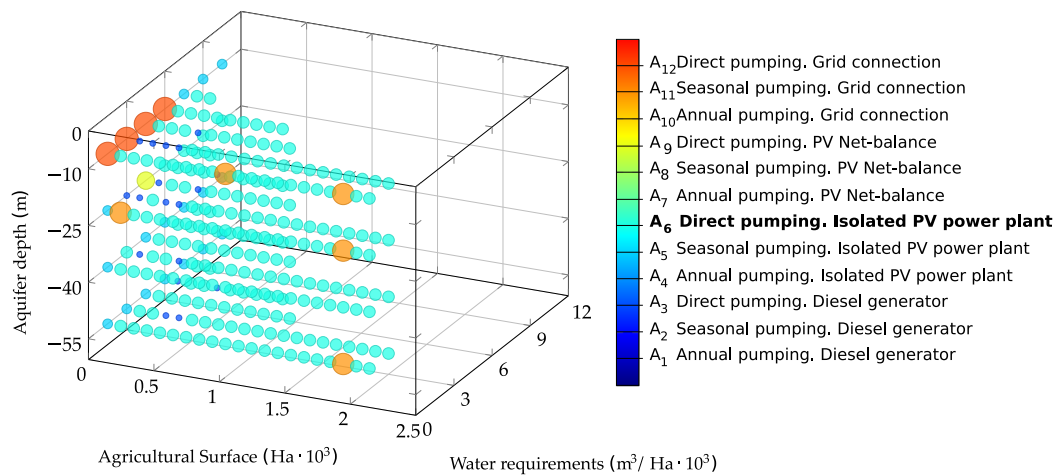
Figure 7: Third optimal alternatives selected by the experts.

able alternative only for very low aquifer depths and small agricultural areas, which is not in line with usual aquifer depths and water requirements. Figure 8 shows the ranking position of the Direct Diesel Pumping alternative (Alternative A_3) based on aquifers of different depths, different aggregated agricultural areas, and water requirements of various crops. A color scale is used proportional to the sphere size, depending on the ranking position of the represented Direct Diesel Pumping alternative. As can be seen, Alternative A_3 is ranked between positions 6 and 7, assuming that position 1 is the most valuable alternative. Only for very low-depth aquifers and a small aggregated agricultural area, A_3 is considered the most suitable groundwater pumping solution by the experts; for such a cases, they experts move A_3 from positions 6 and 7 to position 1.

4.3. Priorization of optimal combinations: homogeneous weighting vector results

Complementary to Section 4.2 and as described in Section 2.5, the TOPSIS methodology is also applied with a homogeneous weight vector to determine a different ranking of alternatives compared to the expert ranking results. From these results, Figure 9 shows the first optimal alternatives selected by the homogeneous weight vector, which differs from the expert selection. In this case, seasonal pumping based on the PV net-energy metering (labeled as Alternative A_8) is estimated to be the optimal alternative for most deep aquifers, aggregated agricultural areas, and crop irrigation configurations. In a similar way, Figures 10 and 11 present, respectively, the second and third best optimal alternatives determined from the homogeneous weight vector, which correspond to direct pumping net-balance and seasonal pumping isolated PV power plant, respectively. As previously discussed, seasonal pumping alternatives are prioritized by the homogeneous weight vector approach. Moreover, due to the decreased economic criterion weight in comparison to the expert decision vector (see Table 6), alternatives with higher investment costs (including PV installations), either isolated or connected to the grid, increase their ranking positions compared to lower investment cost solutions —mainly alternatives based on direct grid connections without any additional facilities.

Finally, in an attempt to compare the expert and homogeneous selection of alternatives, Table 7 compares the ranking position order of the alternatives for both approaches. The nomenclature is in line with the identification of alternatives described in Section 3.2; nevertheless, a brief description of each alternative is also included in the table. In quantitative terms, the alternatives vary, on average, between positions 3 and 4 (see the column *Ranking differences* in Table 7, which indicate the relative change of ranking position with respect to the expert ranking). Consequently, seasonal solutions emerge as preferable alternatives to direct pumping systems. Diesel solutions (the alternatives from $A1$ to $A3$), are less preferred by the homo-

geneous weight vector, mainly due to the greater relevance of the environmental criterion, according to Table 6.

5. Conclusions

A multidimensional analysis, including economic, energy, and environmental (3E) criteria, is proposed to characterize different groundwater pumping solutions based on energy resources and water storage options. The AHP/TOPSIS method is used to prioritize the groundwater pumping alternatives depending on the corresponding water storage conditions (annual, seasonal, or direct) and the selected energy resourced (PV, diesel, or grid). A real aquifer located in the southeast of Spain is considered in a case study, in which twelve different groundwater pumping alternatives are defined. By applying the MCDM process using a group of experts, a comparison between expert ranking and homogeneous weight vector ranking is also conducted. Based on the expert decisions, alternatives that avoid any water storage are preferred over those that include annual or seasonal water storage options, which require additional facilities. Consequently, water storage initiatives are less preferable than direct groundwater pumping solutions. The most optimal and prioritized alternatives based on the multidimensional criteria are (i) direct grid pumping solutions, (ii) direct PV net energy metering, and (iii) direct isolated PV power plant pumping. With regard to diesel alternatives, despite their negative environmental and energy dependence impact, they are preferred by the experts under very low aquifer depth conditions (between 0 and -15 m) and small agricultural areas (between 0 and 200 ha), being independent of the crop water requirements. The proposed methodology can be applied and extrapolated to other water requirements and aquifer conditions, as well as different energy resources. Other resources based on renewables and their integration and evaluation in the groundwater pumping problem are currently under analysis for future publication by the authors using an MCDM process.

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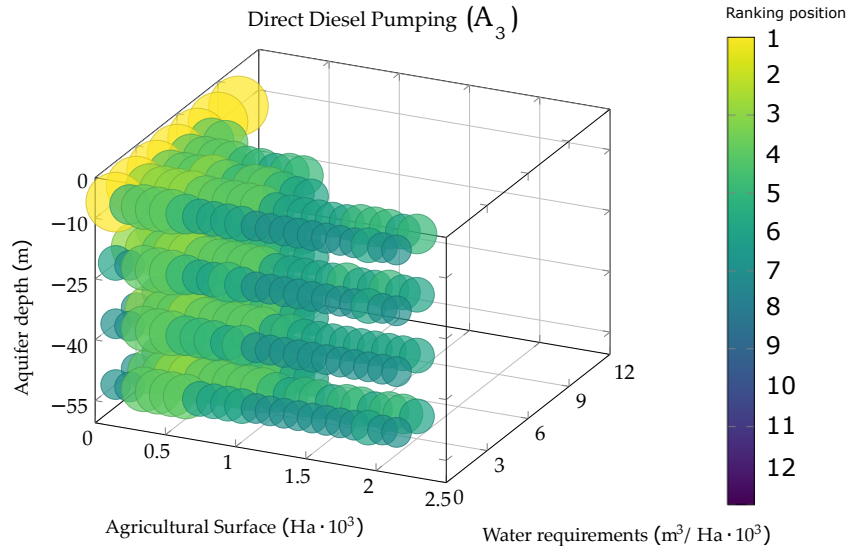
Figure 8: Diesel direct pumping (A_3): ranking position based on the depth of the aquifer and the aggregated agricultural and water crop requirement configurations.
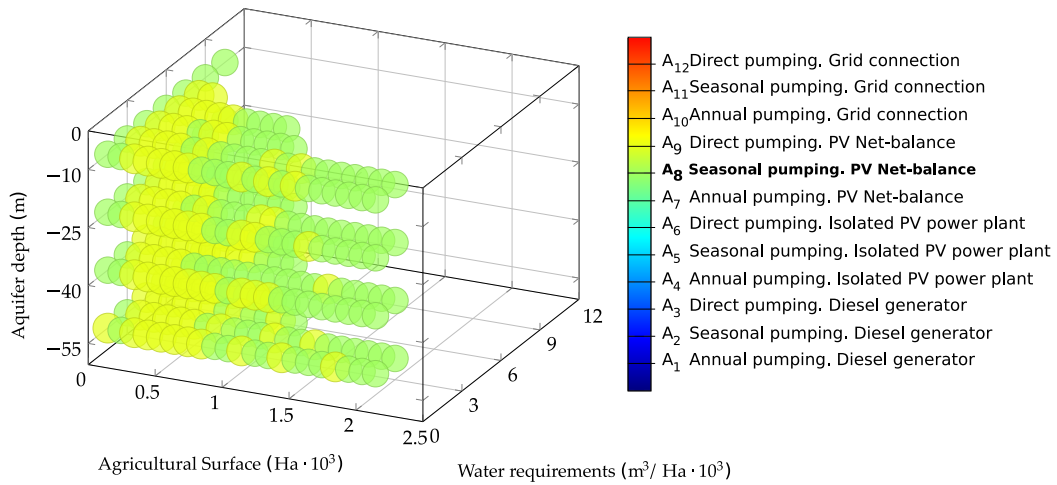

Figure 9: First optimal alternatives selected by the homogeneous weight vector.
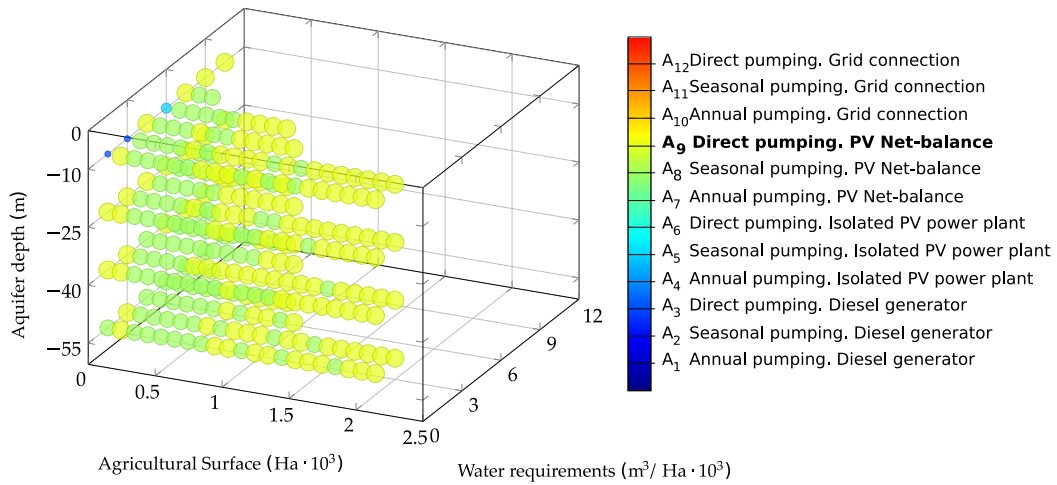

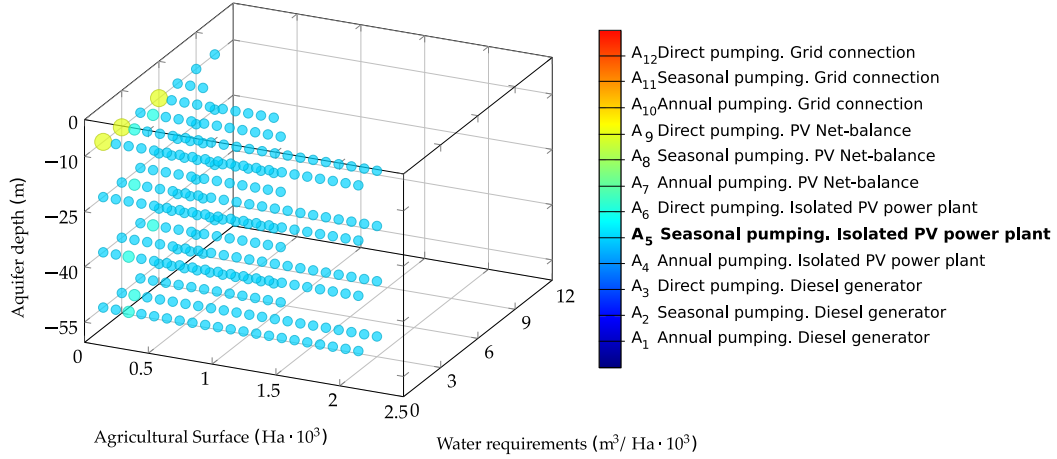Figure 10: Second optimal alternatives selected by the homogeneous weight vector.

Figure 11: Third optimal alternatives selected by the homogeneous weight vector.

Table 7: Comparison of ranking position: homogeneous and expert approaches.

Alternative	Expert ranking position	Homogeneous ranking position	Ranking differences
A1 Diesel — Annual pumping	12	12	0
A2 Diesel — Seasonal pumping	8	11	3 ⇓
A3 Diesel — Direct pumping	[5 − 7]	[9 − 10]	3 − 4 ⇓
A4 Isolated PV — Annual pumping	[9 − 10]	[7 − 8]	2 ⇑
A5 Isolated PV — Seasonal pumping	[5 − 7]	3	2 − 4 ⇑
A6 Isolated PV — Direct pumping	3	4	1 ⇑
A7 Net-balance PV — Annual pumping	[9 − 10]	[5 − 7]	3 − 4 ⇑
A8 Net-balance PV — Seasonal pumping	[4 − 5]	[1 − 2]	3 ⇓
A9 Net-balance PV — Direct pumping	2	2	0
A10 Grid — Annual pumping	11	[9 − 10]	1 − 2 ⇑
A11 Grid — Seasonal pumping	[4 − 7]	[1 − 3]	3 ⇑
A12 Grid — Direct pumping	1	4	3 ⇓

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