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CARACTERIZACIÓN MULTIDIMENSIONAL DE ALTERNATIVAS ENERGÉTICAS EN EL BOMBEO DE AGUAS SUBTERRÁNEAS PARA LA AGRICULTURA DE REGADÍO

Presentada por Álvaro Rubio Aliaga para optar al
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PROGRAMME DOCTORAL EN ÉNERGIES RENOUVELABLES ET EFFICACITÉ ÉNERGÉTIQUE

THÈSE DE DOCTORAT

CARACTÉRISATION MULTIDIMENSIONNELLE DES ALTERNATIVES ÉNERGÉTIQUES DANS LE POMPAGE DES EAUX SOUTERRAINES POUR L'AGRICULTURE IRRIGUÉE

Présentée et soutenue par Álvaro Rubio Aliaga
pour l'obtention du diplôme de Docteur de
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"No nos atrevemos a muchas cosas porque son difíciles, pero son difíciles porque no nos atrevemos a hacerlas".
Lucio Anneo Seneca

"Que algo te parezca difícil no quiere decir que nadie más sea capaz de lograrlo".
Marco Aurelio

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La vida, al igual que hacer un doctorado, es un largo camino repleto de experiencias que te hacen crecer como persona. Es un viaje lleno de buenos momentos y entusiasmo, pero en el que también aparecen pequeños baches, malos ratos y escollos. Pero un día se acaba, y echas la vista atrás para ver los resultados, observas cada paso que diste en el pasado y ves a toda la gente que ha estado junto a ti en este caminar incesante. Te das cuenta que lo que has conseguido no es solo un logro tuyo, sino que es parte también gracias al apoyo de muchas personas que han ido dejando su grano de arena, para que esta singladura por este mundo académico haya culminado satisfactoriamente y con toda la felicidad que ello significa.

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Declaration of the Thesis by Compendium of Publications

This PhD thesis is presented according to the Compendium of Publications mode, regulated under art. 20 of the Regulation of Official Doctoral Studies of the Technical University of Cartagena of March 24, 2021. These papers were published with the authorization of the supervisor and co-supervisor of this Thesis. They can be found in the corresponding editorial databases where the contributions are published and available under their specific copyright conditions. All papers were prepared and published after the beginning of this Thesis, and their references are listed below:

Publications

- **Paper 1 (P01)**. Rubio-Aliaga, Á., Sánchez-Lozano, J.M., García-Cascales, M. S., Benhamou, M., & Molina-García, A. (2016). *GIS based solar resource analysis for irrigation purposes: Rural areas comparison under groundwater scarcity conditions*. Solar Energy Materials and Solar Cells, 156, 128-139. http://dx.doi.org/10.1016/j.solmat.2016.06.045 International journal indexed in the Journal Citation Report (Q1 with an Impact Factor of 4.10 in 2016). https://repositorio.upct.es/bitstream/handle/10317/9408/gbs.pdf?sequence=1&isAllowed=y .

- **Paper 2 (P02)**. Rubio-Aliaga, Á., García-Cascales, M. S., Sánchez-Lozano, J. M., & Molina-García, A. (2019). *Multidimensional analysis of groundwater pumping for irrigation purposes: Economic, energy and environmental characterization for PV* *power plant integration*. Renewable Energy, 138, 174-186. https://doi.org/10.1016/j.renene.2019.01.077 International journal indexed in the Journal Citation Report (Q1 with an Impact Factor of 4.90 in 2019). https://repositorio.upct.es/bitstream/handle/10317/9405/mag.pdf?sequence=1&isAllowed=y .

- **Paper 3 (P03)**. Rubio-Aliaga, A., Molina-Garcia, A., Garcia-Cascales, M. S., & Sanchez-Lozano, J. M. (2019). *Net-Metering and Self-Consumption Analysis for Direct PV Groundwater Pumping in Agriculture: A Spanish Case Study*. Applied Sciences, 9(8), 1646. https://doi.org/10.3390/app9081646 International peer-reviewed open access journal on all aspects of applied natural sciences, MDPI, with an Impact Factor (Scopus 2019 data): 2.474, which is equivalent to the rank 32/91 in " Engineering Multidisciplinary", which is corresponds to Q2.

- **Paper 4 (P04)**. Rubio-Aliaga, A., García-Cascales, M. S., Sánchez-Lozano, J. M., & Molina-Garcia, A. (2021). *MCDM-based multidimensional approach for selection of optimal groundwater pumping systems: Design and case example*. Renewable Energy, 163, 213-224. https://doi.org/10.1016/j.renene.2020.08.079 International journal indexed in the Journal Citation Report (Q1 with an Impact Factor of 6,274 in 2020). https://repositorio.upct.es/bitstream/handle/10317/9404/mbm.pdf?sequence=1 .

Declaración de Modalidad de Tesis por Compendio de Publicaciones

La presentación de esta tesis doctoral se realiza bajo la modalidad de “Compendio de Publicaciones”, atendiendo a lo establecido en el artículo 20 del Reglamento de Estudios Oficiales de Doctorado de la Universidad Politécnica de Cartagena de 24 de marzo de 2021. Los trabajos han sido publicados con la autorización expresa del director y codirector de la presente tesis. Se pueden encontrar en las bases de datos editoriales correspondientes donde se publican las contribuciones y están disponibles bajo sus condiciones específicas de derechos de autor. Todos los artículos fueron preparados y publicados después del comienzo de esta Tesis, y sus referencias se enumeran a continuación:

Publicaciones

- **Artículo 1 (P01)**. Rubio-Aliaga, Á., Sánchez-Lozano, J.M., García-Cascales, M. S., Benhamou, M., & Molina-García, A. (2016). *GIS based solar resource analysis for irrigation purposes: Rural areas comparison under groundwater scarcity conditions*. Solar Energy Materials and Solar Cells, 156, 128-139. http://dx.doi.org/10.1016/j.solmat.2016.06.045 Revista Internacional indexada en el Journal Citation Report (Q1 con un Factor de Impacto de 4.10 en 2016). https://repositorio.upct.es/bitstream/handle/10317/9408/gbs.pdf?sequence=1&isAllowed=y .

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Indice

“La seule chose que l'on puisse décider est quoi faire du temps qui nous est imparti”.
Gandalf
J.R.R. Tolkien *"Le Seigneur des anneaux"*

1. Résumé

1.1 Abstract

During the last decade, numerous international environmental agreements have been reached with the main objective of mitigating the climate change effects by promoting actions aimed to reduce CO_2 emissions, and integrate renewable energy resource solutions in most sectors of society. Among these sectors, agriculture is susceptible to changing its energy model.

From an international point of view, the agricultural sector, and more specifically such agriculture based on groundwater for irrigation, must achieve a set of energy, environmental and economic challenges for the future. Among them, the energy problem emerges as a relevant target, mainly due to the high fossil fuel dependence and its production cost influence. Others aspects, such as the relevant water resource dependence (very scarce in the Mediterranean area), as well as emissions should be also considered and solved. Nowadays, different organizations and administrations, such as the European Union (EU), are promoting a variety of energy model changes through agricultural process and facilities improvements. These solutions are mainly based on the integration of renewable energy systems, due to their potential energy independence benefits their positive environmental impact in terms of emissions. Focused on the groundwater pumping agriculture sector, PVWP (Photovoltaic Water Pumping) systems were proposed in the specific literature as a remarkable alternative to replace current diesel equipment. Nevertheless, most of the reviewed works only analyze their integration in remote rural areas of Africa or Asia, or small agricultural applications. Only a few of papers describe an extensive study (such as *Kelley et al., in 2010*). Therefore, there is a lack of contributions that address this integration and transition from a multidimensional point of view: economic, energy, environmental, social and hydric management. Moreover, some questions regarding efficiency, sizing or level of use of the energy capable of providing the required pumping power should be analyzed. This scenario thus represents the starting point of this thesis, underlying the developed contributions.

The proposed methodology of this thesis was based on the solar and water data gathered from two agricultural areas with an over-exploitation problem of the water resources: the aquifer in the region of La Mancha (Aquifer 23) in Spain; and the aquifer in the area of the Fès-Meknès plain (Saïss Aquifer) in Morocco. Subsequently, a statistical study of the resources was carried out and a Geographic Information System (GIS) was integrated into the study, in order to analyze geographically the distribution of resources and their applicability. With the aim of considering other alternatives and pumping system configurations, beyond such solutions commercially offered by the sector, a neural network-based architecture was designed to configure a map of potential alternatives, including: diesel equipment, PVWP isolated and connected to the grid, and systems supplied only by the power systems. These alternatives were then evaluated and characterized from a multidimensional point of view, taking into account different criteria within the economic, energy, environmental, and social fields. A 4D graphical environment was used to make more friendly and easier the characterization and comprehension of the results. Additionally, it was selected a multi-criteria decision-making process (MCDM) based on the classical AHP-TOPSIS methodologies to order the group of identified alternatives. Consequently, these alternatives were classified and prioritize according to their suitability, reliability, benefits and their adaptation to the conditions of each specific case study. This process entailed a preliminary inquiry of experts.

From the results, this thesis provides a series of relevant **contributions** to the integration of renewable energy sources in the groundwater pumping agriculture sector. These contributions include: (i) the determination of the main impacts affecting the sector from a multi-focus analysis; (ii) the multidimensional characterization of energy alternatives aimed at pumping groundwater; (iii) a statistical and geographical analysis with the support of both exportable and scalable GIS methodology for the PVWP implementation and hydric resource management; and (iv) the application of an AHP-TOPSIS decision-making process (MCDM) to evaluate the suitability, reliability and benefits of the different alternatives to supply energy to the pumping systems.

Finally, note the relevance of cooperative pumping systems supplied by PV installations connected to grid; mainly due to their potential economic benefits to the sector, their relevant use-of-energy and their high utilization of these renewable installations.

1.2 Résumé

Au cours de la dernière décennie, de nombreux accords environnementaux internationaux ont été conclus avec pour l'objectif principal d'atténuer les effets du changement climatique en promouvant des actions visant à réduire les émissions de CO_2 dans l'atmosphère et l'intégration de solutions d'énergie renouvelable dans tous les secteurs de la société. Parmi ces secteurs, l'agriculture est susceptible de changer son modèle énergétique.

D'un point de vue international, le développement du secteur agricole, et plus particulièrement l'agriculture basée sur les eaux souterraines pour l'irrigation doit faire face à une serie de défis énergétiques, environnementaux et économiques pour l'avenir. Parmi eux, la problématique énergétique se démarque, principalement en raison de la forte dépendance aux énergies fossiles et de son influence sur les coûts de production. D'autres aspects doivent également être pris en compte et résolus, comme la dépendance à la ressource en eau (très rare en région méditerranéenne), ainsi que les émissions. Actuellement, certaines organisations et administrations, comme l'Union européenne (UE), promeuvent ce changement de modèle énergétique par l'amélioration des processus et des installations agricoles. Ces solutions reposent principalement sur l'intégration de systèmes d'énergie renouvelable, en raison de leur indépendance énergétique potentielle et de leur impact environnemental positif en termes d'émissions. Plus précisément, dans le secteur agricole du pompage des eaux souterraines, les systèmes PVWP (Photovoltaic Water Pumping) ont déjà été proposés comme une alternative directe pour remplacer les équipements diesel. Néanmoins, la plupart des travaux examinés n'analysent que leur intégration dans les zones rurales reculées d'Afrique ou d'Asie, ou les petites applications agricoles. Seuls quelques articles décrivent une étude approfondie (tels que *Kelley et al., in 2010*). On manque donc de contributions qui abordent cette intégration et cette transition d'un point de vue multidimensionnel: gestion économique, énergétique, environnementale, sociale et hydrique. De plus, certaines questions concernant l'efficacité, le dimensionnement ou le niveau d'utilisation de l'énergie capable de fournir la puissance de pompage requise doivent être analysées. Cette approche est le point de départ de cette thèse de doctorat et la base des contributions apportées.

La méthodologie proposée dans cette thèse est basée sur les données solaires et hydriques recueillies dans deux zones agricoles présentant un problème de surexploitation des ressources en eau: l'aquifère de la région de La Mancha (Aquifère 23) en Espagne, et l'aquifère de la région de la plaine de Fès-Meknès (Aquifère de Saïss) au Maroc. Ensuite, une étude statistique des ressources a été réalisée, ainsi qu'une analyse géographique de la distribution des ressources et de leur applicabilité avec un système d'information géographique (SIG). Dans le but d'envisager d'autres alternatives et configurations de systèmes de pompage, au-delà des solutions proposées commercialement par le secteur, un réseau neuronal artificiel a été conçu pour configurer une carte des alternatives potentielles, incluant: équipement diesel, systèmes PVWP isolés et connectés au réseau, et systèmes fournis uniquement par les réseaux électriques. Ces alternatives ont ensuite été évaluées et caractérisées d'un point de vue multidimensionnel, en tenant compte de différents critères dans les domaines économique, énergétique, environnemental et social. Un espace graphique 4D a été utilisé pour visualiser plus facilement la caractérisation et la compréhension des résultats. De plus, un processus d'aide à la décision multicritères (MCDM) basé sur les méthodologies classiques AHP-TOPSIS a été sélectionné pour classifier le groupe d'alternatives identifiées. Par conséquent, ces alternatives ont été classifiées et hiérarchisées en fonction de leur adéquation, de leur fiabilité, de leurs avantages et de leur adaptation aux conditions de chaque étude de cas spécifique. Ce processus impliquait une enquête préliminaire d'experts.

A partir des résultats, cette thèse fournit une série de contributions pertinentes à l'intégration des sources d'énergie renouvelables dans le secteur agricole du pompage des eaux souterraines. Ces contributions comprennent: (i) la détermination des principaux impacts affectant le secteur à partir d'une analyse multi-focus; (ii) la caractérisation multidimensionnelle des alternatives énergétiques visant le pompage des eaux souterraines; (iii) une analyse statistique et géographique avec le soutien d'une méthodologie SIG exportable et évolutive pour la mise en œuvre des systèmes PVWP et la gestion des ressources hydriques; et (iv) l'application d'un processus d’aide à la décision AHP-TOPSIS (MCDM) pour évaluer l'adéquation, la fiabilité et les avantages des différentes alternatives pour fournir de l'énergie aux systèmes de pompage.

Enfin, l'une des contributions plus importantes est la mise en évidence des systèmes de pompage coopératifs alimentés par des installations photovoltaïques connectées au réseau électrique, en raison de leurs avantages économiques potentiels pour le secteur et de la plus grande utilisation de l'énergie et de l'installation.

1.3 Resumen

En la última década se han alcanzado numerosos acuerdos internacionales en materia ambiental con el objetivo principal de paliar los efectos del cambio climático promoviendo acciones que se dirijan hacia la reducción de emisiones de CO_2 a la atmósfera, y la integración de soluciones energéticas renovables en todos los sectores de la sociedad. Entre estos sectores destaca la agricultura como uno de los más susceptible cambiar su modelo energético.

En el panorama internacional, el desarrollo del sector agrario, y concretamente la agricultura que se provee de aguas subterráneas para el riego, debe afrontar de manera añadida una serie de retos de cara al futuro. Entre ellos destaca el problema energético, principalmente debido a su fuerte dependencia de los combustibles fósiles afectando finalmente al coste de producción. Sin embargo, no hay que olvidar la dependencia con los recursos hídricos, muy escasos en la franja mediterráneas, y los problemas de emisiones a los que contribuye la agricultura. En la actualidad, algunos organismos y administraciones, como la Unión Europea (UE), están propiciando ese cambio de modelo energético a través de mejoras en los procesos e instalaciones agrícolas, integrando sistemas de energía de carácter renovable por sus beneficios hacia la independencia energética del sector y por su positivo impacto ambiental en cuanto a las emisiones de CO_2.

De manera más concreta, en el sector de la agricultura por bombeo de aguas subterráneas los sistemas PVWP (Photovoltaic Water Pumping) ya han sido propuestos como alternativa directa como protagonistas de la sustitución de los equipos diésel. Sin embargo, aunque muchos estudios anteriores versan sobre estos sistemas, la mayoría de ellos solamente analizan su integración en zonas rurales remotas de África o Asia, o se centran en aplicaciones agrícolas de pequeño tamaño. Por lo tanto, se observa que, a tenor de los pocos estudios existentes en profundidad (como el de *Kelley en al., en 2010*), esta transición se está realizando sin el rigor de un análisis académico en profundidad que indague de las configuraciones óptimas o más idóneas para su aplicación en el sector. Este escenario genera algunas cuestiones sobre la eficacia en su aplicación, dimensionamiento o nivel de aprovechamiento de la energía capaz de generar el sistema respecto de la requerida para el bombeo. Por tanto, se destaca la necesidad de un examen exhaustivo de las soluciones energéticas para la agricultura abastecida por el bombeo de aguas subterráneas y la forma óptima de aplicarlas desde un enfoque multidimensional: económico, energético, hídrico, ambiental y social. Este enfoque supone el punto de partida de la presente tesis doctoral y la base de las aportaciones realizadas.

Así, la metodología general de la investigación llevada a cabo partió de la recopilación de datos solares e hídricos de dos zonas agrícolas con un evidente problema de sobreexplotación de los recursos hídricos del acuífero: el área de La Mancha (Acuífero 23) en España y la zona de la llanura de Fès-Meknès (Acuífero Saïss) en Marruecos. Posteriormente, se realizó un estudio estadístico de los recursos y se integró un Sistema de Información Geográfica (SIG) con el que analizar geográficamente la distribución de los recursos y su aplicabilidad. Con el fin de considerar otras alternativas y configuraciones en los sistemas de bombeo, más allá de los que el mercado ofrece para los agricultores, se diseñó una red de alternativas a partir de varias opciones, entre ellas: los equipos diésel, los sistemas PVWP aislados y conectados a la red eléctrica, y los sistemas abastecidos solamente por la red eléctrica. A continuación, y con el objetivo de poder evaluar cada alternativa, se caracterizaron desde un punto de vista multidimensional, atendiendo a diferentes criterios dentro de los ámbitos económicos, energéticos, ambientales, hídricos y sociales. Para visualizar los resultados de este proceso de caracterización, se utilizaron gráficas 4D con las que ofrecer una información lo más completa y visual posible. Tras ello, se hizo uso de técnicas de toma de decisiones multicriterio (MCDM), a través de una metodología conjunta AHP-TOPSIS, con la que, a partir de los criterios con los que se evaluaron las alternativas, clasificar en orden de idoneidad la solución que mejor se adaptase a las condiciones del caso de estudio. Este proceso conllevó también una encuesta previa a expertos.

Atendiendo a los resultados, esta tesis doctoral ha supuesto una serie de **contribuciones** relevantes en la integración de soluciones de carácter renovable en el sector de la agricultura de bombeo de aguas subterráneas. Entre ellas destacan: (i) la determinación y el análisis de los principales impactos que afectan al sector desde diferentes puntos de vista; (ii) la caracterización multidimensional de las alternativas energéticas dirigidas al bombeo de aguas subterráneas; (iii) el análisis geográfico con el apoyo de una metodología de información geográfica (GIS) exportable y escalable de los recursos hídricos y solar para la implantación de PVWP; (iv) y finalmente la utilización de un proceso AHP-TOPSIS de toma de decisiones multicriterio (MCDM) para evaluar la idoneidad de las configuraciones y alternativas con el fin de suministrar y cubrir las necesidades energéticas los sistemas de bombeo.

Finalmente, una de las contribuciones destaca sobremanera, y es la puesta en relevancia de los sistemas de bombeo cooperativo abastecidos por instalaciones fotovoltaicas conectadas a la red eléctrica, por sus posibles beneficios económicos al sector y el mayor aprovechamiento de la energía y de la instalación.

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"N'abandonnez jamais un rêve.
Essayez simplement de voir les signes qui vous mènent à lui".
Paulo Coelho

3. Objectifs

3.1 Objectifs

L'objectif principal de cette Thèse de Doctorat est ***l'Analyse et la caractérisation des différentes alternatives énergétiques pouvant être utilisées pour le pompage des eaux souterraines en agriculture et leurs configurations***. Pour atteindre cet objectif principal, il est nécessaire de développer une méthodologie qui intègre une Base de Données Géographiques, un processus de calcul, suivi d'une procédure d'Aide à la Décision Multicritères (MCDM) et enfin un Système d'Information Géographique (SIG) permettant l'analyse et la visualisation des résultats.

Pour atteindre l'objectif proposé, les étapes ou objectifs secondaires suivants sont formulés:

- O1. Identifier et analyser les principaux problèmes liés au pompage des eaux souterraines pour l'irrigation en agriculture, du point de vue énergétique, hydrique, socio-économique et environnemental, en accordant une attention particulière à la dépendance énergétique.
- O2. Caractériser en profondeur l'intégration de l'énergie solaire photovoltaïque dans l'agriculture pour le pompage des eaux souterraines, en tenant compte des dernières études.
- O3. Analyser géographiquement, à l'aide d'un outil SIG, les conditions initiales qui interviennent dans les systèmes PVWP: profondeur de la nappe phréatique, besoins en eau et rayonnement solaire disponible, entre autres.
- O4. Proposer un processus d'Aide à la Décision Multicritère pour déterminer l'option la plus avantageuse pour fournir l'énergie nécessaire au pompage agrícola, en fonction des différents critères préalablement établis et évalués par des experts.
- O5. Utilisation d'un outil SIG, pour visualiser les résultats de la méthodologie de calcul exposée, dans le but qu'elle puisse être analysée du point de vue géographique et qu'elle supporte le processus d'Aide à la Décision Multicritère.
- O6. Appliquer la méthodologie exposée à deux études de cas spécifiques l'un en Espagne et l' autre au Maroc, avec une agriculture de pompage des eaux souterraines,

avec l'analyse des résultats obtenues dans les différentes configurations d'installations énergétiques du point de vue énergétique, hydrique, économique et environnemental.

- O7. Analyser les systèmes PVWP connectés au réseau électrique, ainsi que l'énergie non utilisée afin d'étudier son éventuelle injection dans le réseau et déterminer ses avantages.

3.2 Objetivos

El objetivo principal de la presente Tesis Doctorales el ***Análisis y caracterización las diferentes alternativas energéticas susceptibles de ser utilizadas para el bombeo de aguas subterráneas en la agricultura y sus configuraciones***. Para la consecución de este objetivo principal, es necesario desarrollar una metodología que integre una Base de Datos Geográficos, un proceso de cálculo, seguido de un procedimiento de Toma de Decisión Multicriterio (MCDM) y finalmente por un Sistema de Información Geográfico (SIG) que aporte un análisis y visualización de los resultados.

Para alcanzar el objetivo propuesto, son formulados los siguientes hitos u objetivos secundarios:

- O1. Identificar y analizar los principales problemas asociados al bombeo de aguas subterráneas para el riego en la agricultura, desde el punto de vista de los aspectos: energético, hídrico, socio-económico y ambiental con especial atención a la dependencia energética.
- O2. Caracterizar en profundidad la integración de la energía solar fotovoltaica en la agricultura para bombeo de aguas subterráneas, analizando las últimas aportaciones.
- O3. Analizar geográficamente, mediante una herramienta GIS, las condiciones iniciales que se dan en los sistemas PVWP: profundidad del nivel freático, necesidades de agua y radiación solar disponible, entre otras.
- O4. Proponer un proceso de Toma de Decisiones Multicriterio para determinar la opción más ventajosa a la hora de suplir de energía la demanda del bombeo en la agricultura, en base a diferentes criterios previamente establecidos y evaluados por expertos.
- O5. Aplicación de una herramienta SIG, para visualizar los resultados de la metodología de cálculos expuesta, con la finalidad que pueda ser analizado desde un entorno geográfico y que dé apoyo a la toma de decisiones multicriterio.
- O6. Aplicar la metodología expuesta a dos casos de estudio concretos de España y Marruecos, con una agricultura de bombeo de aguas subterráneas, con análisis de los resultados obtenidos en las diferentes configuraciones de instalaciones energéticas desde el punto de vista energético, hídrico, económico y ambiental.

- O7. Analizar los sistemas PVWP conectados a la red eléctrica, así como la energía no utilizada para estudiar su posible inyección a la red y determinar sus ventajas.

“La historia del hombre es la historia de la búsqueda permanente de fuentes de energía y de sus formas de aprovechamiento, con el propósito humano de servirse del ambiente”.
Roberto E. Cunningham

4. Introduction et État de l’Art

4.1 Introduction

Actuellement, le secteur agricole des pays méditerranéennes fait face à un scénario difficile pour son développement en raison des faiblesses qu'ils présentent pour l'avenir. Parmi ses diverses faiblesses, il présente deux dépendances fortes, d'une part, la dépendance aux ressources en eau disponibles, qui sera un problème de plus en plus important en fonction de la prévision des précipitations et de l'augmentation de la température au cours de ce siècle. Et, d'autre part, la dépendance énergétique aux énergies fossiles d'un secteur de plus en plus technique et consommateur d'énergie, qui le soumet à la volatilité des prix du pétrole, rendant parfois l'agriculture non viable en raison des prix de production élevés.

Dans certains cas, comme celui qui concerne cette étude, le pompage des eaux souterraines, la relation entre les coûts de production alimentaire et les coûts énergétiques devient encore plus visible, et peut générer à terme une perte économique qui entraîne certains problèmes sociaux parmi lesquels le dépeuplement du monde rural est souligné.

Pour résoudre ce problème, le modèle énergétique agricole actuel de pompage des eaux souterraines est susceptible de conduire au changement attendu vers un modèle énergétique respectueux de l'environnement et non dépendant des énergies fossiles avec l'intégration des énergies renouvelables qui permettent de subvenir à leurs besoins énergétiques.

Mais pour franchir cette étape, il est nécessaire de procéder à un examen et d'une étude approfondis afin de profiter au maximum du potentiel offert par ces technologies énergétiques, en différenciant les applications et en déterminant précisément la manière la plus efficace de les appliquer, en tenant compte de tous les facteurs qui peuvent intervenir. Cependant, les dynamiques des études dans l'intersection actuelle entre le domaine de l'énergie et de l'agriculture semblent fonctionner séparément, indépendantes l'une de l'autre, puisque ce n'est que récemment que l'énergie demandée par l'agriculture est devenue domaine d'étude lorsque le dépendance aux énergíes fossiles s'est avérée assez forte.

Au sein de la littérature se référant au binôme agriculture et énergie, les solutions de pompage au moyen d'énergies renouvelables, et plus particulièrement de l'énergie solaire photovoltaïque, pour des applications agricoles en milieu rural ont été analysées par diverses études, bien que très peu visent à résoudre ce problème actuel dans l'agriculture. La plupart tentent de résoudre des problèmes particuliers, tels que l'accès aux eaux souterraines grâce à des systèmes photovoltaïques de faible puissance pour l'approvisionnement en eau potable, du bétail ou des potagers traditionnels de petite taille dans les zones rurales ou dans les pays en voi de développement.

Par conséquent, il existe peu d'études centrées sur les objectifs concernant les alternatives énergétiques de l'agriculture par pompage d'une manière similaire à celle réalisée dans cette étude (*Hammad, 1995*) (*Kelley et al., 2010*) (*Odeh et al., 2006*). Cependant, les contributions mentionnées ne parviennent pas à inclure la diversité de variables qui interviennent dans le problème mentionné, ni à offrir non plus des configurations alternatives dans les installations énergétiques, vu qu'il s'agit dans la plupart des cas de zones trop étendues, parfois éloignées de la réalité de la parcelle agraire que demandent les ressources hydriques et énergétiques.

À ce scénario s'ajoute le fait que, dans le domaine de l'agriculture, la transition vers les énergies renouvelables est en train de se produire sans la rigueur d'une analyse académique approfondie. Dans le cas du PVWP à un niveau particulier, ils ont été installés rapidement dans le seul but de couvrir la demande énergétique existante, sans les conseils appropriés et en omettant ou en ignorant d'autres facteurs tous aussi importants. Ainsi, il y a une série de questions non résolues sur l'efficacité de son usage, telles que le bon dimensionnement et sa sectorisation, le niveau d'utilisation du système ou l'utilisation de l'énergie qui n'est pas utilisée en dehors de la saison d'irrigation.

Par ailleurs, les derniers accords internationaux contraignants dans le domaine environnemental et les dernières politiques énergétiques européennes en vue des Objectifs de Développement Durable (ODD) du Programme 2030, promeuvent et renforcent la mise en place de modèles énergétiques favorables à la réduction des émissions de CO_2.

En même temps, la plupart des politiques agricoles, y compris la politique agricole européenne, promeuvent des améliorations dans les processus agricoles qui entraînent une stabilité économique et environnementale en termes de réduction de la dépendance aux combustibles fossiles, en priorisant les installations d'énergies renouvelables et en visant également à réduire les émissions de CO_2 dans ses processus. Ces changements dans l'agriculture, en function du pays, sont encourages par des subventions et des aides, et donc une opportunité de progrès dans l'utilisation de l'énergie. Cependant, l'application de ces politiques nécessite d'outils précis, comme les Systèmes d'Information Géographique (SIG), qui permettent d'évaluer en detail la réduction de CO_2 par l'exploitation agricole, dans ce cas, dans le pompage d'eau pour l'irrigation.

Compte tenu de la situation exposée et de ce qui a été révélé par les études citées, il est nécessaire d'examiner de manière exhaustive les solutions pour parvenir à des systèmes d'irrigation efficaces sous différents points de vue: celui de la gestion de l'eau, de l'énergie, des ressources économiques et de la réduction des émissions de CO_2. En même temps, une analyse spécifique est nécessaire pour combiner optimisation, dimensionnement et rentabilité économique des solutions photovoltaïques appliquées à l'irrigation.

Pour toutes ces raisons, cette étude part du problème, cité antérieurement, du manque d'études spécifiques sur le pompage des eaux souterraines pour l'agriculture, pour proposer une méthodologie de génération d'alternatives pour le pompage de l'eau, un Système d'Information Géographique (SIG) fonctionnant avec une Base de Données Géographiques et un Processus d'Aide à la Décision comme outil permettant d'apporter une vision plus globale de la problématique de l'eau souterraine à usage agricole, ainsi que la caractérisation et l'analyse de différentes configurations de pompage.

Dans ce but, deux études de cas ont été proposées, dans des pays aux caractéristiques et particularités différentes du point de vue climatologique, agricole et énergétique, en Espagne et au Maroc, où il existe des problèmes agricoles dus à la façon d'exploitation des aquifères et à une forte dépendance aux énergies fossiles.

4.2 Introducción

En la actualidad, el sector agrario en países de la franja mediterránea se encuentra ante un panorama difícil para su desarrollo debido a las debilidades que presentan de cara al futuro. Entre sus diversas debilidades presenta dos fuertes dependencias, por un lado, la dependencia de los recursos hídricos disponibles, la cual será un problema cada vez más importante a tenor de la previsión de precipitaciones y aumento de temperatura durante este siglo. Y, por otro lado, la dependencia energética de los combustibles fósiles de un sector cada vez más tecnificado y cada vez más consumidor de energía, que lo hace estar sujeto a la volatilidad de los precios del petróleo haciendo algunas veces inviable la agricultura por los elevados precios de producción.

En algunos casos como en el que atañe a este estudio, el bombeo de aguas subterráneas, la relación entre los costes de producción de alimentos y los costes de energía se hace aún más visible, pudiendo generar a la postre, una pérdida económica que trae consigo ciertos problemas sociales entre los que destacar la despoblación del mundo rural.

Para solucionar este problema, el modelo energético en la agricultura actual de bombeo de aguas subterráneas es susceptible de propiciar el cambio esperado hacia un modelo energético respetuoso con el medio ambiente y lejos de la dependencia de combustibles fósiles con la integración de energías renovables que permitan abastecer sus necesidades energéticas.

Pero para dar este paso se hace necesario realizar una revisión y un estudio minucioso con el fin de aprovechar el máximo potencial que ofrecen estas tecnologías energéticas, diferenciando las aplicaciones, y determinando de una forma precisa la forma más eficaz de aplicarlas teniendo en cuenta todos los factores que puedan intervenir. Sin embargo, la dinámica investigadora en la intersección actual entre el ámbito de la energía y el de la agricultura parecen discurrir separadas, de forma independiente, ya que, hasta no hace mucho tiempo, la energía demandada por la agricultura no era un campo de estudio prioritario. Hubo que esperar hasta alcanzar una elevada dependencia de los combustibles fósiles, para que estos estudios fueran necesarios.

Dentro de la literatura referente al binomio agricultura y energía, las soluciones de bombeo con energías renovables, y específicamente la energía solar fotovoltaica, para aplicaciones agrícolas en entornos rurales han sido analizadas por diversos estudios, aunque muy pocos están orientados a solucionar este problema actual de la agricultura. La mayoría tratan de solventar problemas particulares, como puede ser el acceso a agua subterránea mediante sistemas fotovoltaicos de baja potencia para el abastecimiento humano, ganadero o para cultivo de huertos tradicionales de pequeña superficie en zonas rurales o países en vías de desarrollo.

Por tanto, pocos son los estudios que se centran en unos objetivos referentes a las alternativas energéticas de la agricultura de bombeo de manera similar a la que se realiza en este estudio (*Odeh et al., 2006*) (*Kelley en al., 2010*). Aunque estas aportaciones mencionadas no alcanzan a incluir la diversidad de variables que intervienen en el problema mencionado, ni ofrecen configuraciones alternativas en las instalaciones energéticas, tratando en la mayor parte de los casos áreas demasiado extensas, lejos, a veces, de la realidad de la parcela agraria que demanda los recursos hídricos y energéticos.

A este panorama se añade que, en el ámbito de la agricultura, la transición hacia las energías renovables se está llevando a cabo sin un rigor de análisis académico en profundidad. En el caso de los PVWP a nivel particular se han instalado de forma rápida con el único fin de que cubra la demanda energética existente, sin un correcto asesoramiento y olvidando u obviando otros factores también importantes. Existiendo de esta forma, una serie de interrogantes pendientes sobre la eficacia de su aplicación como son el dimensionamiento correcto y su sectorización, el nivel de aprovechamiento del sistema o el aprovechamiento de la energía que no es utilizada fuera de la temporada de riego.

Por otro lado, los últimos acuerdos internacionales vinculantes de carácter ambiental y las últimas políticas energéticas europeas de cara a los Objetivos de Desarrollo Sostenible (ODS) y la Agenda 2030, promueven y potencian la implantación de modelos energéticos que propicien una reducción de las emisiones de CO_2.

A su vez, la mayor parte de las políticas agrarias, entre ellas la Política Agraria Europea, promueve mejoras en los procesos agrícolas que generen una estabilidad económica y ambiental referente a la reducción de la dependencia de combustibles fósiles, dándole un papel protagonista a las instalaciones de energías renovables y orientadas también a la reducción de emisiones de CO_2 en sus procesos. Estos cambios en la agricultura, en según qué países son estimulados gracias a subvenciones y ayudas, y por tanto una oportunidad para el progreso en el uso de la energía. Sin embargo, la aplicación de estas políticas requiere de herramientas precisas, como los Sistemas de Información Geográfica (SIG), que permitan valorar la reducción pormenorizada de CO_2 por explotación agraria, en este caso, en el bombeo de agua para el riego.

Ante la situación expuesta y lo manifestado por los estudios mencionados, existe la necesidad de un examen exhaustivo de las soluciones para lograr sistemas de riego eficientes desde distintos puntos de vista: de la gestión del agua, de la energía, de los recursos económicos y de la reducción de emisiones de CO_2. A su vez, es necesario un análisis específico para combinar optimización, dimensionamiento y viabilidad económica de las soluciones fotovoltaicas aplicadas a la irrigación.

Por todo esto, este estudio parte del problema mencionado del vacío de estudios concretos en el bombeo de aguas subterráneas para la agricultura, para proponer una metodología de generación de alternativas para el bombeo de agua, un Sistema de Información Geográfica (SIG) trabajando con una Base de Datos geográficos y un Proceso de Toma de Decisión como herramienta para aportar una visión más global del problema de la agricultura de aguas subterráneas así como la caracterización y análisis de diferentes configuraciones de bombeo.

Y para conseguir esto, se han propuesto dos casos de estudio, en países con unas características y peculiaridades diferentes desde el punto de vista climatológico, agrícola y energético, en España y en Marruecos en los que se tienen problemas agrícolas debido al régimen de explotación de los acuíferos y un alto grado de dependencia de los combustibles fósiles.

4.3 État de l’Art

L'énergie est la ressource fondamentale qui a permis à l'homme d'atteindre des degrés supérieurs de développement technologique et socio-économique. Cependant, toutes les sources d'énergie n'ont pas le même impact sur l'environnement et les autres ressources naturelles. L'orientation actuelle des **politiques énergétiques** et des accords-cadres qui se développent au niveau international visent à rechercher un changement de modèle énergétique en favorisant les sources d'énergie renouvelables par opposition aux sources d'énergie fossiles, dans le but ultime de minimiser l'impact de l'humanité dans le environnement.

Ces accords se sont développés à partir du Protocole de Kyoto, dans différents sommets sur le climat, parmi lesquels se distingue la COP21 à Paris en 2015, dans laquelle un consensus important a été atteint pour la réduction des émissions de GES (réduction de 45 % en 2030, par rapport à la niveau existant en 2010) et la promotion des Energies Renouvelables. De son côté, l'Union européenne (UE) est en train d'élaborer une loi européenne sur le climat dont l'objectif est d'atteindre la réduction d'émissions impose pour la COP21. Il convient de noter le grand effort que l'UE a déployé, au cours des deux dernières décennies, pour promouvoir des mesures en matière d'efficacité énergétique, d'énergies renouvelables et de sensibilisation des citoyens à l'environnement.

Parmi les secteurs économiques, le secteur primaire, qui intègre l'élevage et l'agriculture, a une importante demande d'énergie, principalement sous forme de combustibles fossiles, et est également l'un des secteurs qui émet le plus d'émissions de GES par rapport à son PIB (*Sutherland et al., 2015*). Dans ce secteur et dans certains cas, l'énergie n'est pas utilisée de manière efficace et durable dans son application aux tâches agricoles les plus courantes. De plus, le potentiel offert par l'agriculture d'un point de vue énergétique n'est pas exploité puisque la plupart des efforts de recherche et développement (R&D) sur l'énergie et ses applications sont destinés aux secteurs industriel et domestique.

Il y a donc un manque de synergie dans le trinôme Eau-Agriculture-Énergie qui facilite le transfert des connaissances technologiques et énergétiques vers l'agriculture et offre l'opportunité d'étudier la mise en œuvre de nouvelles technologies énergétiques. Si ce lien est exploité, le secteur pourrait faire face à trois défis d'importance internationale: la réduction des coûts de production alimentaire, la réduction des émissions de CO_2 et la réduction de la dépendance énergétique du secteur avec des ressources décentralisées et locales.

L'agriculture moderne basée sur les eaux souterraines, l'objet principal de cette étude, a commencé à se développer vers le milieu du XXe siècle et s'est rapidement étendue à différents aquifères à travers le monde. Actuellement, la plupart des systèmes qui fournissent de l'énergie à l'agriculture en pompant les eaux souterraines sont des **groupes électrogènes diesel** et des **systèmes alimentés par le réseau électrique**. Les groupes électrogènes isolés représentent une technologie mature avec de faibles coûts d'investissement. Cependant, ils sont alimentés par un carburant dérivé du pétrole et donc, avec un prix de marché volatil, et avec un taux d'émissions polluantes important. Cette situation génère une forte dépendance des prix du carburant sur les coûts de production et la marge bénéficiaire de l'agriculteur. Les systèmes alimentés par le réseau électrique, généralement pour de grandes parcelles ou des groupes (en raison de leurs coûts d'investissement élevés), peuvent également générer des effets négatifs sur l'économie de l'agriculteur dérivés des prix des tarifs de l'électricité. De plus, il représente une solution aussi polluante en émissions de CO_2 que le mix énergétique national.

A cela s'ajoutent différents problèmes qui menacent le secteur, notamment ceux dus aux facteurs climatiques (diminution des précipitations et hausse des températures) et ceux dus à une mauvaise gestion de l'eau (surexploitation des aquifères). Cela se traduit, finalement, par la perte de rentabilité des exploitations agricoles. Cette situation met en évidence la nécessité, déjà commentée, d'un effort de recherche plus important dans le nexus agriculture, eau et énergie.

Si l'on considère **l'agriculture de pompage des eaux souterraines d'un point de vue énergétique**, il s'agit de l'un des processus plus demandeurs d'énergie. Cette utilisation représente un pourcentage significatif par rapport à tous les types d'agriculture dans le monde, et en prenant l'exemple de l'Espagne, les méthodes d'irrigation par pompe représentent 26,7% de la superficie totale irriguée (*Carpintero & Naredo, 2006*), avec une demande énergétique actuelle qui atteint 45.000 GWh par an, pratiquement un tiers de l'énergie demandée par toute l'agriculture espagnole. Ces données peuvent être extrapolées à d'autres pays du bassin méditerranéen ou dans des zones arides disposant d'aquifères fournissant des ressources en eau pour l'agriculture locale.

Par conséquent, se manifeste l'importance de l'aspect énergétique pour l'agriculteur et pour la production agricole finale en termes économiques. Ainsi, l'agriculture devient un secteur plombé par la dépendance aux énergies fossiles qui l'alimentent, comme c'est le cas de l'Espagne dont l'agriculture était dépendante à 88,27 % entre (2009-2013).

Dans ce contexte, la ligne qui est proposée par de nombreuses études est **l'intégration des ressources énergétiques renouvelables dans l'agriculture de pompage des eaux souterraines**. En effet, sa mise en œuvre entraîne une série d'impacts positifs: indépendance par rapport aux coûts de production agricole, réduction des émissions de GES (*Meah et al., 2008*) (*Aliyu et al., 2018*) (*Odeh et al., 2006*) (*Kelley et al., 2010*), et la meilleure adaptabilité aux conditions d'isolement en milieu rural éloigné du réseau électrique. Techniquement, il existe trois sources d'énergie renouvelable qui peuvent potentiellement alimenter à court terme des équipements diesel, ce sont: l'énergie solaire, l'énergie mini-éolienne et le biogaz (*Campana et al., 2017*).

Parmi ces sources, l'énergie solaire a un grand potentiel dans les pays méditerranéens, et d'autre part, elle offre une meilleure sécurité d'approvisionnement face à la variabilité du vent. **L'énergie solaire photovoltaïque** apparaît donc comme une technologie faisable lorsqu'il s'agit de répondre à la demande énergétique de pompage, de remplacer les systèmes diesel traditionnels ou de combiner avec le réseau électrique.

Les principales **contributions concernant l'intégration de l'énergie solaire photovoltaïque dans l'agriculture pompée** ont été analysées (*Sontake & Kalamkar, 2016*). Cependant, ce n'est pas un nouveau concept, les premières études dans ce domaine sont plutôt nées avec le développement même de la technologie photovoltaïque. Bien que ce soit vrai, au cours de la dernière décennie, les études sur l'intégration des systèmes PV dans le pompage se sont multipliées, en raison d'un intérêt progressif. Bien que nouveau, ce domaine d'étude n'a pas été largement étudié, et les quelques études existantes ont un impact et une contribution importants.

Sur la base des contributions apportées dans la littérature spécifique consultée, ces études se distinguent pour avoir étudié des aspects aussi pertinents que les nouvelles méthodologies de dimensionnement des installations (*Ammar et al., 2018*), les prévisions d'opération, l'optimisation à la fois économique et énergétique en exploitation, la configuration et composants de systèmes PV (*Al-Badi et al., 2018*), l’analyse du cycle de vie et des émissions de GES des systèmes (*Yang et al., 2014*), simulation ou modélisation de systèmes PVWP

(*Nikzad et al., 2017*) la comparaison technico-économique des systèmes de pompage et des sources d'énergie utilisées (*Carrelo et al., 2020*) (*Rizi et al., 2019*) (*Reca et al., 2016*). Certaines études sur la dynamique de fonctionnement des modules et de la pompe sont également récurrentes, ainsi que les variations de pression, de débit d'eau, de rayonnement solaire, l'encrassement des modules et les ombrages.

D'autre part, l'innovation dans d'autres domaines scientifiques a permis l'incorporation de certains outils aux études sur les systèmes PV. C'est le cas des Systèmes d'Information Géographique (SIG) ou des méthodologies d'aide à la décision (*Muhsen et al., 2018*) (*Olcan, 2015*) (*Sánchez-Lozano et al. 2013*).

Certains auteurs (*Córcoles et al., 2016*) ont souligné la nécessité d'approfondir les connaissances et les actions en vue de **réduire la demande et d'optimiser l'utilisation de l'énergie** dans les processus et les composants de pompage dans l'agriculture.

Les avancées technologiques dans le domaine des nouvelles cellules photovoltaïques avancent sur plusieurs aspects fondamentaux. D'une part, et c'est le plus important, les progrès réalisés dans l'efficacité de la cellule photovoltaïque ont permis de construire des modules qui fournissent un plus grand potentiel électrique sur une surface réduite. Parmi elles, se distinguent les cellules à technologie silicium, les cellules PERC, les cellules bifaciales et les cellules de concentration. Certaines aussi nouvelles que les cellules CIGS et les cellules à pérovskite. A son tour, un module plus efficace et plus compact permet de réduire la taille de l'installation et donc d'économiser du matériel et des éléments nécessaires à sa fabrication. Dans le même ordre d'idées, la réduction de matière des procédés de fabrication peut permettre de réduire les émissions de gaz à effet de serre et plus précisément de CO_2, dans le cycle de sa vie utile (*Fthenakis & Alsema, 2006*). Certains aspects nouveaux dans l'élaboration du module, comme l'augmentation de la résistance aux agressions climatiques, ou la recyclabilité du module photovoltaïque, sont des propriétés importantes en cours d'investigation.

De la même manière, les progrès dans l'amélioration de l'efficacité de l'élément générateur et de la pompe ont été revus. Ainsi, a été analysée les études avec le but de réduire et optimiser la demande énergétique des pompes et des onduleurs, soit depuis sa conception dans la conception électrique et avec l'inclusion d'éléments de contrôle pour l'automatisation et la régulation de l'irrigation. Soulignant également les contributions dans le processus de dimensionnement, de gestion, d'optimisation et de régulation de toute l'installation.

Parmi les principaux piliers de la recherche agricole au cours des dernières décennies, **les contributions à l'efficacité de l'eau** dans les processus d'irrigation ont eu une grande importance. Cela est dû au fait qu'il existe une vulnérabilité aux sécheresses dans l'agriculture irriguée dans des milieux comme la Méditerranée, ce qui pousse les usagers à mieux profiter des ressources en eau et à en réduire la consommation, ce qui se traduit par une moindre demande en énergie.

Divers articles et études ont été analysés visant, d'une part, l'analyse biologique de la plante à différentes doses d'eau, la réduction de la consommation d'eau et l'observation de son incidence sur la production. D'autre part, d'autres études proposent des améliorations dans la maîtrise de l'eau du système d'irrigation hydraulique et son bon dimensionnement, ainsi que dans les méthodes d'irrigation. D'autres études importantes portent sur la sectorisation de la parcelle, la simultanéité des relais d'irrigation et la programmation temporaire de l'irrigation, et plus particulièrement celles qui traitent de l'irrigation de nuit. À leur tour, des études ont été analysées qui préconisent la mise en œuvre de mesures barrières contre les pertes d'eau dues à l'évaporation dans les bassins d'irrigation, à travers différents formats de couverture. Enfin, bien que plus innovants et récents, d'autres ont proposé de réduire la demande en eau grâce à la surveillance et à la détection des besoins de la plante ainsi qu'à la technologie SIG.

Certaines études environnementales établissent également des **stratégies passives pour réduire la demande d'énergie** dans l'agriculture pompée. Il s'agit notamment de la protection des ressources en eau de l'aquifère, de la protection des zones d'infiltration et des processus de recharge des aquifères, qui favorisent une restauration et une récupération de la nappe phréatique, réduisant la hauteur de pompage.

Enfin, il est important de souligner les études qui, profitant de l'application de mesures d'efficacité énergétique dans le pompage des eaux souterraines, approfondissent la **réduction des émissions de CO_2 et d'autres gaz GES dans l'atmosphère**.

4.4 Estado del Arte

La **energía** es el recurso fundamental que ha permitido al hombre alcanzar mayores grados de evolución y desarrollo tecnológico y socioeconómico. Sin embargo, todas las fuentes de energía no tienen el mismo impacto sobre el ambiente y sobre otros recursos naturales. La dirección actual de las **políticas energéticas** y acuerdos marco que se desarrollan a nivel internacional tienen como objetivo de busca un cambio de modelo energético impulsando las fuentes de energía renovable frente a las fuentes de energía fósil, con fin último de minimizar el impacto de la humanidad en el medio ambiente.

Estos acuerdos desarrollados desde el Protocolo de Kyoto, en diferentes cumbres entre las que destaca la COP21 de París en 2015, en la que se alcanza un importante consenso para la reducción de emisiones GEI (un 45% respecto del nivel de 2010 para 2030) y la promoción de las Energías Renovables. Por su parte la Unión Europea (UE) está desarrollando una Ley Europea del Clima cuyo objetivo es alcanzar la reducción de emisiones impuesta, a lo que habría que sumar el gran esfuerzo que en las dos últimas décadas este organismo está promoviendo en materia de eficiencia energética, energías renovables y concienciación ciudadana.

Entre los sectores económicos, el sector primario, el cual integra la ganadería y la agricultura, posee una importante demanda de energía principalmente en forma de combustibles fósiles, siendo además de los sectores que mayores emisiones de GEI emite en comparación con su PIB (*Sutherland et al., 2015*). En este sector, en algunos casos la energía no es aprovechada de una forma eficiente y sostenible en su aplicación a las labores agrícolas más comunes. Tampoco el potencial que ofrece la agricultura desde la perspectiva energética, ya que la mayor parte de los esfuerzos en I+D+i sobre energía y sus aplicaciones, son destinados a ámbitos industriales y domésticos.

Por tanto, existe una falta de sinergia en el trinomio entre el Agua-Agricultura-Energía, donde se dé cabida a la transferencia de conocimientos tecnológicos y energéticos hacia la agricultura y donde se ofrezca la oportunidad de estudiar la implantación de nuevas tecnologías energéticas. De explotarse este nexo, podrían hacer frente a tres retos de calado internacional: la reducción de los costes de producción de alimentos, la reducción de emisiones de CO_2 o la reducción de la dependencia energética del sector con recursos descentralizados y autóctonos.

El sector objeto de estudio, la agricultura moderna que se abastece de aguas subterráneas, comenzó a desarrollarse hacia mediados del siglo XX, y rápidamente se extendió por los potenciales acuíferos del mundo. En la actualidad, la mayoría de los sistemas que suplen de energía a la agricultura de bombeo de aguas subterráneas son los **equipos electrógenos diésel** y los **sistemas alimentados por la red eléctrica**. Los equipos electrógenos aislados representan una tecnología madura y con unos costes de inversión bajos. Sin embargo, son abastecidos por un combustible derivado del petróleo y por ende, con un precio de mercado volátil, y con un grado de emisiones contaminantes significativas. Esto genera una gran dependencia de sus precios sobre los costes de producción y el margen de beneficios del agricultor. Los sistemas alimentados por la red eléctrica, generalmente para parcelas o agrupaciones de gran tamaño (debido a sus altos costes de inversión), también pueden generar efectos negativos en la economía del agricultor derivados de los precios de la tarifa eléctrica. Además, representa una solución tan contaminante en emisiones de CO_2 como lo es el mix energético nacional.

A esto se añaden diferentes problemas que ponen en jaque al sector, entre ellos los debidos a factores climáticos (reducción de precipitaciones y aumento de la temperatura) y los debidos a una deficiente gestión hídrica (sobreexplotación de acuíferos). Esto se traduce finalmente en la pérdida de rentabilidad de las explotaciones agrícolas. Esta situación pone de manifiesto la necesidad, ya comentada, de un mayor esfuerzo en investigación en el nexo agricultura, agua y energía.

Atendiendo a la **agricultura de bombeo de aguas subterráneas desde el punto de vista energético**, éste es uno de los procesos más demandantes de energía más. Este uso representa un importante porcentaje respecto de todas las tipologías de agricultura a nivel global, y que poniendo como ejemplo España, los métodos de riego por bombeo son un 26,7% de la superficie irrigada total (*Carpintero & Naredo, 2006*), con una demanda energética actual que alcanza los 45.000 GWh anuales, prácticamente un tercio de la energía que demanda toda la agricultura de España. Este dato puede extrapolarse a otros países de la cuenca mediterránea o de zonas áridas que cuenten con acuíferos que abastezcan a la agricultura local.

Por lo tanto, se evidencia la importancia que tiene el componente energético para el agricultor y para la producción agraria final en términos económicos, convirtiéndose en un sector lastrado por la dependencia de los combustibles fósiles que lo abastecen, como es el caso de España cuya agricultura fue un 88,27% dependiente entre (2009-2013).

Ante este panorama, la línea que se propone por numerosos estudios es la **Integración de recursos energéticos renovables en la agricultura de bombeo de aguas subterráneas**, ya que su implantación supone una serie de impactos positivos: la independencia energética de los costes de producción agrícola, a la reducción de emisiones GEI (*Meah et al., 2008*) (*Aliyu et al., 2018*) (*Odeh et al., 2006*) (*Kelley en al., 2010*), y la mejor adaptabilidad a las condiciones aisladas en entornos rurales alejados de la red eléctrica. Técnicamente existen tres fuentes de energía renovable que potencialmente pueden suplir a corto plazo a los equipos diésel, estas son: son la energía solar, la energía mini-eólica y el biogás (*Campana et al., 2017*).

Entre estas fuentes, la energía solar posee un gran potencial en los países mediterráneos, y por otro lado, ofrece una mejor seguridad de suministro frente a la variabilidad del viento. Por lo tanto, **la energía solar fotovoltaica** se erige como una tecnología factible a la hora de suplir la demanda energética de los bombeos sustituyendo los sistemas tradicionales diésel, o combinándola con la red eléctrica.

Las principales **contribuciones en materia de integración de energía solar fotovoltaica en la agricultura de bombeo**, han sido analizadas (*Sontake & Kalamkar, 2016*). Sin embargo, no se trata de un concepto nuevo, sino que los primeros estudios en dicho campo se originaron con el propio desarrollo de la tecnología fotovoltaica. Si bien es cierto, en la última década los estudios sobre integración de sistemas PV en el bombeo ha despertado se han incrementado, fruto de un progresivo interés. Aunque novedoso, este campo de estudio no ha sido ampliamente estudiado y en el que los pocos estudios existentes son de gran impacto y contribución.

Atendiendo a las contribuciones aportadas en la literatura especifica consultada, estos estudios destacan por haber investigado aspectos tan relevantes como las nuevas metodologías de dimensionamiento de instalaciones (*Ammar et al., 2018*), predicciones de funcionamiento, optimización tanto económica como energética en el funcionamiento, configuración y componentes de los sistemas PV (*Al-Badi et al., 2018*), análisis de ciclo de vida y emisiones de GEI de los sistemas (*Yang et al., 2014*), simulación o modelización de sistemas PVWP (*Nikzad et al., 2017*) o comparativas tecno-económicas de los sistemas de bombeo y de las fuentes energéticas utilizadas (*Carrelo et al., 2020*) (*Rizi et al., 2019*) (*Reca et al., 2016*). También son recurrentes algunos estudios sobre la dinámica en el funcionamiento de los módulos y la bomba y variaciones en la presión, caudal, radiación solar, ensuciamiento de los módulos y sombras.

Por otro lado, la innovación en otras ramas de la ciencia ha permitido, la incorporación de ciertas herramientas a los estudios de acerca de sistemas PV. Este es el caso de los Sistemas de Información Geográfica (SIG) o las metodologías de toma de decisiones (*Muhsen et al., 2018*) (*Olcan, 2015*) (*Sánchez-Lozano et al. 2013*).

Algunos autores (*Córcoles et al., 2016*) han señalado la necesidad de un mayor conocimiento y acciones en la línea de la **reducción de la demanda y la optimización del uso de la energía** en los procesos y en los componentes del bombeo en la agricultura.

Los avances tecnológicos en materia de nuevas células fotovoltaicas avanzan en varios aspectos clave. Por un lado, y la más importante, se ha progresado en la eficiencia de la célula fotovoltaica pudiendo construir módulos que aporten un mayor potencial eléctrico en menor superficie, entre las que destacan las de tecnologías del silicio, las células PERC, las bifaciales y las de concentración. A su vez, un módulo más eficiente y más compacto permite reducir el tamaño de la instalación y por ende el ahorro de material y elementos necesarios para su fabricación. En esa misma línea, la reducción material de los procesos de fabricación, puede permitir la reducción de emisiones de gases de efecto invernadero y concretamente de CO_2, en el ciclo de su vida útil (*Fthenakis & Alsema, 2006*). Ciertos aspectos novedosos como la elaboración de módulo: como son el aumento de resistencia frente a aspectos climáticos, o la reciclabilidad del módulo fotovoltaico, también son propiedades importantes en estudio, destacando las células CIGS y las de perowskita.

De la misma forma que se han revisado los avances en la mejora en la eficiencia del elemento generador, también se han hecho en la carga, desarrollado investigaciones para reducir y optimizar la demanda energética de bombas e inversores, ya sea desde su concepción en el diseño eléctrico como con la inclusión de elementos de control para la automatización y regulación del riego. Destacando también estudios en el proceso de dimensionamiento, gestión, optimización y regulación del conjunto de la instalación.

Entre los principales pilares de la investigación en la agricultura en las últimas décadas, las **contribuciones en eficiencia hídrica** en los procesos de riego han tenido un gran peso. Esto es debido a que existe una vulnerabilidad frente a las sequías en la agricultura de regadío en entornos como el mediterráneo que empuja a los usuarios a un mayor aprovechamiento y a un consumo menor, lo cual **finalmente redunda en una menor demanda energética**.

Se han analizado diversos artículos y estudios encaminadas, por un lado, al análisis biológico de la planta ante diferentes dosis hídricas reduciendo el consumo de agua y observando cómo afecta a la producción. Por otro lado, otros estudios proponen mejoras en el control hídrico del sistema hidráulico de riego y su correcto dimensionamiento, y en los métodos de riego. Destacan también otros estudios sobre la sectorización de la parcela, la simultaneidad de turnos de riego y la programación temporal de la irrigación, y en concreto los que abordan el riego nocturno. A su vez, han sido analizados estudios que abogan por implantar medidas de barrera frente a las pérdidas hídricas por evaporación en balsas de riego, a través de diferentes formatos de cobertura. Por último, aunque más innovadores y recientes, otros han propuesto la reducción de la demanda hídrica a través de la monitorización y sensorización de las necesidades de la planta unido a la tecnología SIG.

Algunos estudios de carácter ambiental, además establecen **estrategias pasivas para reducir la demanda energética** en la agricultura de bombeo. Entre ellas destacan la protección de los recursos hídricos del acuífero, la protección de las zonas de infiltración y los procesos de recarga de los acuíferos, los cuales propician un restablecimiento y recuperación del nivel freático, reduciendo la altura de bombeo.

Finalmente, es importante reseñar aquellos estudios que aprovechando la aplicación de las medidas de eficiencia energética en el bombeo de aguas subterráneas profundizan en la consiguiente **reducción de las emisiones de CO_2 y otros gases GEI a la atmósfera**.

"Guarda el orden y el orden te guardará a ti".
San Agustín de Hipona

5. Articles qui composent la Thèse par Compendium

5.1 Artículo 1 | GIS based solar resource analysis for irrigation purposes: Rural areas comparison under groundwater scarcity conditions.

Las estrategias internacionales, y en especial las europeas; en materia de energía han girado sobre todo en el cambio del modelo energético en todos los sectores económicos, promoviendo la integración de fuentes de energía renovable, en especial, la energía solar fotovoltaica. Entre los diferentes sectores, el sector agrícola se está convirtiendo en un participante más para reducir la dependencia de los combustibles fósiles y reducir las emisiones de CO_2.

De hecho, la agricultura, en especial la del entorno mediterráneo, suele combinar una alta demanda de energía con problemas hídricos asociados a la sobreexplotación de los acuíferos, a lo que hay que añadir dificultades energéticas debido a altos costes de los combustibles necesarios en las labores agrícolas. Este panorama brinda la oportunidad para un cambio de modelo energético racional, como una nueva forma de desarrollo rural sostenible donde la clave sea la optimización de los recursos tanto hídricos como energéticos.

Teniendo en cuenta este marco, el estudio llevado a cabo describe y compara la integración del recurso solar y sus efectos sobre el bombeo agrícola en dos países mediterráneos, España (La Mancha) y Marruecos (Llanura Saïss o de Meknès-Fès), con diferencias significativas en términos de condiciones climáticas y políticas energéticas, pero con similitudes relacionadas con la agricultura vitivinícola y hortofrutícola y con la sobreexplotación de los recursos hídricos de los acuíferos.

Metodológicamente este estudio cuenta con tres partes bien diferenciadas, por un lado, un análisis estadístico del recurso solar disponible, un análisis geográfico de los recurso solar e hídrico y finalmente, un estudio técnico de análisis comparativo del cambio de modelo energético de un equipo diésel a un sistema PV.

Como aportación novedosa en este trabajo, se ha propuesto el uso de un Sistema de Información Geográfico (SIG), para analizar la variabilidad espacial y temporal del recurso solar a través de datos reales, tomados en estaciones piranométricas, de ambas localizaciones. Para ello se ha realizado previamente un análisis estadístico del recurso solar disponible. Con dichos datos se construyeron las capas tanto de Radiación Solar Anual, como Mensual de los meses característicos. De la misma forma se ha evaluado los niveles piezométricos, en base a datos de pozos de control, con los cuales evaluar la dinámica hidrogeológica del entorno, construyendo así una capa relativa a la profundidad del nivel freático, tomando como referencia la superficie terrestre. Con ambas capas se construye la capa de aplicabilidad. Seguidamente han sido comparados desde un punto de vista técnico dos sistemas de bombeo, a través del cambio de modelo energético.

Los resultados de la evaluación de la metodología propuesta como modelo para resolver problemas multidimensionales 3E (Económica, Energética y Ambiental) relacionados con el riego con aguas subterráneas, arrojan unas evidencias significativas.

Por un lado, muestra la conveniencia y la utilidad de la propuesta metodológica basada en SIG a la hora de analizar y comparar zonas agrícolas para proponer un cambio del modelo energético, dirigido hacia la instalación de sistemas de bombeo alimentados mediante plantas fotovoltaicas (PVWP), integrando criterios cualitativos y cuantitativos ligados tanto con el recurso solar y con la profundidad del acuífero.

Además, y como principal contribución la capa de aplicabilidad, como la relación entre la radiación incidente y la profundidad del acuífero, permite mostrar los valores donde la inversión sería menor en el cambio de modelo energético y, por ende, donde sería más fácil aplicar esta tecnología. A su vez, diferentes datos cuantitativos asociados a cada parcela (o conjuntos de parcelas) pueden representarse mediante capas geográficas: emisiones de cada parcela, requerimientos energéticos o la potencia instalada.

Por otro lado, y atendiendo a los casos de estudio (las dos regiones de España y Marruecos), el análisis determina la idoneidad que presenta la propuesta del uso del entorno SIG para analizar la variabilidad espacial u temporal del recurso solar, así como para visualizar los recursos hídricos en los acuíferos subterráneos para ambas áreas con fines de riego por bombeo.

Profundizando en cada uno de ellos, según los resultados, el acuífero de Saïss (Marruecos) tiene una mayor demanda energética para elevar agua en comparación con La Mancha (España), así pues, requiere una mayor potencia en sus equipos generadores y de bombeo, y, por tanto, en términos de emisiones de CO_2, éstas serían tres veces superiores en el caso de un generador diésel en Marruecos que en La Mancha (España).

El cambio de modelo energético en ambos casos proporciona un ahorro significativo en términos económicos atribuidos a la sustitución de bombas diésel por energía solar fotovoltaica. Además, también se incluye la estimación del ahorro de emisiones de CO_2 para ambas ubicaciones por dicha propuesta de cambio de modelo energético.

Con el presente artículo se aprecia el gran futuro que tiene la energía solar fotovoltaica en su integración en aplicaciones agrícolas. Concretamente, para las zonas que tienen problemas derivados del precio de los combustibles, demostrando que otra forma de obtener los recursos hídricos subterráneos para los cultivos es posible.

GIS Based Solar Resource Analysis for Irrigation Purposes: Rural Areas Comparison under Groundwater Scarcity Conditions

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Abstract

During the past decade, most governments have been promoting energy efficiency programs and the integration of renewable energy sources into the majority of energy uses. Among the diferent sectors, the agricultural sector is becoming a more active participant to reduce fossil fuel dependence and improve environmental sustainability. Indeed, agriculture usually combines both a high energy demand and water problems associated with over-exploited aquifers, providing great potential and remarkable opportunities to change the energy mix and maximize the use and integration of natural resources in a rational way. Considering this framework, the present paper describes and compares the solar resource integration and its effects on agricultural pumping purposes in two Mediterranean countries, Spain and Morocco, with significant differences in terms of energy mix, climatic conditions and energy policies. As a novel contribution in this paper, we propose the use of GIS to analyze the spatial and temporal variability of the solar resource through real data of both locations, as well as to study groundwater resources. With this aim, two technical proposals for irrigation purposes are compared in terms of environmental benefits, CO_2 emissions and agriculture energy model changes: diesel equipment and photovoltaic system. Results based on solar radiation resource, pumping requirements and aquifer depth are included in the paper.

Keywords: Solar Energy Resource, Applicability Solar Energy, Solar Water Pumping, Sustainable Rural Development, Geographic Information Systems (GIS), Photovoltaic Systems.

1. Introduction

Fossil fuels have met most energy needs since the 1^{st} Industrial Revolution, providing remarkable industrial advances in newly developing countries. These changes had significant influences on most sectors, including the modernization and industrialization of agricultural processes: tasks related with growing, harvesting, processing or delivering became high energy-demanding. During the 2^{nd} Industrial Revolution, both fossil fuel dependence and energy consumption were increasing considerably. Industrial and developing countries then continued to meet their energy needs by expanding the supply-base, without regard for efficient use or sustainability [1]. Nowadays, the world energy demand increased at a rate of 5% in 2010, and according to the International Energy Agency (IEA) it will continue increasing until 2050 [2]. This tendency is also motivated by the recent industrialization of countries where demography has soared along with their development, such as China or India [3]; involving further depletion of energy resources and uncertain scenarios for fossil fuel prices and energy demand [4]. As a consequence, energy is currently at the core of the discussion, since energy production and use account for two-thirds of the world's greenhouse-gas emissions [2], certain dependency can be established between the use of fossil fuels and global warming problems. Indeed, emissions have been traditionally linked to SO_2 and CO_2 concentrations, which are considered relevant variables to characterize the greenhouse effect [5].

Taking the finite fossil energy resources into account as well as the severity of pollution emissions, several countries have promoted initiatives related to renewable source integration and the promotion of a more sustainable environment. The main objective is to move from a high CO_2 emission mix generation towards a low–emission model, maintaining long-term sustainable economic and social development [6]. Different programs have been promoted with this aim, such as the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO) and the Intergovernmental Panel on Climate Change (IPCC). In addition, a series of sustainable policies and strategies have been proposed to give an international support, including both the Kyoto Protocol and European Union policies [7]. The use of renewables

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throughout Europe and elsewhere in the rest of the world complies with clear objectives for energy saving and emission reduction [8]. In reference to the road-map of renewables in Spain, significant results have been obtained as a result of subsidies and policies contributing to provide suitable conditions for the integration of renewable solutions, such as PER 2005-2010 [9] and PANER 2011-2020 [10] promoted by IDAE (Spanish Institute for the Energy Diversification) [11]. Additionally, and due to the continued implementation of policies supporting renewable energies in the European Union, around 12% of the total energy in Spain is provided by renewables, with 20% of energy from renewable sources being established by 2020 and considerably reducing greenhouse gas emissions. The location of Spain contributes significantly to the high levels of solar radiation, supposing a clear advantage for the integration of solar PV solutions [12]. However, and despite Morocco having favorable conditions of solar radiation and also wind resource, the low price of electricity and fuel supposes a major drawback for the integration of renewables in this North African country. In fact, this sector is currently becoming strategic and relevant for the government in Morocco, especially for the large scale integration of solar thermal and wind power solutions [13].

Agriculture in both countries has been modernized and upgraded with more and more energy requirements, usually supplied by fossil fuels. In Spain, a specific subsidized diesel for agriculture is available for the sector. In Morocco, fuel is not differentiated depending on applications and uses, with the price being considerably lower than in Spain. Therefore, solutions based on diesel equipment still remain as a very common practice for pumping groundwater purposes. Under this scenario, agricultural emissions have been increased from 4.7 billion tons of carbon equivalent (CO_2 eq) in 2001 to more than 5.3 billion tons in 2011 [14]. Moreover, the equipment usually used in the agriculture sector commonly presents low energy efficiencies and other factors such as obsolescence, and wear and tear. On the other hand, there are well-known water scarcity problems in both Mediterranean countries. For the specific aquifers to be analyzed, an over-exploitation situation of aquifers has been detected, where farmers are using a larger and larger share of their profits to afford fuel for pumping purposes. To provide an alternative solution for the agriculture sector, and according to current programs promoting the integration of renewables, a conversion of irrigation systems from fossil fuel to solar energy source should be addressed [15] [16, 17]. These initiatives lead to a sustainable environment, providing environmental and social-economic benefits [18], at local and regional levels [19]. Among the different resources, solar energy has been widely extended as an alternative resource during the last decades. Both efficiency improvements and process optimization in Silicon production and manufacture have become a mature industry, supporting a high demand of PV modules and reducing the Wp price to lower than 0.5 $Euro/Wp$. Consequently, solar resource is considered as an alternative and competitive solution [20, 21]. With the aim of exploring the solar resource in detail, a Geographical Information System (GIS) is proposed in this paper to integrate, analyze and efficiently represent geographical information and physical conditions. The GIS application allows us to depict the solar radiation spatial variability due to the topography of the area [22] under different levels: global, regional or local level. Indeed, the success and competitiveness level of solar technology is based on analyzing the available solar resource throughout its temporal, spatial and spectral characteristics [23, 24]. Consequently, the geographical analysis of the solar resource in these two Mediterranean areas provides significant information regarding the solar resource distribution. A suitable evaluation model is proposed taking into account geographical characteristics, optimal locations for solar energy solutions, environmental concerns, as well as social-economic factors associated with solar resource integration into agriculture [25, 6]. In addition, the combination of solar energy with other energy sources (hybrid applications) is also considered by including feasibility and cost analysis [26, 22]. According to the specific literature, different contributions about solar atlas and solar pumping can be found aiming to analyze the viability of these systems [23]. Previous GIS application studies are focused on discussing the vulnerability of aquifers or their emissions, including solar resource evaluation [27]. However, there is a lack of contributions addressed to jointly evaluating solar and water resources in the agricultural sector [28], being desirable to include CO_2 emission reductions. In [29], the feasibility or alternative solutions are analyzed from several aspects: technical, economic and environmental; without including GIS technical and economic information nor analyzing the applicability concept of solar resource in the studied field. In comparison with recent studies, [29], the present paper focuses on an exportable and flexible methodology based on a GIS solution, which provides an extensive solar resource analysis in an easily understandable manner thanks to software at regional scale.

The rest of the paper is structured as follows: Section 2 describes the energy requirements and solar resource potential in agriculture for the selected areas, including geographical description and water resources for both locations and countries. The proposed methodology is described in Section 3, where the collected data are analyzed from a statistical, geographical and technical point of view. Results are discussed in Section 4. Finally, the conclusion is given in Section 5.

2. Energy Requirements and Solar Resource Potential in Agriculture: a Mediterranean Case Study

2.1. Location of Areas: General Description

From the geographical and geological point of view, the study region of La Mancha (Spain) is a vast plain (around

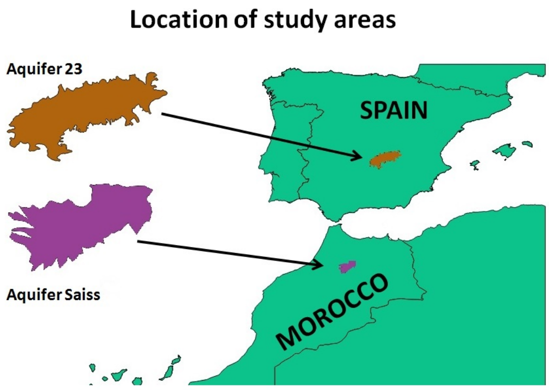

Figure 1: Location of study areas: La Mancha (Spain) and the Saiss plain (Morocco)

5500 km^2) dependent on Aquifer 23 (04.04 hydrogeological unit or the Western-La Mancha). It is located in the Central area of the high Guadiana river, a sedimentary basin mainly dominated by a limestone ('karst') region [30, 31]. The relief of the Morocco region, the Saiss plain (2100 km^2) [32], also known as the Fez-Meknes plain, resembles the La Mancha plain on karst [33, 34, 32]. Regarding weather conditions, La Mancha area is considered as a continental *Bsk* Mediterranean climate (Köppen-Geiger climate classification), typically associated with dry and hot summers (over 43°C) and high solar radiation levels (over 4500kWh/m^2 per day), as well as cold winters with most days below 0°C, see Figure 1 for geographical location. A significant low rain-fall (between 300-400 mm) and very high evaporation during most months clearly reflect the arid climate conditions in this Spanish area. The Saiss region has a *Csa* Mediterranean climate (Köppen-Geiger climate classification), with annual average temperatures about 17.3°C [32], dry and very hot summers (over 40°C) and also with high solar radiation levels. By contrast, winters are milder than in the Spanish region, and winter and spring seasons present higher rainfall values (490-560 mm per year) [32]. This region can be thus classified as a semiarid-zone according to the *Martonne index*.

In the region of La Mancha (Spain), the Aquifer 23 mainly comprises medium–sized cities, accounting for fewer than 400000 people, with a low population concentration and minor requirements supported by the aquifer. However, in the Maghreb region, the population is over 1.5 million of people, thus increasing the requirements on the Saiss aquifer in comparison with the Aquifer 23. Both areas belong to the Mediterranean agricultural landscape: olives, wheat and grapes; as well as other tree dry land crops (almonds, figs...) and small orchards (fruit, vegetables...) In particular, La Mancha Region offers a remarkable example of vast plains and dry land, supporting irrigation crops during the last centuries. In the area located in Meknes (Morocco), agriculture contributes significantly to economic aspects by promoting jobs and improving rural incomes [35]. The landscape is still dominated by wheat, along with irrigation of vegetables, total 45%, and fruit (citrus, olive and vine) with 36% [35]. The area comprises an agricultural surface area of approximately 191000 Ha, around 80% of the total area. The irrigation crops account for less than a quarter of the land use (about 37000 Ha), the land with irrigation potential commissioning is over 123000 Ha [35].

2.2. Water Resources for Irrigation Purposes

The Mediterranean region is undergoing rapid local and global social and environmental changes. All indicators point to an increase in environmental and water scarcity problems with negative implications towards current and future sustainability [36]. The risk of water scarcity is proposed to be managed by preparedness rather than by a crisis approach, along with the importance of local management at basin scale [37]. Moreover, several researchers have even pointed out the links between social-political relations and water management, including power-plays in irrigation policies [38, 39, 40]. In both areas, irrigation is a crucial aspect directly linked to the agricultural production and with significant impact on the environment. In Spain, the awareness to natural resources and agricultural modernization has led to irrigation methodologies based on drip and sprinkler solutions. However, gravity irrigation methods still remain in Morocco, being at this moment the most popular solution. In both cases, high water demand and inefficient irrigation methods should be improved, proposing alternative solutions in line with the hydrological cycle characteristics of the area. Additionally, unsustainable irrigation patterns should be modified, promoting new policies from government and organizations responsible for the care of water resources [41]. In this way, the groundwater levels have dropped dramatically during the last years, with scarcity problems and difficulties to reconcile agriculture with the environment.

In La Mancha (Spain), the piezometric evolution of Aquifer 23 during the period 1980-2008 can be summarized as a sort of declining level periods, with the presence of notable but isolated partial recovering intervals mainly due to wet periods, see Figure 2 [42, 43]. As a consequence of a continuous over–exploitation of the Aquifer, pumping is currently the only way to extract water [44]. Therefore, rigid constraints and requirements have been issued for irrigation, such as a maximum of 1500m^3/(Ha-per-year) for vineyard crops.

The hydrogeological map of the Saiss aquifer (Fez-Meknes) was published in 1960 [45]. The Saiss aquifer —with contributions by infiltration of rainwater among other processes of 296-346 million m^3/year— is currently estimated to provide an annual demand between 275 and 400 million m^3/year due to rivers, drought and desiccation of some springs, drinking water and intensive agriculture (mainly since the 1980's). The aquifer currently has water deficit conditions with non-pumping limitations, with the average water demand of crops per hectare being between

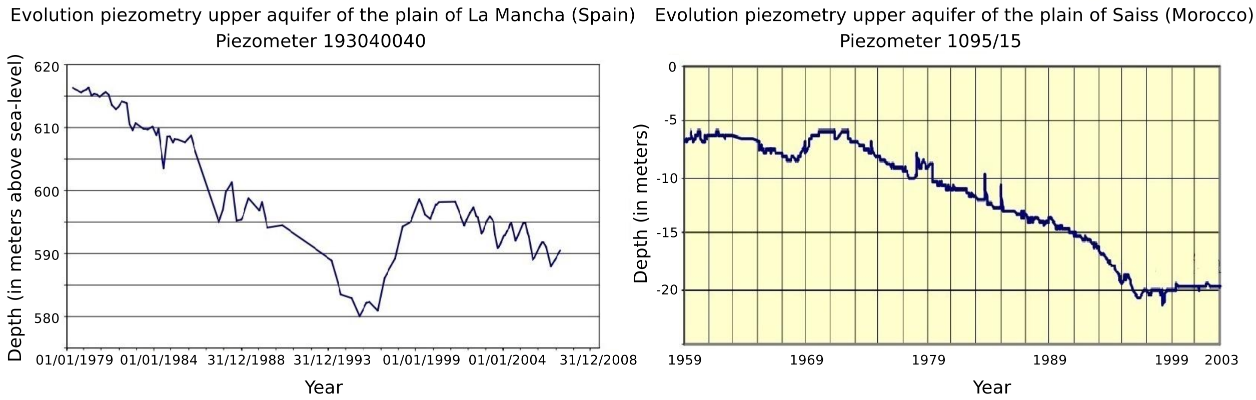

Figure 2: Evolution piezometry upper aquifer of the La Mancha plain (Spain) [42] and the Saiss plain (Morocco) [35]

3500 m^3/Ha and 5600 m^3/Ha, see Figure 2 [35]. The Saiss aquifer presents a large depth variability as a consequence of geological influences. Indeed, near Fez located at the East of the Ain Taoujdate line, it is over 60 m deep, even reaching over 350 m in some piezometers [34]. The chronological evolution of the Saiss aquifer gives a clear imbalance between exploitation and recharge of water resource [33, 34].

2.3. Energy Requirements and Solar Resource Potential

Both areas are located in the *'sun belt'* area [23], between 40°N and 40°S latitudes, with high solar radiation levels throughout the year. Spain is a country with a high energy dependence, around 71% in 2013 of primary energy [46] and 27.3% of power demand covered by renewables [47]. Energy demanded by agriculture was 3.3% in 2013 of total primary energy, and over 76% is covered with fossil fuels. As mentioned before, this great energy dependence and the fuel price increasing is leading Spanish agriculture to an unsustainable situation. To overcome these drawbacks, the Spanish government promotes initiatives to subsidize fuel for agricultural applications, as a way to reduce the pressure on Spanish farmers. Until 2011, the Spanish government also financially supported the integration of renewables, with a large economic contribution in R&D. Although the renewable energy sector has always been expanding during the last decades, the crisis has affected it strongly, mainly driven by the reduction of programs and initiatives.

The price of fuel in Morocco is fully regulated by the Moroccan government. In that country, fuel prices are 30-40% cheaper than in Spain, and a few programs and initiatives can be found to promote the renewable energy source integration, despite Morocco being highly dependent on imported energy, with over 90% dependence on other countries [48]. Nevertheless, there are few solar thermal systems and photovoltaic installations connected to the grid, and few projects promoting renewable energy source integration. Today, several specialized weather stations can be found in the country. To overcome technological deficiencies, Morocco has already started different initiatives to characterize the solar radiation resource in the country. The objective is to analyze and study accurately the solar resource conditions in each region of Morocco. Nowadays, the Meteorological Institute of Morocco has some weather facilities in different parts of the country, and the IRESEN (L'Institut de Recherche en l'Energie Solaire et Énergies Nouvelles) and MASEN (Moroccan Agency for Solar Energy) are also promoting the installation of new stations for solar radiation studies. In line with the great development of photovoltaic technology, it would be desirable to have an extended knowledge of the geographical distribution and variability of the solar resource [28, 17]. Furthermore, an accurate database of suitable locations for renewable energy facilities is suggested by some authors as a relevant tool to optimize the integration of these renewable solutions [25].

3. Methodology: GIS Solution for Solar Resource Comparison and Applicability Purposes

3.1. Preliminaries

Energy resources are usually spatially distributed, and GIS applications can be used as suitable solutions providing a logical environment to analyze a variety of spatially related data in a cost-effective way [49]. For the development of the maps, Quantum GIS (QGIS) (version 2.14 ESSEN) was selected by the authors. It is a GIS Open-Source solution, lightweight and with a friendly graphical interface, and is flexible and easy to use. It can be freely installed and modified according to the specific functionality required by the application. It has a great interoperability and works with all operating systems [50, 51]. QGIS provides a growing range of capabilities through basic functions and accessories. It also allows to manage, edit and analyze data and design printable maps; performing map algebra, terrain analysis, hydrological models and supports a series of formats of raster and vector data. As remarkable advantages, the possibility of integrating

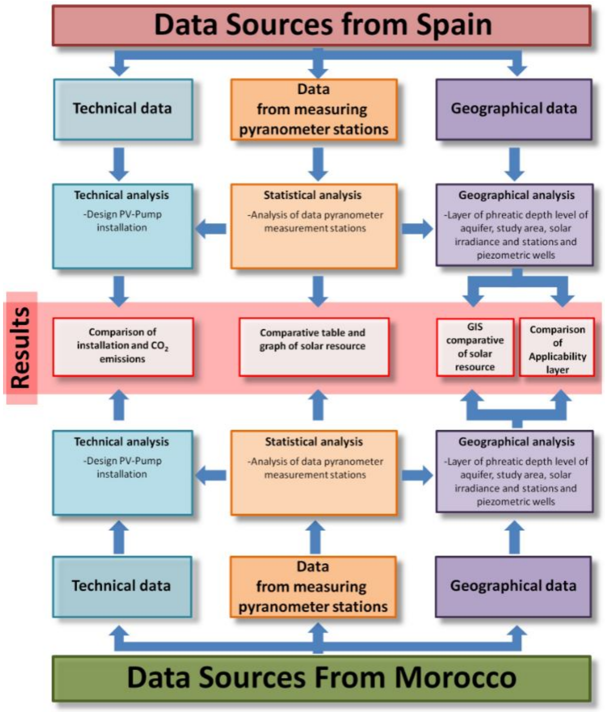

Figure 3: Proposed methodology based on solar resource analysis and comparison for irrigation purposes

GRASS (Geographic Resources Analysis Support System) in QGIS, and the ease connection as PostGIS database can be highlighted.

GIS can handle geo-referenced information to assess technical and economic feasibility of the source exploitation. Since the 1970s, different contributions have been developed, considerably solving problems in land management, such as evaluation of natural resources, agricultural land management, water management and control, or environmental planning [15, 52, 53]. According to [54], the application of geomatics to renewable resource assessment, in particular to the solar resource, is a topic worth investigating [55]. GIS is thus a suitable solution for spatial analysis of solar resources, considering spatial distribution of the potential, dependence on geographical locations, and levels of use according to the technology [6]. Moreover, an effective selection of locations depends on considering several independent factors concerning geomorphology, aquifer depths and solar radiation.

The proposed methodology includes the analysis of three different types of data, which gives an extended comparative of the solar resource possibilities: *(i)* statistical data of aquifers and solar resource; *(ii)* geographical data in both areas; and *(iii)* technical analysis data. As can be seen in Figure 3, the proposed methodology can be summarized as: Comparison of installations and CO_2 emissions; Comparative tables and graphs; GIS comparative of solar resource; and Comparison of applicability layer.

3.2. Data Sources

In line with the previous section, the Spanish data corresponding to the studied area can be divided into three categories: statistical, geographical and technical data. The solar resource has been provided through *SiaR* data-base of Castilla La Mancha Region, an agricultural organization in charge of collecting data to provide this information for irrigation purposes (`http://crea.uclm.es/siar/`). In our case study, a historical series of data from January 2001 to December 2014 is considered with the values in MJ/m^2 per day. The historical data are used to analyze the incident solar resource in the area of the aquifer. Annual data from nineteen stations allow us to determine a detailed map of solar radiation under a GIS environment. Geographic data including the geo-positioning of all pyranometer stations is also available. The solar radiation layer can be matched with data concerning the aquifer, thus it is possible to propose a layer with a GIS area of the aquifer. Another source of data provides the aquifer depth estimated in February 2014 for different points of the study area through information given by 26 piezometric stations with their corresponding UTM (Universal Transverse Mercator) position. This information is supported by the Confederación Hidrográfica del Guadiana, in collaboration with the irrigation Community of Aquifer 23. Figure 4 shows the pyranometer station locations. Similar types of data corresponding to the Morocco location were collected as a result of a collaboration with the Meknes University. A historical solar radiation data series from February 2004 to December 2013 was provided by lÍnstitut de Recherche en Énergie Solaire et en Énergies Nouvelles in Rabat (IRESEN) (`http://www.iresen.org/fr/index.html`), in Wh/m^2 per day, corresponding to seven pyranometer stations, see Figure 5.

Geographical data are also available from geo-referenced data stations, including contour and piezometric stations with their UTM locations for the aquifer. These data have been provided by the Agence du Bassin Hydraulique du Sebou (Morocco). Technical data were collected from previous contributions and other installations in a similar way to the Spanish case.

3.3. Statistical Analysis of Solar Resource

Solar resource data for both areas are analyzed in detail to determine average monthly data as well as station variability. Firstly, a classification of the data collected in both countries and a selection of common units is carried out. In our case, all data are expressed in Wh/m^2 per day, determining maximum, minimum and monthly average values for each station. Secondly, a summary of variability and range of the data including standard deviation between stations are compared by using monthly values of each year. Data variation between stations is lower than 10% for both locations. An equivalent average value is considered as valid for all stations, and variability

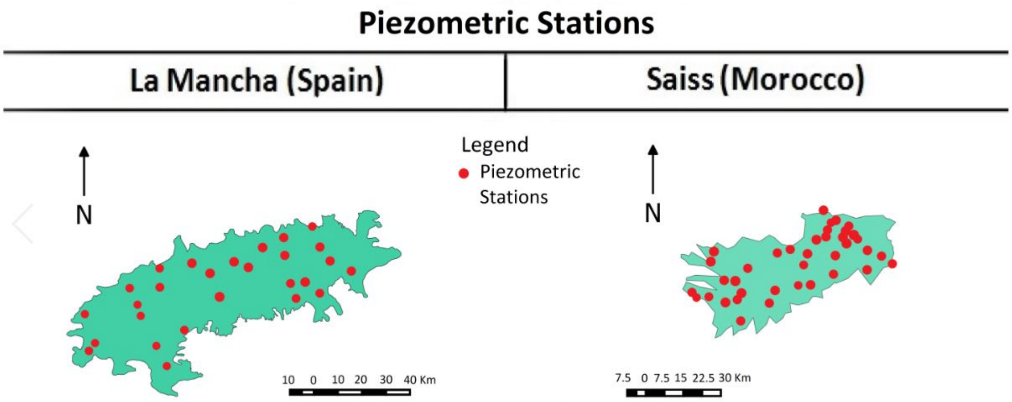

Figure 4: Location of measuring Piezometric Stations by reference to the aquifer

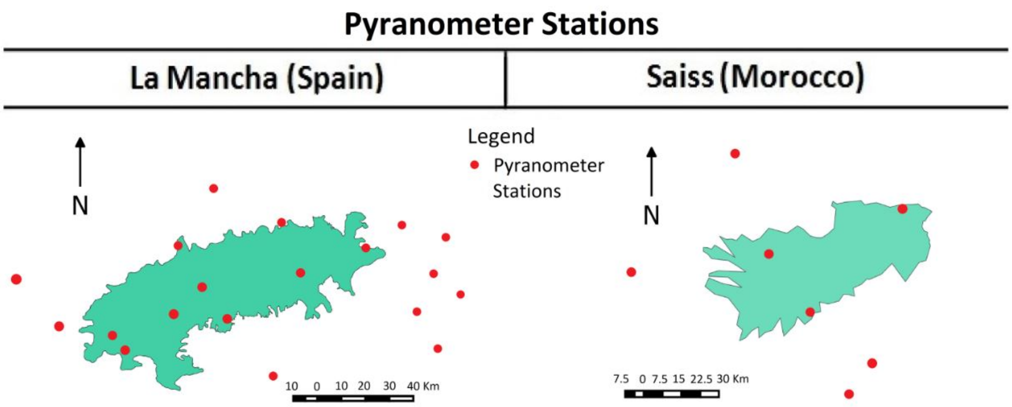

Figure 5: Location of measuring Pyranometer Stations by reference to the aquifer

Annual average and standard deviation between measurement stations			
La Mancha (Spain) Annual Average		Saiss (Morocco) Annual Average	
Measuring station	**Wh/m² day**	**Measuring station**	**Wh/m² day**
Álcazar de San Juan	4934.01	Meknes	5362.14
Argamasilla de Alba	4941.35	Ifrane	5358.71
Bolaños	5001.08	Fes	5341.04
Daimiel	4989.56	El Hajeb	5349.67
El Pedernoso	4816.83	Azrou	5339.83
El Sanchón-Vara del Rey	4971.48	Khemisset	5342.83
Herencia	4940.56	Sidi Kacem	5335.39
Juanaco-Villarrobledo	4759.53	**Stand. Deviation**	**10.10**
Manzanares	5084.76		
La Puebla de Almuradiel	4826.23		
La Gineta	4819.36		
El Picazo	4816.87		
Tarazona de La Mancha	4502.81		
Porzuña	4947.49		
Villanueva de la Jara	4708.40		
Ciudad Real	4862.22		
Albacete	4858.41		
Villahermosa-Tajoneras	5058.53		
Motilleja	4798.52		
Stand. Deviation	**135.72**		

Figure 6: Annual average and standart deviation among measurement stations

between stations is also depicted in this study, see Figure 6. From the monthly average values per station, an equivalent average monthly value from all measured stations is estimated to compare both countries. In a similar way, an annual average value is determined for each station, and the corresponding annual equivalent average value can be calculated for each study area and country. The geographical analysis inputs are the monthly average values per station and per country [26, 56].

3.4. Geographical Analysis of Solar Resource

With landscape scales, topography is a key factor determining the spatial variability of radiation. Variation in elevation, orientation (slope and aspect), and shadows cast by topographic features all affect the amount of radiation received at different locations [25]. The first step is focused on limiting the study area and the extension of both aquifers, based on maps and table information including coordinates of the aquifers provided by the Confederación Hidrográfica del Guadiana (Spain) [43, 44, 57] and the Agence du Bassin Hydraulique du Sebou (Morocco)[58, 59]. The estimation of the aquifer outline is related to a dynamic mass of water influenced by two main factors: the high water table and the geological materials that serve the continent, which can be used as waterproofing or otherwise can be permeable and present a very narrow boundary line. Data corresponding to the statistical analysis (monthly and annual solar radiation for each measurement station at their own UTM coordinates) are then exported to the geographical analysis. To give an example of the proposed methodology, only characteristics of representative months are considered in the Results section: January, April, July and October; as well as the annual values offering additional geo–referenced information. Data from piezometers and aquifer depths corresponding to each study area give the groundwater status by a simple yet adequate estimation.

The next step is to determine the aquifer maps and solar radiation distributions corresponding to both locations. The GIS process deals with radiation data and geographical locations to determine the study area layer and estimate the space-temporal data. A depth map of each aquifer is calculated in a similar way [60]. Information regarding the aquifer borderlines, solar radiation resource and aquifer depths is then used to determine the distribution of the water resource and energy needs, see Figure 7. The results involve a comparison of both monthly and annual solar resource as well as an applicability layer. This layer provides an index of the applicability as the role of solar radiation resources and the water table, or expressed differently, a map showing the areas with the best sun-aquifer conditions to implement a solar pumping system. This map does not indicate the viability of the system as it is necessary to consider other important factors such as crop irrigation, irrigation frequency, energy prices, etc. This technology has already proven its reliability [61].

The IDW (Inverse distance weighting) interpolation method is applied to estimate values between stations. The sampling points are weighted during the interpolation and then the influence of a point relative to another is decreasing with the distance from the new point to be estimated, determining an IDW surface [62]. The weighting is assigned to the sampling points using parameters and weighting coefficient modeling how the influence of the weighting decays as the distance to the new point increases. As the ratio increases, the value of the unknown points approximates the value of the closest observation point. It is important to point out that the IDW interpolation method presents several drawbacks: the maximum and minimum values in the interpolated surface can be drawn only at points of sample data. This often results in small peaks and wells around the location of the data.

3.5. Technical Analysis of Solar Resource

In addition to the previous analysis, and for a more complete comparison of both areas, an extended study of the agricultural sector is also proposed. Subsequently, and after analyzing the applicability layer, a comparison based on physical data for two installations in terms of CO_2 saving emissions and energy needs by using photovoltaic and diesel solutions is carried out. The same Mediterranean crops in these areas are considered, assuming similar surfaces to ensure such comparability. From these areas, crop needs and irrigation profiles for the design of agricultural pumps are determined from both points of view: diesel solution and PV installation.

4. Results

4.1. Statistical Analysis of Solar Resource

For both study areas, Figure 8 depicts the solar resource values through the statistical analysis. Considering winter months, Morocco has higher solar resorces than Spain.

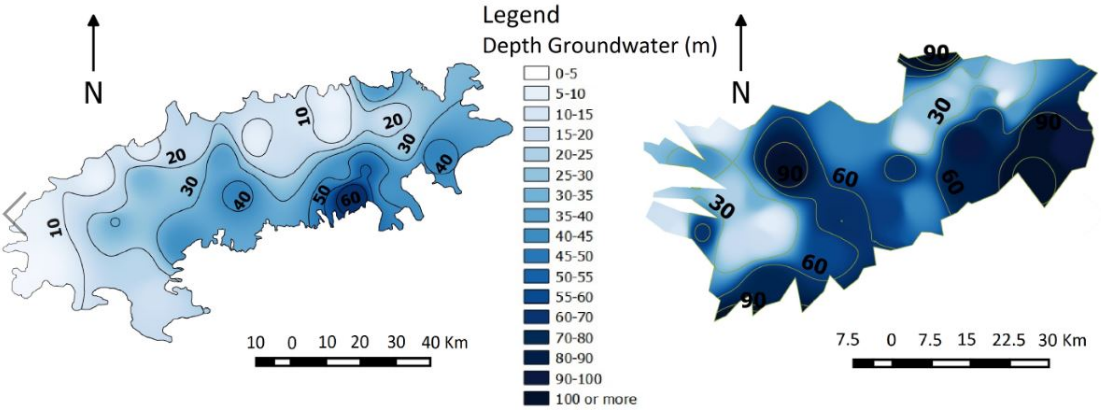

Figure 7: Depth aquifers: distribution of water resource

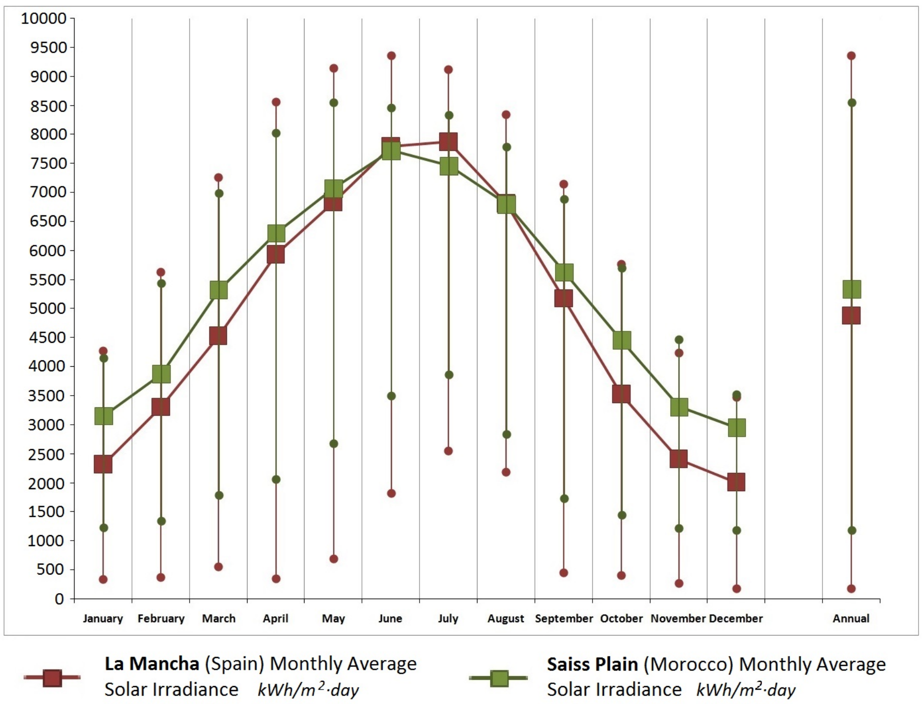

Figure 8: Solar resource in both locations: Spain and Morocco

Monthly average, maximum, minimum and standard deviation of the measurements of each month

		$(Wh/m^2 day)$		
La Mancha (Spain)	**Max**	**Min**	**Average**	**Stand. Deviation**
January	4271.63	336.54	2314.47	953.98
February	5628.94	369.15	3303.81	1246.72
March	7261.54	553.65	4529.01	1556.51
April	8560.23	342.83	5935.20	1705.69
May	9139.18	686.98	6831.77	1668.76
June	9351.75	1821.78	7793.30	1195.70
July	9114.76	2550.43	7873.10	846.13
August	8347.51	2188.59	6813.97	1032.04
September	7142.54	451.31	5173.06	1309.59
October	5764.91	407.89	3525.06	1180.18
November	4236.98	263.15	2409.36	919.35
December	3469.01	180.70	2006.51	816.78
Annual	9351.75	180.70	4875.72	309.93
		$(Wh/m^2 day)$		
Saiss (Morocco)	**Max**	**Min**	**Average**	**Stand. Deviation**
January	4151.67	1242.90	3162.45	746.28
February	5437.49	1354.35	3881.83	1108.03
March	6992.61	1791.11	5331.06	1366.01
April	8030.03	2074.28	6306.72	1546.45
May	8548.56	2679.27	7079.09	1538.88
June	8461.54	3506.58	7727.69	975.93
July	8332.85	3869.82	7463.24	791.98
August	7788.34	2843.63	6803.62	861.86
September	6884.35	1741.36	5635.62	1094.86
October	5699.05	1450.01	4466.30	979.96
November	4478.39	1220.99	3318.07	843.85
December	3531.06	1195.41	2959.33	625.32
Annual	8548.56	1195.41	5344.58	304.05

Figure 9: Monthly, maximum, minimum and standart deviation of the measurement of each month

Spring and autumn months present solar values almost similar in both countries. During the summer, solar radiation levels in Spain are higher than in Morocco, with even more daily sun hours. In terms of average levels, the Spanish annual average is 4.8 kWh/m^2 per day, lower than the annual average of Morocco (5.3 kWh/m^2 per day), see Figure 9. Regarding the spatial variability among seasons, the Spanish standard deviation is higher (135.74) than in Morocco. This difference is due to the effect of a larger area for the Spanish case, a height difference of 94 m, as well as a distance of around 160 km between the Spanish western and the eastern part. In Morocco, with 10.10 standard deviation, a smaller study area is considered, with 100 km width and a difference in elevation of over 200 m.

4.2. Geographical Analysis of Solar Resource: GIS Comparison

Figure 10 compares solar resource data corresponding to different months for both locations. In the Spanish area, a clear distinction between the east and west parts can be observed, with a global variability below 10%. The east zone presents less solar radiation and coincides with an upper height. In the region of Meknes-Fez (Morocco), the results show a very slight spatial variability in most months with a decreasing radiation in the South part. The East-northeast (ENE) gives less solar radiation and higher values around Meknes. These data provide a spatial variability and distribution of solar resources in both areas. An additional map is shown in Figure 11, where a comparison between average annual solar resource for both study areas is depicted.

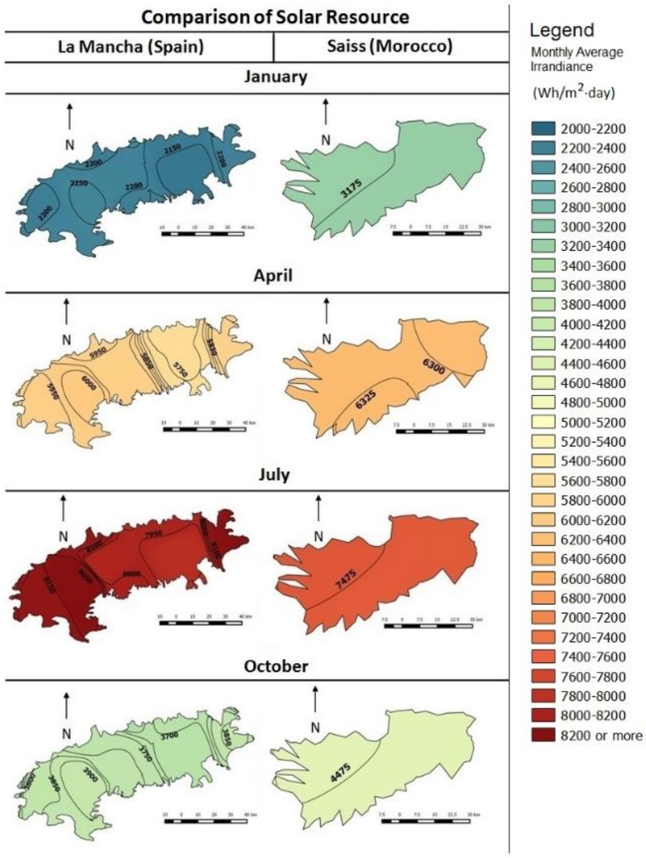

Figure 10: Solar resource for different months: comparison of maps

Figure 12 compares the applicability layers for both study areas. This layer provides an index of applicability associated with the relationship between the solar radiation values and the water level measured in Wh· m/m^2 per day. Through the comparison of these two areas, it can be deduced that solar radiation values are almost constant along the aquifer areas, with the aquifer depths being a more decisive variable. In this way, groundwater data corresponding to the Moroccan aquifer show it to be deeper than the Spanish aquifer (named Aquifer 23). In Saiss (Morocco), data with greater applicability levels correspond to values closer to the borderlines of the plain, near three rivers in the basin of the Sebou river. On the contrary, the Spanish data show aquifer depths almost uniform on the Western-side, being deeper than on the Eastern-side. These results point out the Guadiana river band nearby areas, lagoons and its tributaries as areas with remarkable rates of applicability. The results provide relevant information regarding the potential of solar energy in such areas, meaning that the applicability of solar water pumping depends on the location. In line with these results, the investments will be higher or lower. It is possible to establish a comparison between these economic requirements and the current expenses incurred by farmers in pumping diesel, see [63] for further information.

In order to provide additional information about the

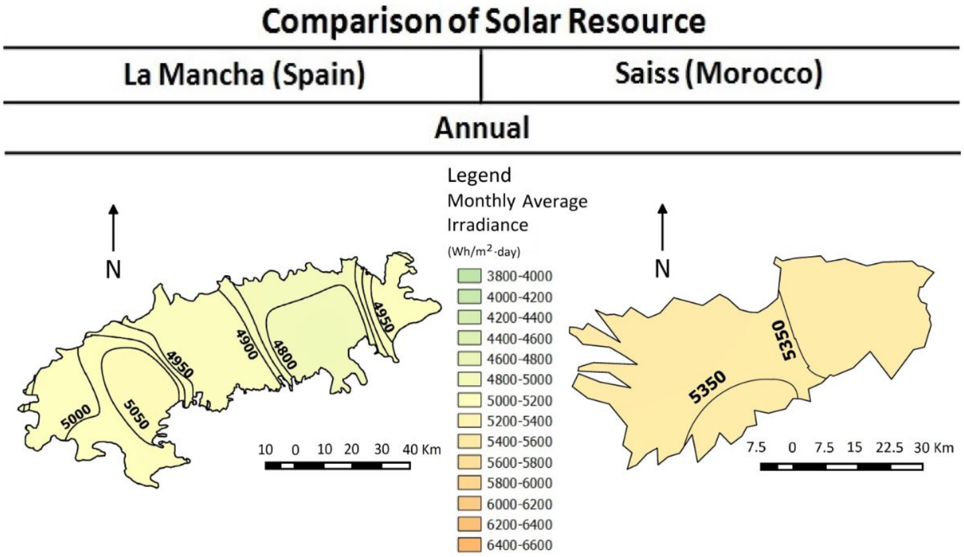

Figure 11: Annual solar resource: comparison of maps

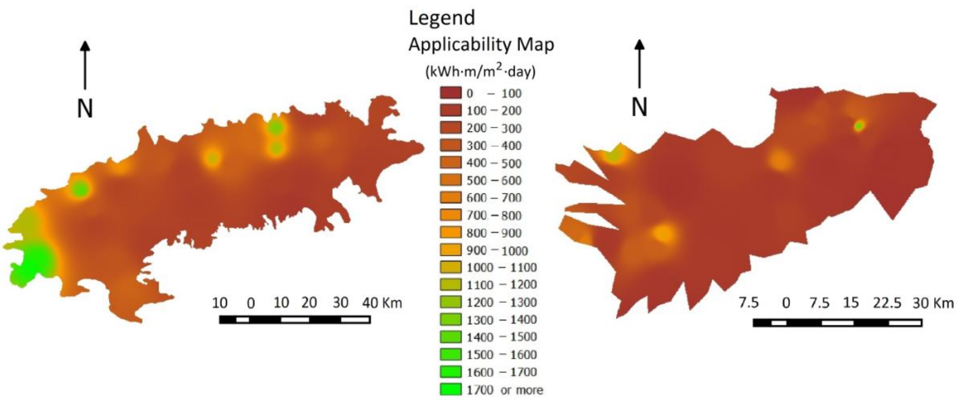

Figure 12: Geographical Analysis of Solar resource: Comparison of applicability layers

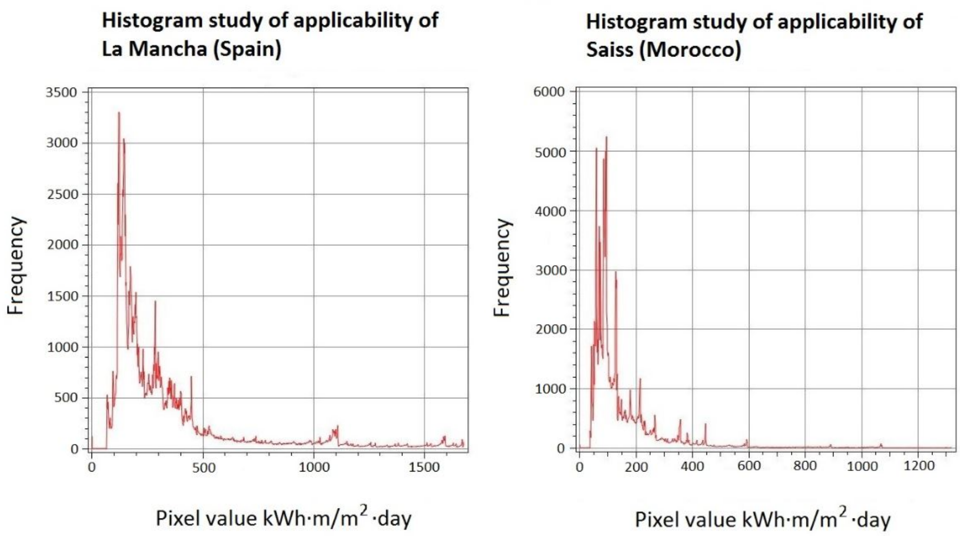

Figure 13: Histogram study of applicability of La Mancha (Spain) and Saiss (Morocco)

applicability layer, Figure 13 shows the histogram results for these values. As can be seen, for the Spanish case over 80% of the values are between 44.21 and 486.36 Wh·m/m^2 per day, with an average value of 223.37 Wh·m/m^2 per day. Regarding the Saiss plain (Morocco), these values show that 81.77% of data are between 44.50 and 222.54 Wh·m /m^2 per day, presenting a lower standard deviation and an average value of 105.40 Wh·m/m^2 per day.

4.3. Technical Analysis of Solar Resource and CO_2 emissions

A comparison of energy needs and emissions for both locations is carried out in this section. Indeed, the Spanish aquifer has an average applicability value of 223.37 Wh·m/m^2 per day corresponding to an average annual radiation of 4.87 kWh/m^2 per day and with an average aquifer depth of 21.82 m. For the aquifer located in Morocco, the average value of applicability is estimated to be 105.40 Wh·m/m^2 per day, corresponding to an average annual radiation of 5.34 kWh/m^2 per day and with an average depth of 50.76 m. Therefore, and by considering both study areas and previous analysis, Figure 14 summarizes the water pumping design to support the requirements, estimating water needs for the same crops. These water requirements are slightly higher for the Saiss plain (Morocco), mostly due to higher average temperatures and higher solar radiation levels. According to the results, the study area of Saiss (Morocco) needs more irrigation time and thus, a higher energy demand in comparison with the Spanish case.

By considering these water necessities, Figures 15 and 16 present an extensive comparison between the proposed solutions based on diesel equipment and PV installation. Different economic costs are estimated for both countries, as a consequence of their energy policies and the increasing pressure on the farmer's life. Moreover, in terms of CO_2 emissions, the Saiss plain in Morocco is higher than the same crop in La Mancha (Spain) [64, 65, 66]. If PV solution is selected for pumping purposes, and considering the same pattern of crop water demands, in 82.73% of cases (455015 Ha), La Mancha (Spain) requires a PV-installation with a power rate of 2800 W. By considering the Morocco case study and also assuming a crop demanding the same amount of irrigation as the vineyard, with the climatic conditions of the Saiss plain, in 81.77% of cases (179894 Ha), a PV-installation of 8160 W rate power is necessary [67]. Both systems are designed in terms of the power demanded by the crops according to the energy required for the three months that the plant water demand for growth lasts in time interval, coinciding with the hottest summer months in both areas, and it corresponds to the time period between the flowering and maturation of the crop chosen (from June to August). Through the system demand, it is possible to estimate CO_2 emissions [68, 69, 70]. Comparing both systems and estimating the emission reduction provided by the energy model change toward a model based on renewables.

Comparing Figures 15 and 16, the energy consumption in the Saiss plain is higher than in the Spanish aquifer, and thus a larger PV installation is required for the same use per Hectare. Along with that, CO_2 emissions would be three times higher in the case of a diesel generator in Morocco than in La Mancha (Spain), mainly due to the depth: 72% higher in Saiss (Morocco) against La Mancha. Nevertheless, it is necessary to point out the low price of fossil fuels in Morocco, which means that this country can still be based on diesel generators for agricultural pumping systems. Finally, the CO_2 emission savings for photovoltaic technologies is very favorable with the use of Mono-Si in both countries, although the savings in CO_2 emissions are much more desirable in the case of the Saiss plain, being possible to save up to five times more CO_2 than in La Mancha (Spain).

5. Conclusions

A proposed methodology based on GIS is described to analyze and compare two areas in different Mediterranean countries suitable for the installation of pumping systems by using PV plants through the aggregation of qualitative and quantitative criteria related to both solar resource and aquifer depth. Significant differences in terms of energy mix, climatic conditions and energy policies have been considered, with the aim of providing an extensive and real comparison. From real data corresponding to both locations (Spain and Morocco), a GIS environment is proposed to analyze spatial and temporal variability of the solar resource, as well as the underground aquifers for both areas for pumping irrigation purposes. Additional energy, economic and environmental savings attributed to the replacement of diesel pumps by solar PV installations are also included in the paper.

The results assess the proposed methodology based on GIS to be able to solve multi-dimensional problems related to agriculture sector and energy requirements applied to irrigation processes based on aquifer, water resource control and solar resource integration. In addition, the replacement of current diesel systems by solar pumping installations is also included, estimating the CO_2 emission savings for both locations. According to the results, the Saiss aquifer (Morocco) has a higher energy demand to obtain water in comparison with La Mancha (Spain). In terms of CO_2 emissions, they would be three times higher in the case of a diesel generator in Morocco than in La Mancha (Spain). Future work is proposed to assess the degree of clustering of plots through agro-energetic cooperatives in order to create irrigation storage facilities.

La Mancha (Spain)		Saiss (Morocco)
	Pump Desing	
10.82	*Q* Max Water pumping (m^3/h)	17.77
21.82	*h* Depth groundwater (HWC)	50.76
13	*h(pg)* Pressure in irrigation network head (HWC)	13
5	*h(a)* Lost by advection (HWC)	5
11	*h(o)* Other losses (HWC)	11
40.82	*H* Total pressure (HWC)	69
0.9	η_m Mechanical performance	0.9
0.9	η_e Electric performance	0.9
1484.63	*P* Power demanded by the pump (W)	4122.13
2	Power (C.V.)	5.6

Figure 14: Water requirements and pumping design in both areas

La Mancha (Spain)			Saiss (Morocco)	
		OPTION 1: Diesel generator equipment		
1484.63		Power required (W)	4122.13	
2 KVA		Power of diesel generator standart (W)	5 KVA	
1.39		Consumption 100% (l/h)	1.56	
0.778		Emissions $kgCO_2/kWh$	0.778	
213.78		Total Energy generated kWh	643.03	
200.16		Total Consumption (l)	246.36	
166.32		Total Emissions ($kgCO_2$)	500.27	
October 2013	**October 2015**	Price of diesel	**October 2015**	**October 2013**
1.38 (0.84*)	1.09 (0.78*)	Price of diesel liter (€) (DH) *with subsidized	7.98	8.54
		Change €-DH	0.75	0.76
275.22 (168.16*)	217.97 (156.13*)	Price of diesel in summer (€)	184.77	187.26

Figure 15: Diesel equipment design and CO_2 emissions in both areas

La Mancha (Spain)				Saiss (Morocco)		
			OPTION 2: PV-Pump			
6.813			PSH Peak Sun Hours	6.903		
8			t Max Hours Operating per day	8		
19º			Optimal angle	13º		
11.37			eD Energy demanded per day (kWh)	32.97		
0.75			cS Coefficient Supply	0.75		
15.16			TeD Total Energy demanded per day (kWh)	43.96		
255			Wp Wp per PV-Module	255		
0.8			Pr Modules Perfomance Ratio	0.8		
11			Nº No Modules	32		
2805			Installed Power	8160		
403.92			Total Energy generated kWh	1272.96		
CdTe	**Mono-Si**	**Poly-Si**	Technologies	**CdTe**	**Mono-Si**	**Poly-Si**
18	47	45	Emissions gCO_2/kWh	18	47	45
7.27	18.98	18.17	Total Emissions $kgCO_2$	22.32	58.29	55.81
159.05	147.34	148.15	**$kgCO_2$ emissions avoided**	477.95	441.98	444.46

Figure 16: PV system design and CO_2 emissions in both areas

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5.2 Artículo 2 | Multidimensional analysis of groundwater pumping for irrigation purposes: Economic, energy and environmental characterization for PV power plant integration.

Ante el panorama energético mundial y las políticas energéticas encaminadas a la promoción de energías renovables, el sector agrícola presenta oportunidades relevantes para integrar fuentes de energía renovable como una solución alternativa para mitigar la dependencia de los combustibles fósiles y disminuir las emisiones GEI. Por consiguiente, los requerimientos energéticos de bombeo de aguas subterráneas para el riego agrícola emergen como un tema relevante a mejorar en términos de demanda de energía.

A través de este artículo, se han analizado diferentes alternativas energéticas para propiciar un cambio eficaz del modelo energético en este sector, en base a la una red neuronal de configuración de alternativas. A su vez, se ha propuesto una metodología para caracterizar las alternativas energéticas para el bombeo de aguas subterráneas, a través de un análisis multidimensional y comparativo 3E (análisis económico, energético y ambiental) tomando siempre como base los condicionantes iniciales de requerimientos hídricos, profundidad del nivel freático, y hectáreas de riego. Adicionalmente se propone un modelo de visualización de datos a través de graficas 4D.

Este documento toma como base las condiciones iniciales del área agrícola de La Mancha (España), una llanura de 5.500 km^2, asentada y abastecida por el Acuífero 23 (actualmente sobreexplotado). Climáticamente se trata de una zona árida, con cultivos de viñedo (60% de la superficie irrigada), olivar, cereal y hortalizas.

La metodología propuesta se ha divido en tres partes: la identificación de alternativas, la caracterización de alternativas y la visualización de resultados con una gráfica 4D.

En primer lugar, se han revisado las principales contribuciones en sistemas de bombeo en la agricultura y se han identificado una serie de configuraciones para diseñar un análisis amplio y abierto de las alternativas energéticas que pudieran cubrir la demanda energética del bombeo agrícola. Esto se ha traducido en una red neuronal de configuración en la que se muestran diferentes opciones con las que diseñar una instalación de bombeo como una guía general para fines de bombeo de aguas subterráneas.

Estas variables se ordenan como: 1) Opciones de almacenamiento de agua, a través de tres configuraciones: almacenamiento de agua anual, estacional y bombeo directo (sin almacenamiento de agua). En el estudio se sopesan las opciones valorando la evaporación de agua desde el reservorio, la inversión inicial, la capacidad del reservorio y la potencia requerida. Le siguen: 2) Opciones de agrupamiento, tanto individuales, muy comunes en la agricultura, como cooperativas, las cuales ofrecen una reducción significativa del tamaño de las instalaciones y por ende de la inversión por agricultor. Por otro lado, 3) Opciones de conexión: se han tomado en cuenta tanto las instalaciones aisladas, las cuales tienen ventajas en términos de versatilidad y fácil implementación, como las instalaciones conectadas a la red eléctrica, permitiendo reducir el tamaño de la instalación y maximizar el uso en el caso de sistemas PVWP. En último lugar 4) Opciones de fuentes energéticas principales: equipos diésel, sistemas fotovoltaicos aislados, sistemas fotovoltaicos conectados a la red eléctrica en autoconsumo y el suministro directo de la red.

La metodología propuesta considera una caracterización multidimensional 3E (económica, energética y ambiental) de las alternativas elegidas como soluciones prácticas. A partir de este análisis complementario, se pueden identificar alternativas eficientes y optimizadas. Por lo tanto, la metodología propuesta proporciona una evaluación global de dichas alternativas.

Dentro de este análisis, se ha tenido en cuenta el criterio del coste económico, ya que suele ser un factor relevante, tal como señalan algunos estudios, y entre ellos los costes de inversión. También se consideran los costes de mantenimiento y operación, así como posibles beneficios por la venta de la energía excedente (solo en casos de sistema PVWP conectado a red). Por otro lado, la perspectiva energética estudio la comparación de diferentes alternativas en términos de potencia instalada y energía requerida por la bomba. Y finalmente la perspectiva ambiental analiza las emisiones de CO_2 de cada una de las alternativas atendiendo al análisis de ciclo de vida de las partes que lo conforman. Los datos resultantes se han representado en graficas 4D para visualizar las diferentes perspectivas.

A partir de los resultados, se observa que los equipos diésel proporcionan costes de inversión considerablemente más bajos en comparación con la solución de la instalación solar fotovoltaica aislada o en autoconsumo. De hecho, el enfoque de uso de equipos diésel es actualmente una de las soluciones más comúnmente seleccionadas por el sector agrícola. Sin embargo, los equipos diésel presentan un nivel de emisiones de CO_2 muy altas, en comparación con la alternativa basada en las instalaciones solares fotovoltaicas. Por otro lado, el suministro eléctrico abastecido por la red ofrece los costes más bajos. Sin embargo, esta solución no se puede implementar en áreas remotas.

Por esto mismo los gobiernos deben promover soluciones basadas en fuentes de energía renovables para disminuir las emisiones de CO_2 en la agricultura y minimizar la dependencia de los combustibles fósiles en el sector.

El análisis realizado en el presente estudio puede ampliarse con la inclusión de otras variables adicionales. De acuerdo con los resultados y la caracterización de alternativas, esta metodología presenta un bajo costo de tiempo computacional, posee una baja complejidad y es apta para ser aplicada en diferentes áreas y escenarios agrícolas, lo cual la hace escalable y exportable. Además, la metodología propuesta también proporciona una estimación de las áreas óptimas para las cooperativas de agroenergía en función de las diferentes profundidades del acuífero y los requisitos de agua de los cultivos.

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.

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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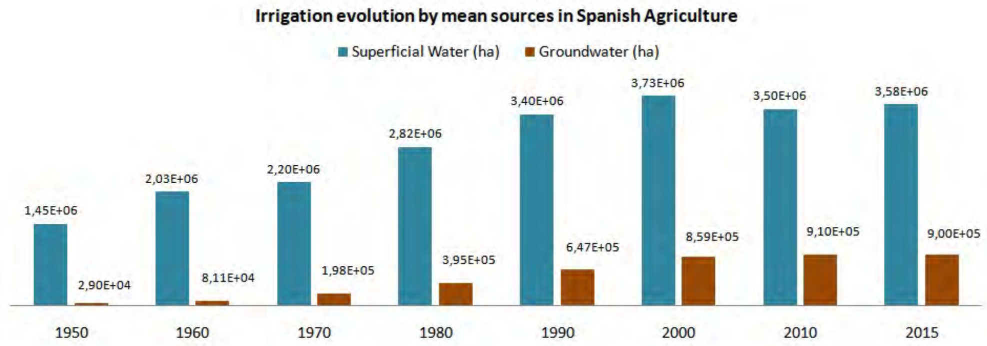
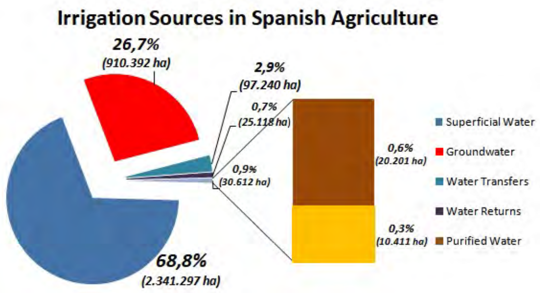
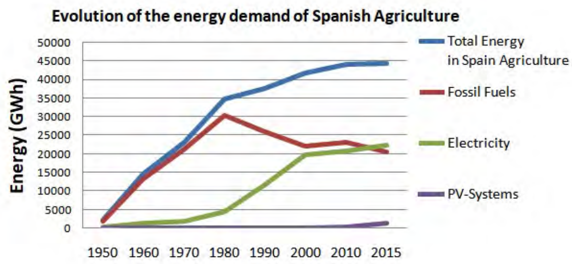


(a) Irrigation evolution in the Spanish agriculture



(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

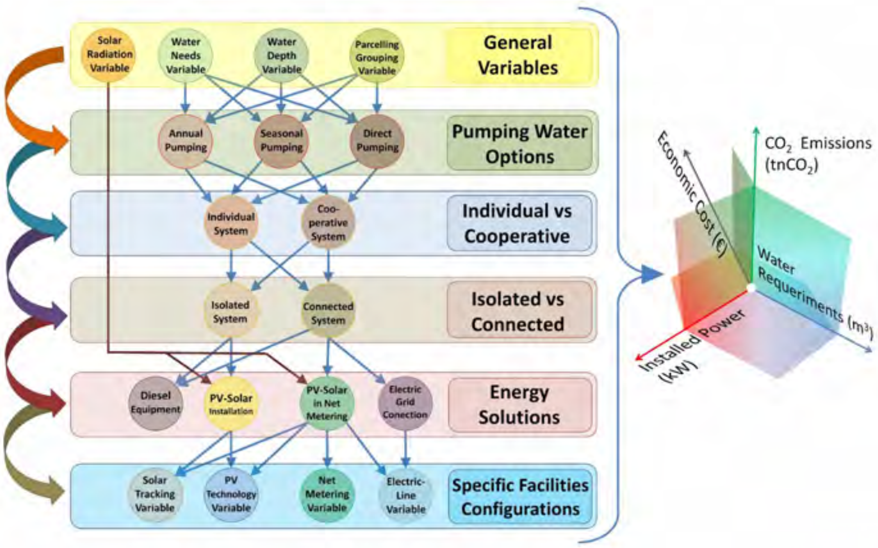


Figure 2: Groups of variables: identification and relations for characterization of initial alternatives.

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.

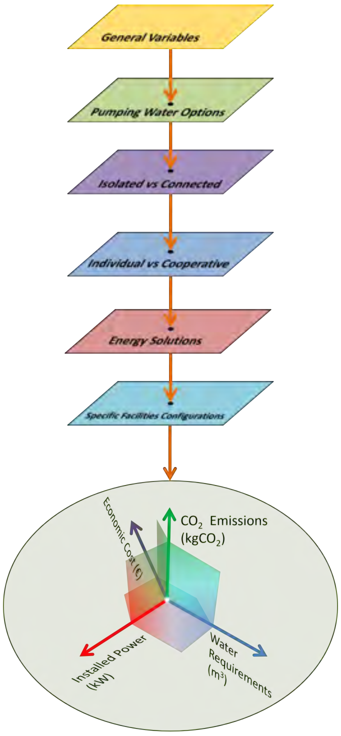


Figure 3: Analysis of variables and characterization of alternatives

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

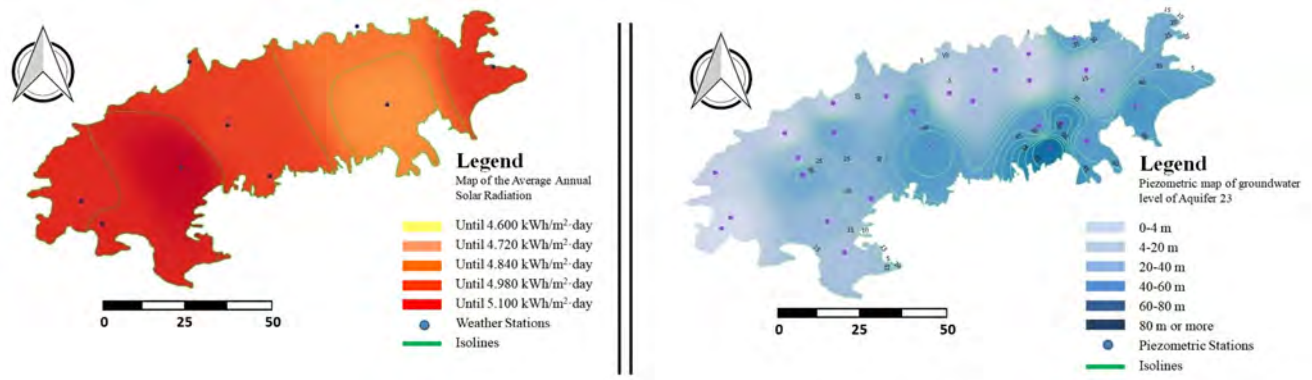
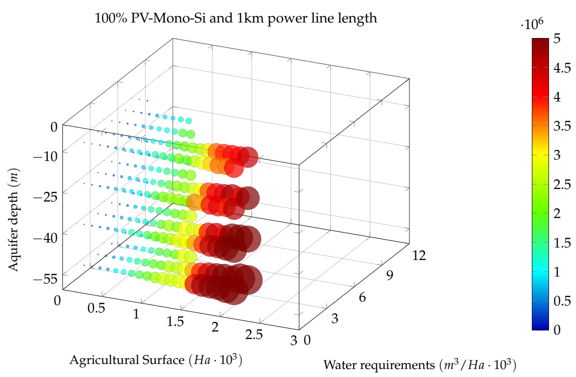
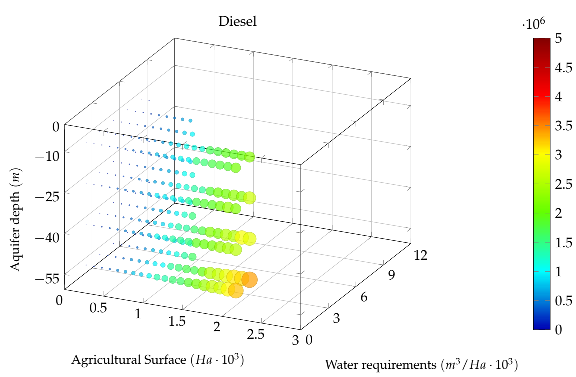


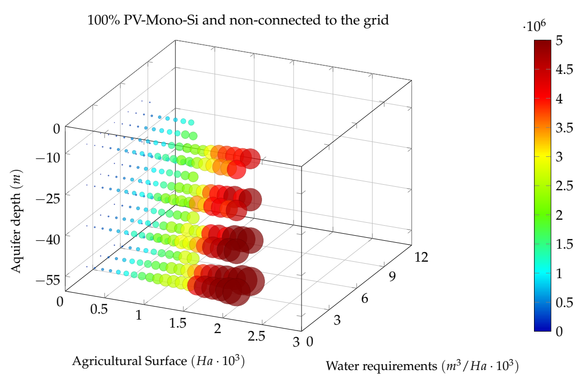
Figure 5: Average Annual Solar Radiation and Phreatic level of Aquifer 23. Castilla-La Mancha (Spain) [63].



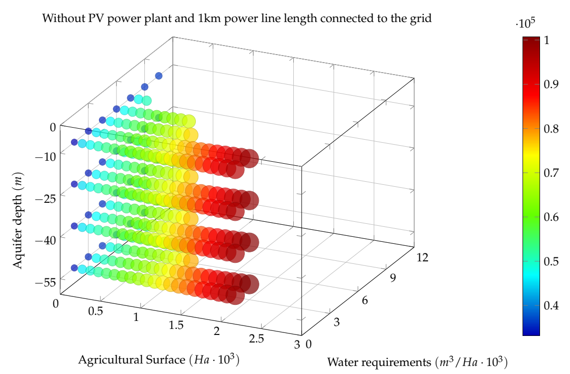
(a) Net Balance



(b) Diesel

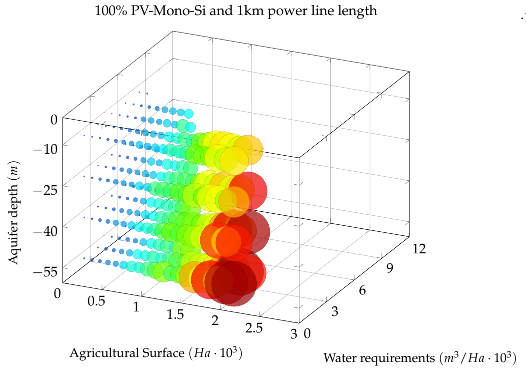


(c) Islanding PV solar installation

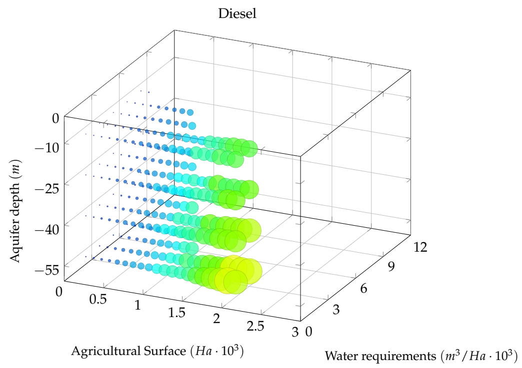


(d) Connected to the grid

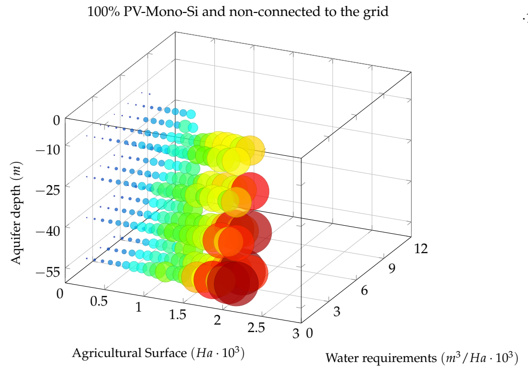
Figure 6: Estimated Seasonal Pumping Cost (Euro). Comparison of sources



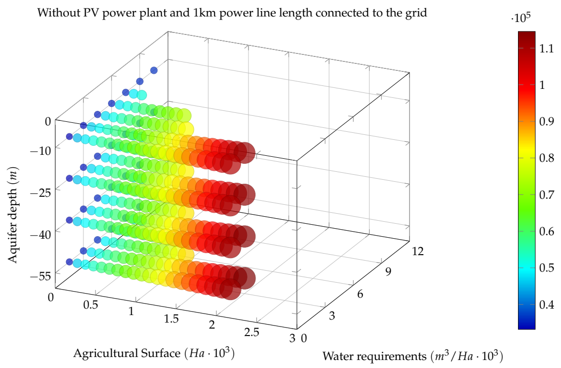
(a) Net Balance



(b) Diesel

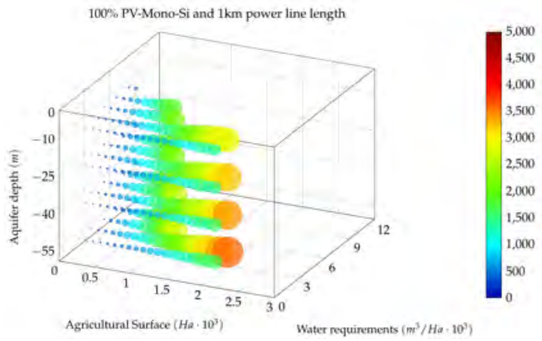


(c) Islanding PV solar installation

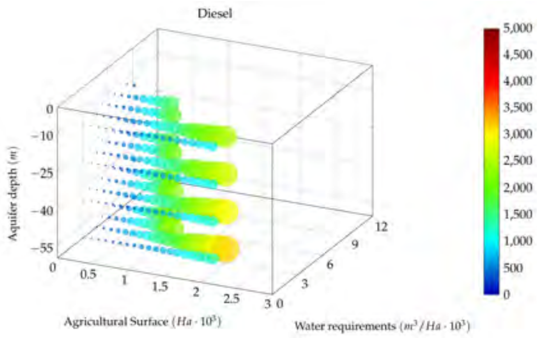


(d) Connected to the grid

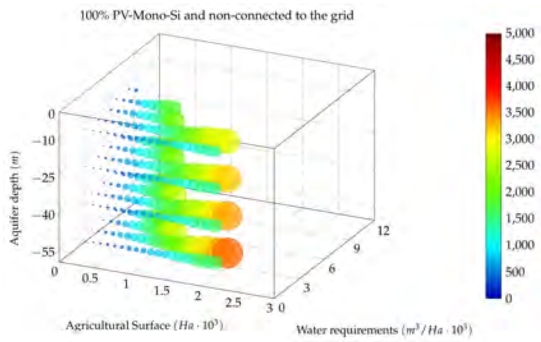
Figure 7: Estimated Direct Pumping Cost (Euro). Comparison of sources



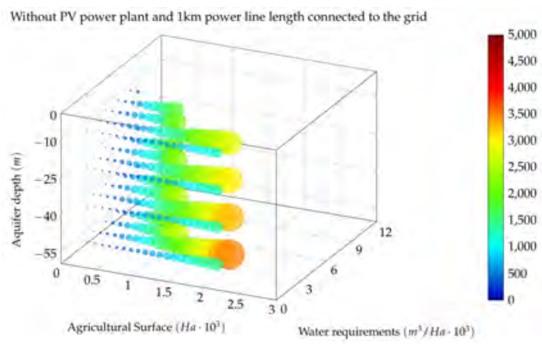
(a) Net Balance



(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.

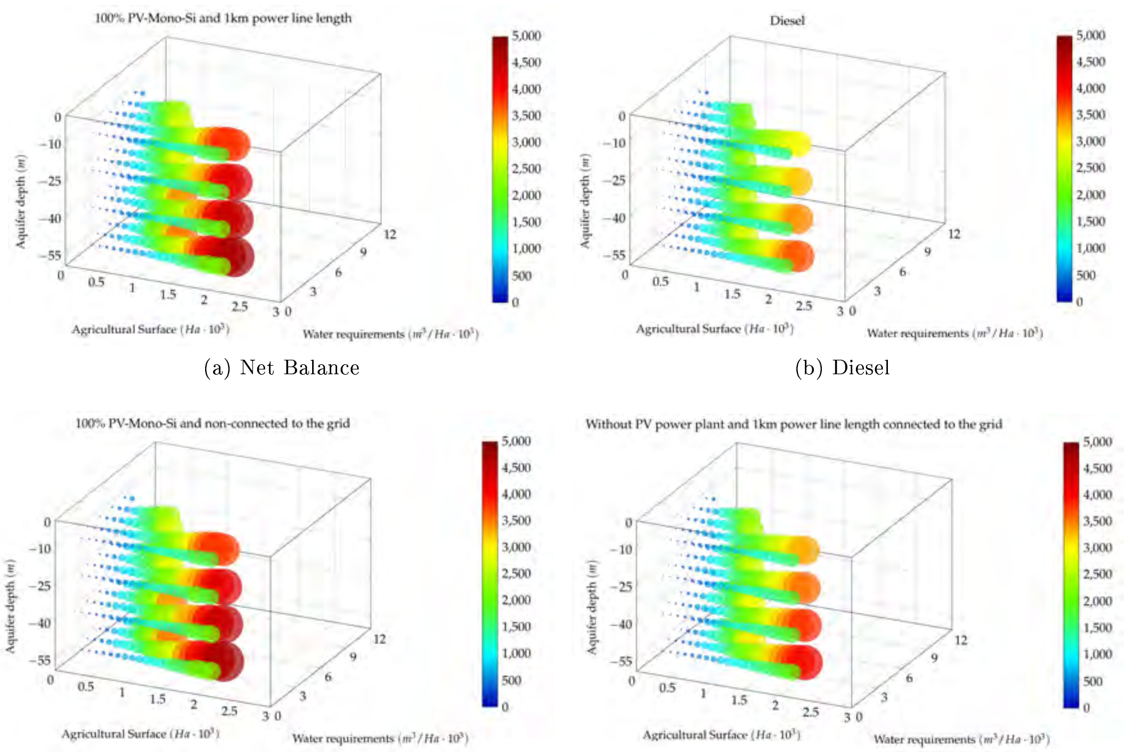
Figure 10 and 11 summarise the CO_2 emissions for the different alternatives. This environmental characterization allows us to visualise and compare how sustainable each solution is in terms of tonnes of CO_2. The diesel equipment obviously gives off the highest emissions, considerably greater than solutions 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



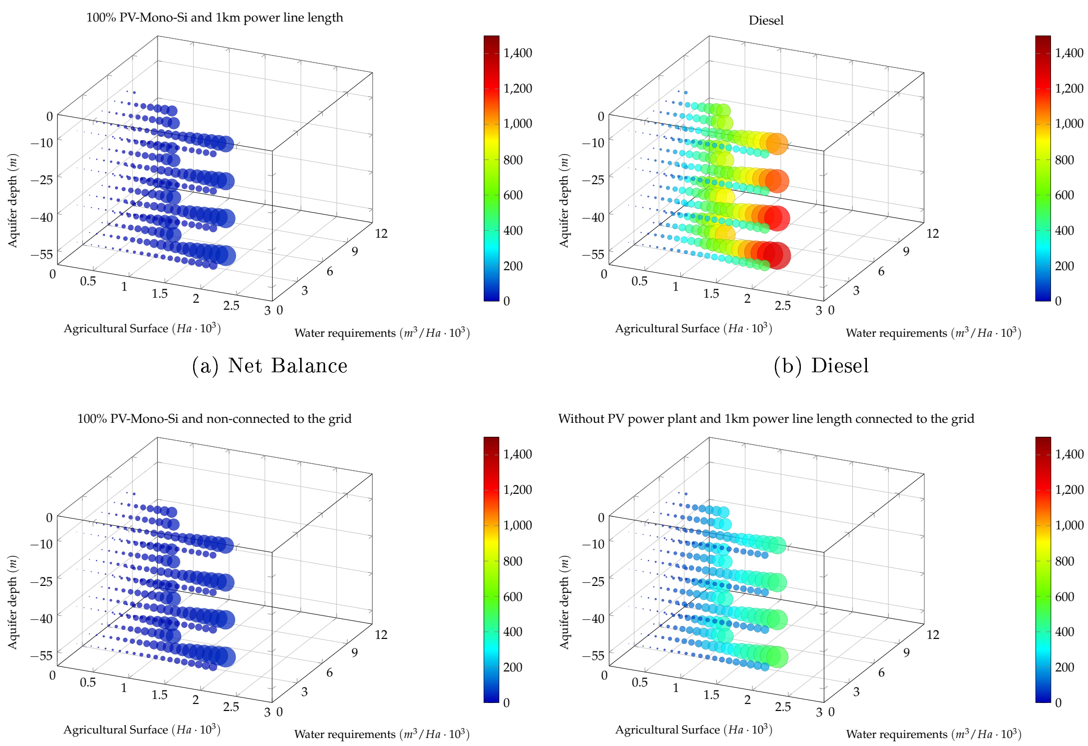
(a) Net Balance

(b) Diesel

(c) Islanding PV solar installation

(d) Connected to the grid

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



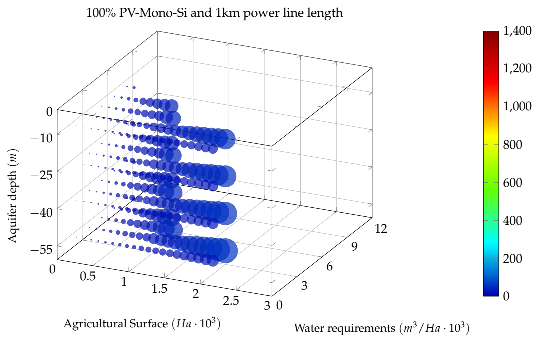
(a) Net Balance

(b) Diesel

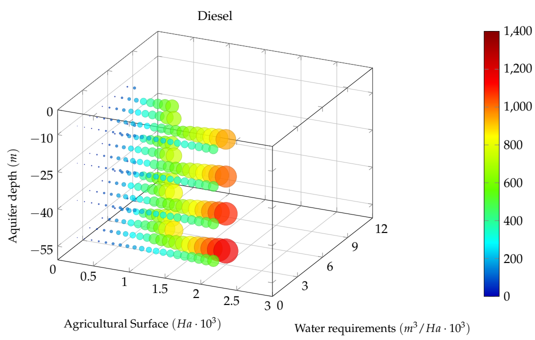
(c) Islanding PV solar installation

(d) Connected to the grid

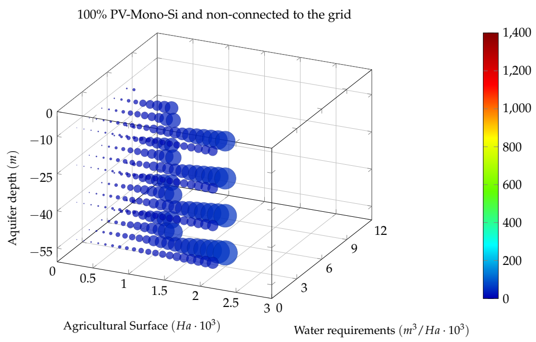
Figure 10: Estimated Seasonal Pumping Emissions (Tonnes of CO_2). Comparison of sources



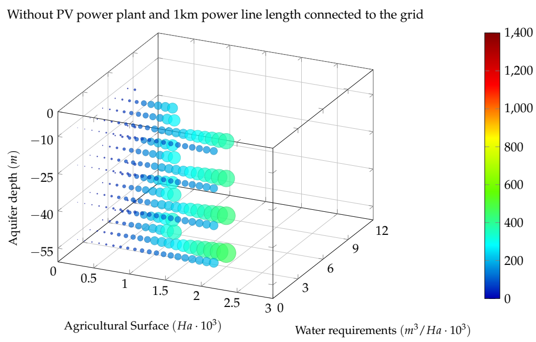
(a) Net Balance



(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

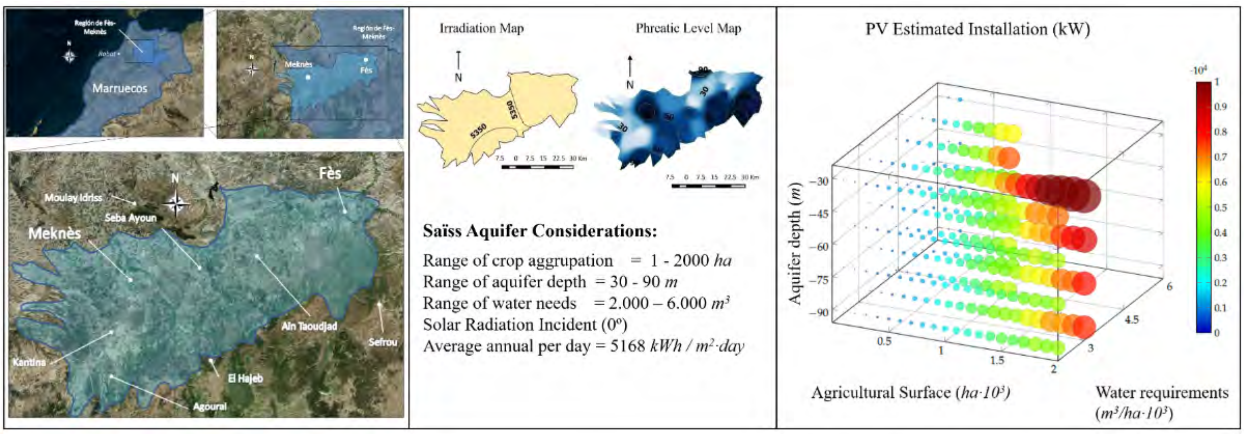


Figure 12: PV estimated installation: Saïss aquifer (Meknès, Morocco).

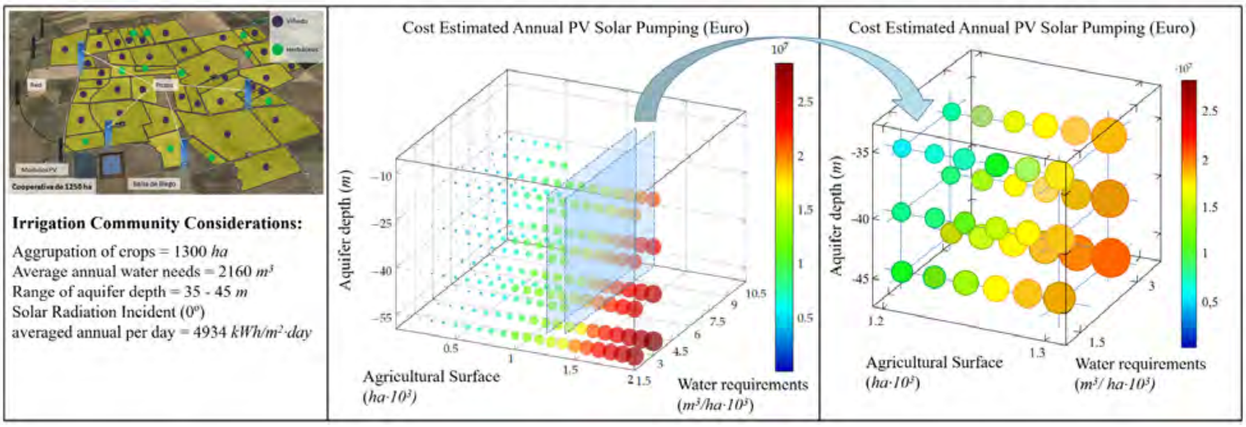


Figure 13: Cost estimated for annual PV installation (1300 ha): Saïss aquifer (Meknès, Morocco).

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

Acknowledgements

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

La reducción de emisiones de gases de efecto invernadero, así como la reducción de la dependencia energética han sido estrategias prioritarias en las políticas energéticas entre la mayor parte de los países desarrollados. Estas acciones tienen como objetivo promover la integración de las energías renovables en los sectores económicos, entre ellos la agricultura, ya que ésta supone el 10 % de las emisiones totales de gases de efecto invernadero (GEI) en la UE. Además, este sector, altamente consumidor, y la vez dependiente, de combustibles fósiles como el diésel está en riesgo ante cambios bruscos de los precios del petróleo. Por lo tanto, deben proponerse acciones enfocadas hacia estrategias e iniciativas sostenibles y que permitan una gestión energética más eficaz.

Dentro del sector agrícola, las soluciones actuales propuestas para un cambio del modelo energético en el bombeo de aguas subterráneas se basan principalmente en la integración de sistemas fotovoltaicos (PVWP). Este cambio en la práctica se ha llevado a cabo de una manera directa, sustituyendo los equipos diésel por sistemas fotovoltaicos, manteniendo su carácter individual y aislado, e igualando la potencia instalada previa. Aunque es cierto que las instalaciones fotovoltaicas de bombeo de aguas subterráneas son propuestas como una solución rentable y adecuada, se requiere un análisis más amplio que estudie la configuración de la instalación, así como aspectos y enfoques relevantes desde el punto de vista económico, energético y ambiental.

En estudios previos, se analizaron diferentes configuraciones PVWP atendiendo al tamaño de la instalación, al caudal de bombeo o a diferentes modos de gestión de balsas de riego (almacenamiento anual, estacional o bombeo directo). Pero destaca sobremanera una configuración, los sistemas PVWP conectados a la red eléctrica. Esto se debe a que ofrecen una oportunidad para optimizar la energía que estas instalaciones son capaces de generar fuera de la temporada de riego, pudiendo inyectar a la red energía excedente.

En este contexto, el estudio se estructura desde el punto de vista de la metodología, por un lado, mediante un análisis desde una perspectiva multidimensional (socio-económico, hídrico, energético y ambiental) del problema energético que sufre el sector agrícola del regadío mediante aguas subterráneas, en especial en las zonas con escasez de agua y con acuíferos sobreexplotados. En dicho análisis se abordan los potenciales beneficios que puede acarrear el cambio de modelo energético.

Y, por otro lado, se cuantificando, en este orden, la energía requerida por el bombeo, la energía capaz de generar el sistema, la energía excedente y finalmente los beneficios económicos que aporta esta solución por la venta de energía. Los resultados se muestran en una gráfica 4D.

A tenor de los resultados, las instalaciones de riego por bombeo abastecidas por sistemas fotovoltaicos conectados a la red eléctrica, en un primer término permiten reducir las emisiones CO_2 del mix energético nacional ya que integran energía con un muy bajo nivel de emisiones (atendiendo al análisis del ciclo de vida). Por otro lado, posibilita de manera directa e indirecta la reducción de la dependencia de los combustibles fósiles. Y finalmente, permite mejorar la rentabilidad de dichas instalaciones, así como la creación de una segunda vía de ingresos al sector con la venta de los excedentes de energía.

Así pues, se muestra que el análisis multidimensional realizado es una solución exportable y escalable que se puede aplicar en diferentes localizaciones, adaptando diferentes parámetros como son la necesidad de agua del cultivo, la profundidad del acuífero y las áreas de cultivo agrupadas.

Sin embargo, los datos que mejor ejemplifican la importancia de la configuración propuesta, los relativos a los beneficios de la venta de energía, los cuales sugieren unos importantes inputs directos a los agricultores en las instalaciones de carácter comunitario. Por tanto, este estudio sienta las bases del concepto de cooperativas agro-energéticas.

Como conclusión, este trabajo pone de relevancia la necesidad de estudios en profundidad de la implantación y de la configuración de los sistemas PVWP, con los que promover políticas globales enfocadas hacia una gestión racional de la integración masiva de este tipo de energías renovables en el sector agrícola.

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

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

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

1. Introduction

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

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

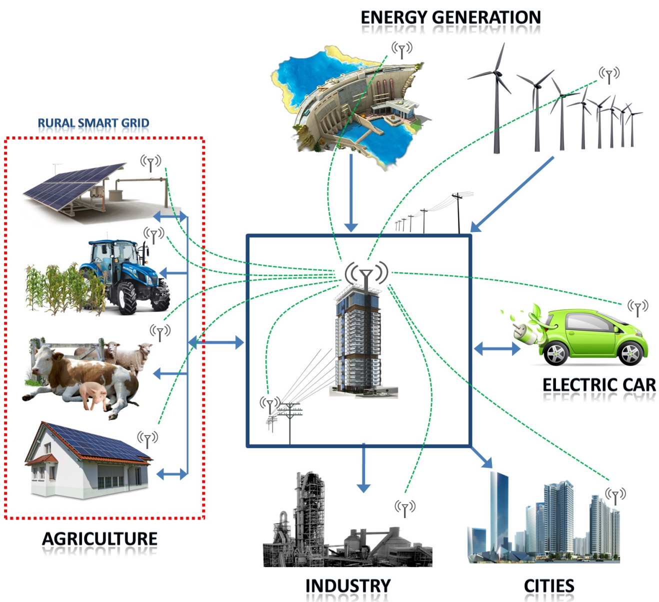

Figure 1. Integration of the agricultural sector into a smart grid: supply and demand-side active roles.

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

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

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

2. Multifocused Analysis Methodology

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

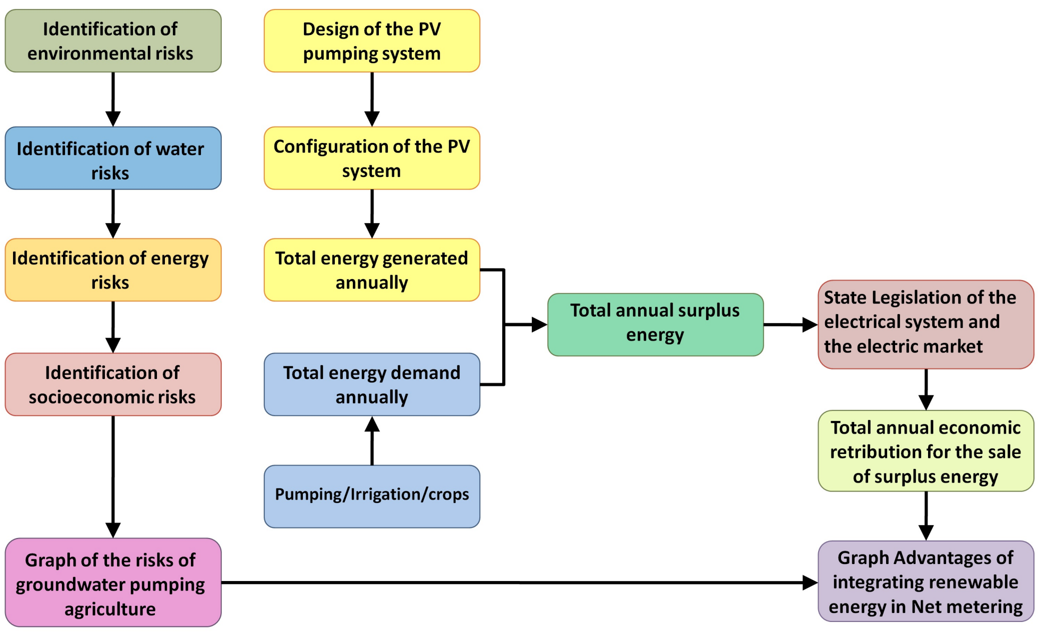

Figure 2. Description of the proposed methodology.

2.1. Groundwater Agriculture Problem: Multifocused Analysis

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

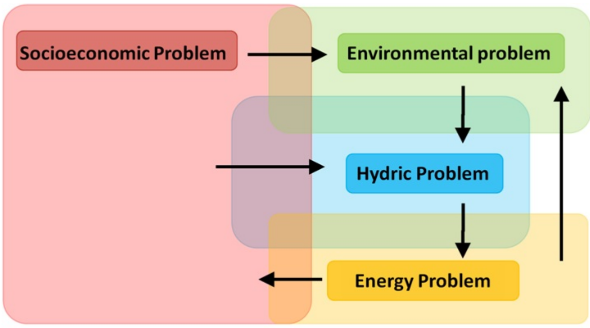

Figure 3. Multifocused analysis for agriculture groundwater pumping purposes.

2.1.1. Environmental Analysis

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

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

2.1.2. Water Analysis

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

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

2.1.3. Energy Analysis

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

2.1.4. Socioeconomic Analysis

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

2.2. PV System Configuration and Surplus Energy Estimation

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

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

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

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

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

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

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

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

3. Case Study

3.1. Preliminaries

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

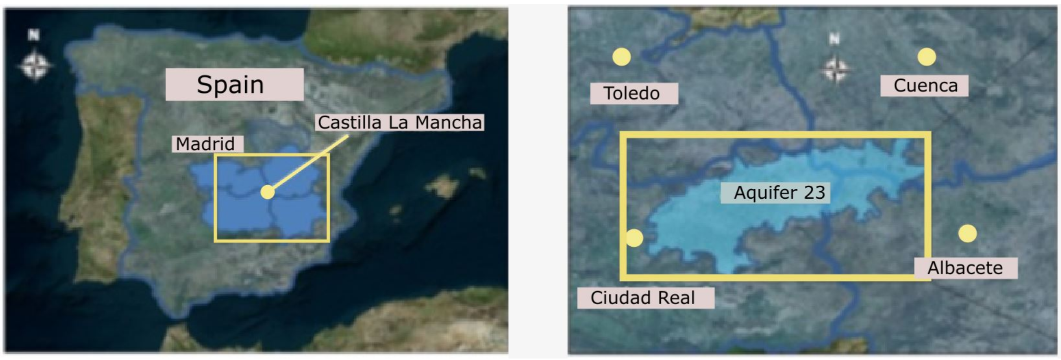

Figure 4. Location of study area and aquifer.

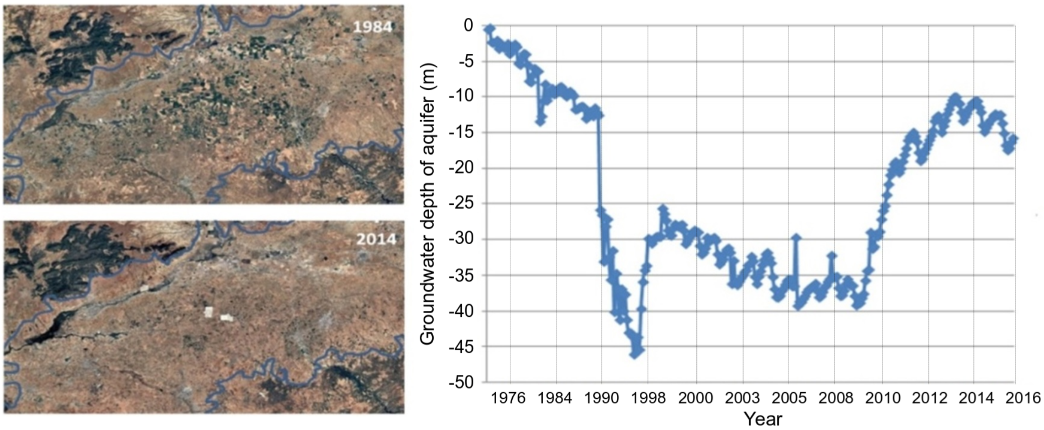

Figure 5. Satellite image of regime of exploitation of water resources and chronological graph of groundwater aquifer level. Source: Authors' elaboration through Google Earth images and CHG data.

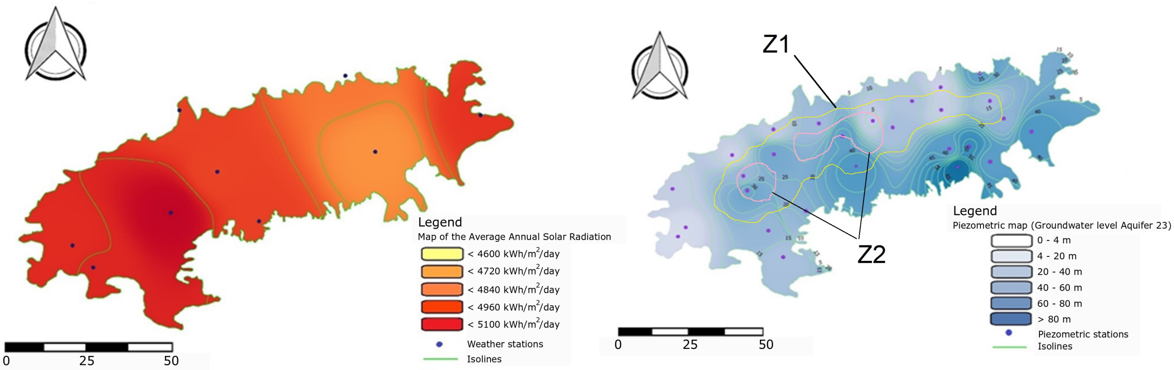

Figure 6. Irradiance solar resource and groundwater depth level: case study. Description of Z1 and Z2.

3.2. Crop Water Need

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

3.3. PV Power Plant Configuration

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

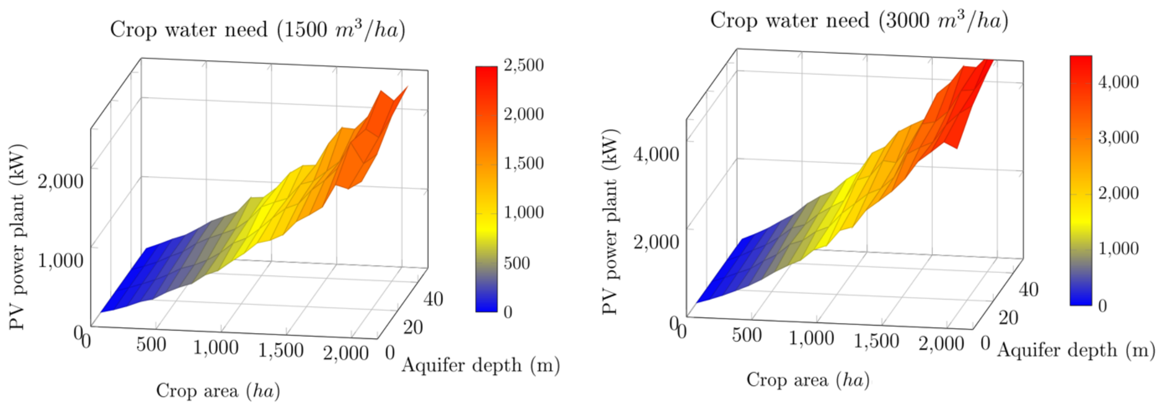

Figure 7. PV power plant capacities for self-consumption scenarios: 1500 m^3/ha and 3000 m^3/ha.

3.4. Self-Consumption: Spanish Legislative Framework

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

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

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

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

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

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

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

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

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

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

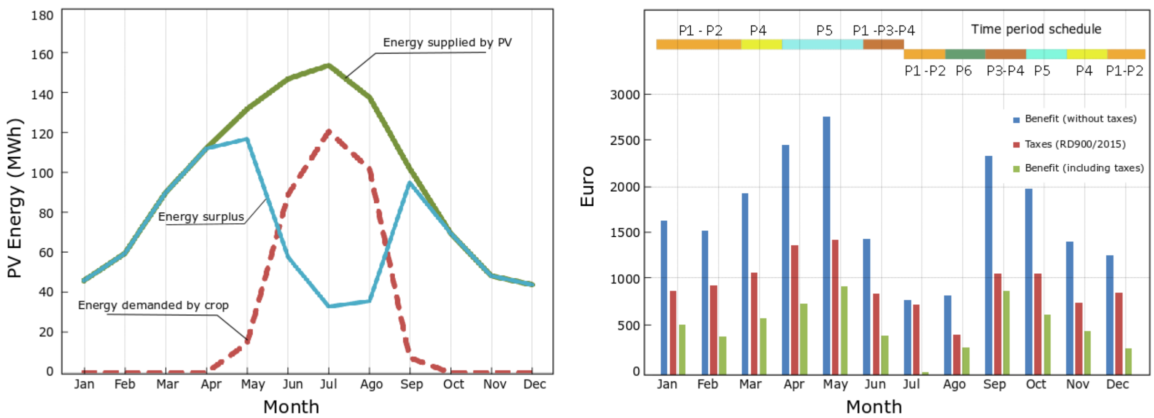

Figure 9. Example of PV generation and surplus of energy. Costs and benefits for the Spanish electricity system.

4. Results and Discussion

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

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

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

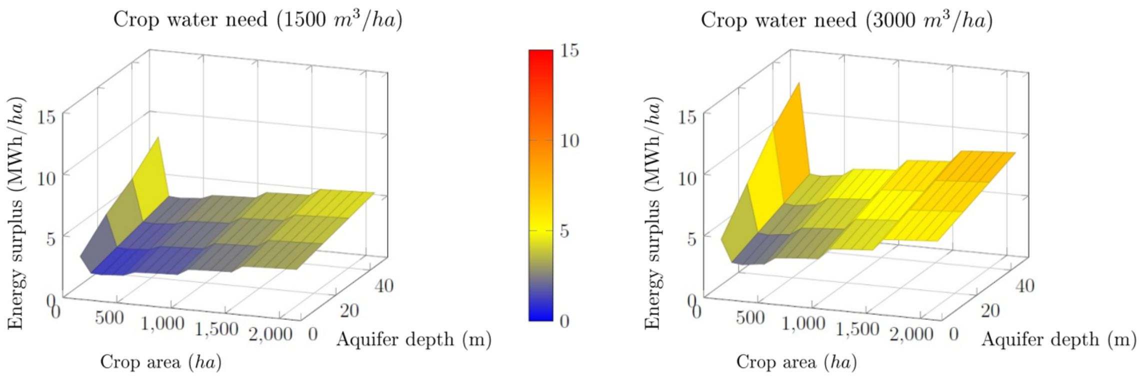

Figure 10. PV installation connected to the grid: annual surplus energy estimation examples (1500 m^3/ha and 3000 m^3/ha).

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

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

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

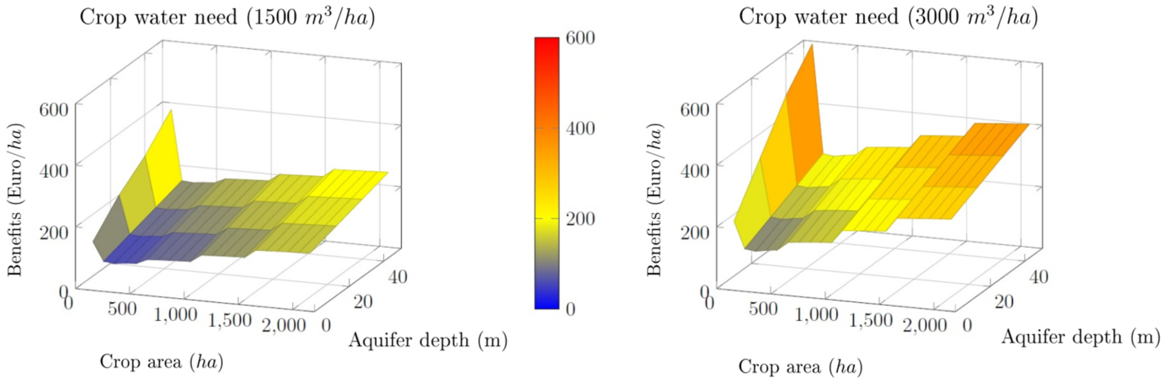

Figure 11. PV installation connected to the grid: annual benefit estimation examples excluding taxes and fees (1500 m^3/ha and 3000 m^3/ha).

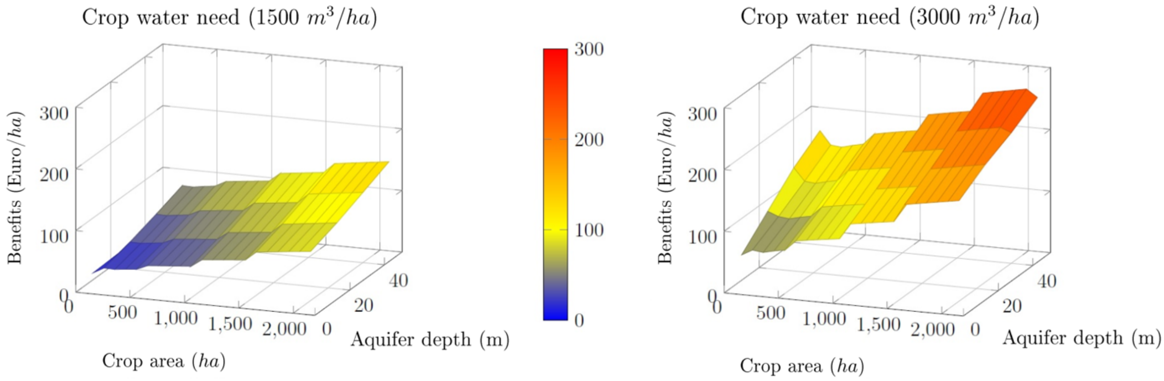

Figure 12. PV installation connected to the grid: annual benefit estimation examples including taxes and fees (1500 m^3/ha and 3000 m^3/ha).

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

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

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

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

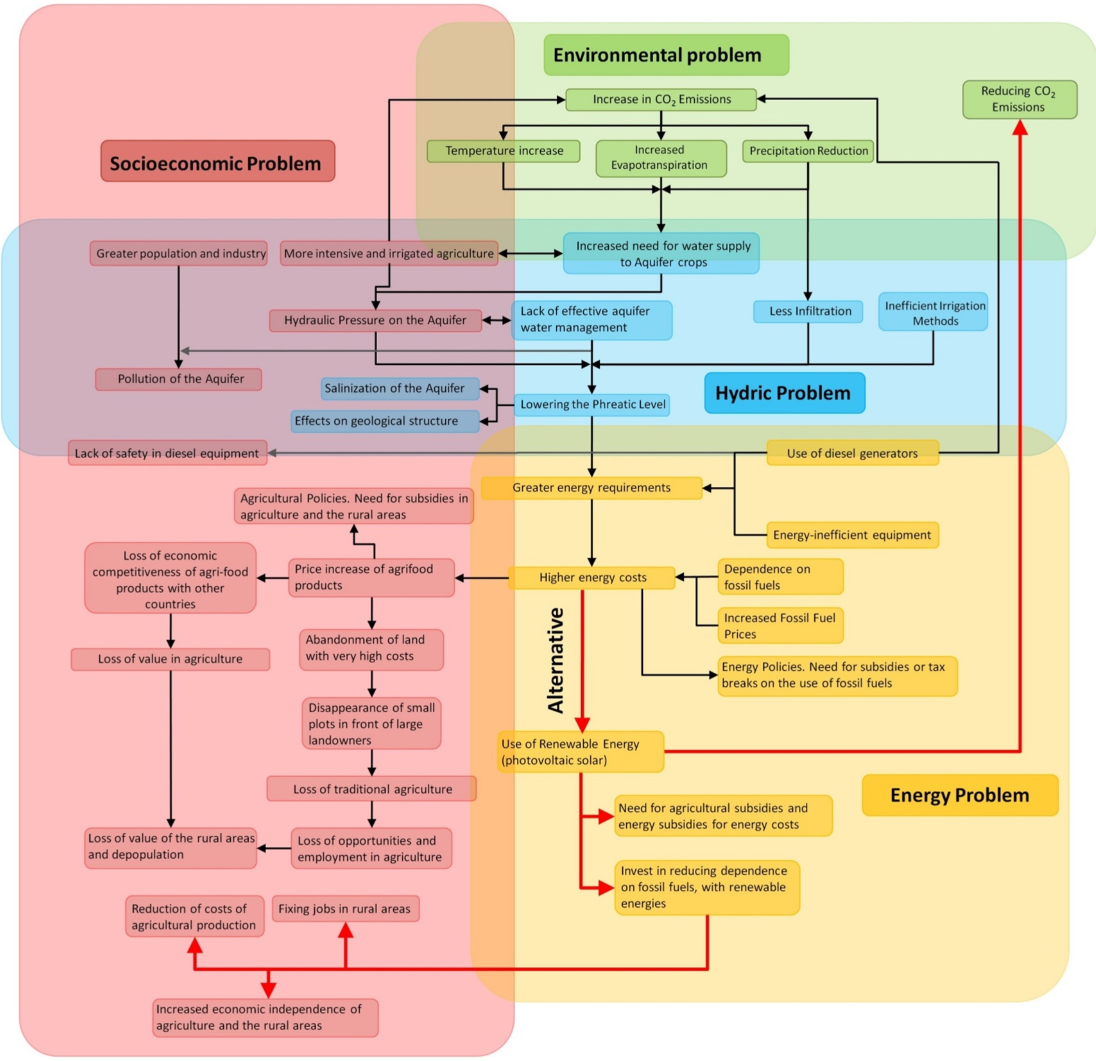

Figure 13. Integrating renewables into net-metering: advantages and multifocused approach.

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

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

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

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

5. Conclusions

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

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5.4 Artículo 4 | MCDM-based multidimensional approach for selection of optimal groundwater pumping systems: Design and case example.

Actualmente los sistemas PVWP se están implantando en el sector agrario que se abastece de aguas subterráneas sustituyendo a los equipos generadores diésel, sin embargo, esta migración de un sistema a otro no se está haciendo con una base científica ampliamente estudiada. Los autores de este estudio previamente habían propuesto y evaluado otras soluciones diferentes y novedosas que acarrean en el sector ciertas ventajas frente al modelo que comercialmente se propone. Entre estas configuraciones los autores proponen sistemas cooperativos o sistemas conectados a la red eléctrica con la capacidad de inyectar la energía excedente generada fuera de la temporada de riego.

Sin embargo, surge un problema de decisión para determinar la alternativa o la configuración óptima cuando existen diferentes criterios o índices de evaluación. Es por esto que se ha resuelto utilizar una metodología de toma de decisiones multicriterio (MCDM), en concreto una ampliamente utilizada combinación AHP-TOPSIS.

Este proceso se realiza tomando como caso de estudio la llanura agrícola sobre un acuífero ubicado en la región de La Mancha, en el centro-sur de España, para el cual se pretende determinar el modelo configuración óptimo de implantación de los sistemas fotovoltaicos a la agricultura de bombeo.

El proceso metodológico seguido por el presente estudio parte del trabajo ya realizado en un artículo previo. En el cual se identificaron las alternativas a analizar en los sistemas de bombeo de aguas subterráneas de carácter cooperativo, clasificándolas a través de cuatro posibles fuentes de energía: los equipos convencionales a base de diésel, las plantas de energía solar fotovoltaica aislada y conectada a la red eléctrica y la conexión directa a la red, así como tres sistemas de almacenamiento de agua: bombeo directo, el almacenamiento estacional y el almacenamiento anual.

Ya en el presente estudio, se identifican los criterios con los que evaluar los datos numéricos resultantes de la caracterización de las alternativas, y que se corresponden, por temáticas, con los valores relevantes: costes de inversión, gastos de operación y mantenimiento, ingresos por venta de energía excedente (Económicos), potencia Instalada (Energéticos), emisiones de CO_2 (Ambientales), evaporación de agua en balsas de riego (Hídricos) y el número de puestos de empleos generados (Social).

Seguidamente, se desarrolló la entrevista y encuesta a los expertos de diferentes campos académicos relacionados con el objeto de estudio. A continuación, se desarrolló el proceso de jerarquía analítica (AHP) para calcular el peso de los criterios, obteniendo así el vector de pesos de los expertos. Después de ello, se realizó la Técnica de Ejecución de Ordenes por Semejanza a la Solución Ideal (TOPSIS), la cual nos permite identificar y priorizar las alternativas óptimas en una clasificación.

El estudio contempla, como parte de la metodología, con un análisis de sensibilidad que trata de evaluar procesamiento seguido y el verdadero peso del uso de expertos en la toma de decisiones. Para ello se repite el proceso anterior pero esta vez con un vector homogéneo en el que todos los criterios poseen la misma importancia.

Finalmente se utilizan las gráficas 4D de nube de puntos para mostrar los resultados para cada punto. Para array de coordenadas {X, Y, Z} (condiciones iniciales) se corresponde a un valor {W} que almacena el resultado de ese punto, ya sea el ranking resultante del proceso TOPSIS entre todas las alternativas o qué posiciones toma una determinada alternativa en cada punto.

Las conclusiones que se alcanzan, ante los resultados que arroja la metodología MCDM utilizada sugieren que, tomando como base en las decisiones de los expertos, éstos prefieren las alternativas que evitan cualquier almacenamiento de agua frente a aquellas que incluyen opciones de almacenamiento de agua anuales o estacionales, las cuales requieren instalaciones adicionales. Las alternativas óptimas más arriba en el ranking son: en primer lugar, la Alternativa 12 (bombeo directo alimentado por la red eléctrica), en segundo lugar, la Alternativa 9 (Bombeo directo alimentado por un sistema PV conectado a la red eléctrica) y en tercer lugar la Alternativa 6 (Bombeo directo alimentado por un sistema PV aislado). A tenor de los resultados, se observa cómo el criterio económico finalmente tiene una clara representación en los resultados. Así pues, los sistemas diésel, una tecnología madura ampliamente utilizada en la actualidad, quedan relegados a sistemas muy pequeños en hectáreas y a profundidades cercanas a la superficie.

Referente al análisis de sensibilidad mencionado, se observa que la opinión de los expertos es relevante ya que existe una diferencia considerable en los resultados. Dicho vector prefiere los sistemas estacionales y discrimina las alternativas más contaminantes. Dichas desviaciones del ranking, con ambos vectores es igual a entre 3 y 4 posiciones.

Por último, la metodología MCDM propuesta permite aplicarla a la resolución de problemas en la integración de sistemas PVWP a otras localizaciones teniendo, por tanto, la propiedad de ser escalable y exportable, con la capacidad de adaptarse a condiciones diferentes de requerimientos hídricos o de alturas de bombeo.

Adicionalmente, y atendiendo a la capacidad de la metodología utilizada, se ha planteado como línea de futura de investigación la aplicación de dicho proceso a otros recursos energéticos renovables, analizando a su vez a su integración en la agricultura de bombeo.

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

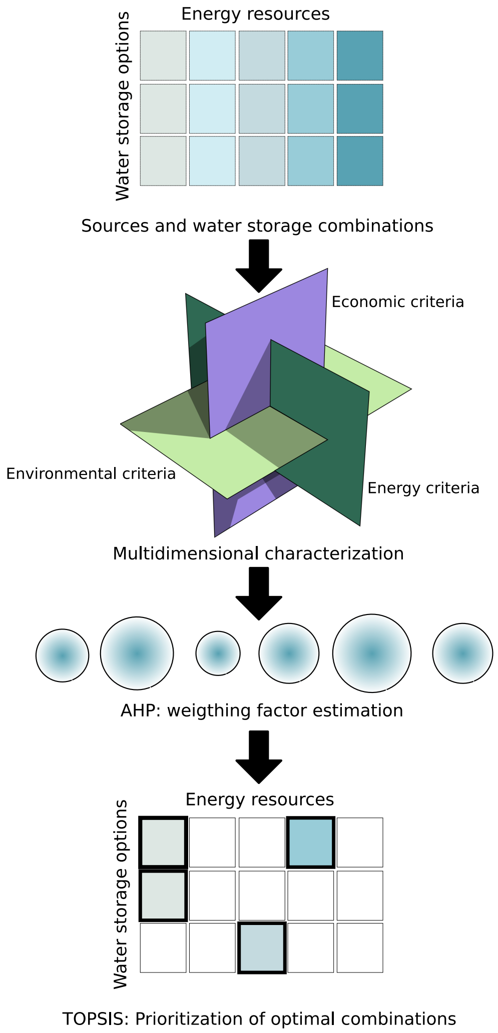

Figure 1: Proposed methodology: general overview.

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 characterized 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:

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*

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 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:

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

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

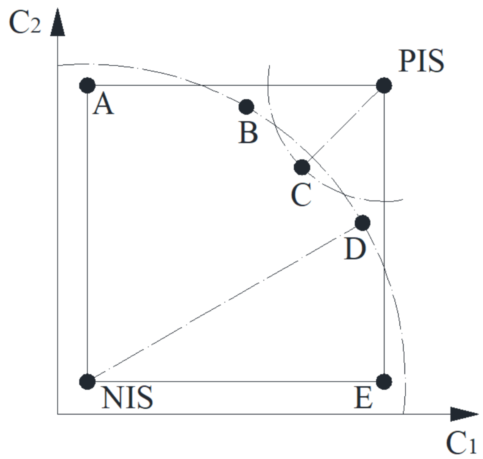

Figure 2: The concepts of PIS and NIS in a TOPSIS approach.

Table 4: Decision matrix for the TOPSIS approach.

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

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

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

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

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 ($i = 1, 2, \ldots, m$):

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

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

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:

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

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

The ranking score R_i is first calculated as follows:

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

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 i^{th} 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.

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^{o}C, 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

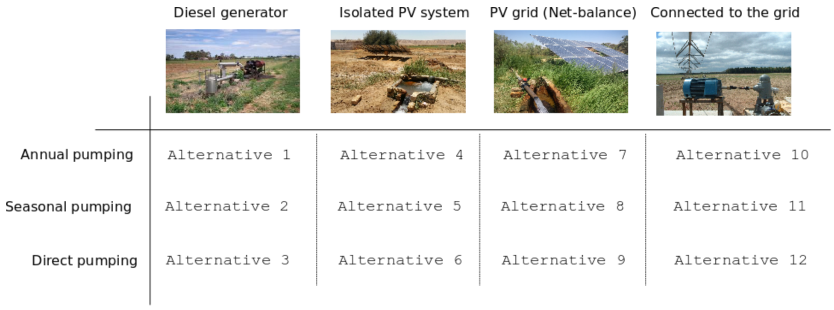

Figure 3: Case study: identification of alternatives.

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-

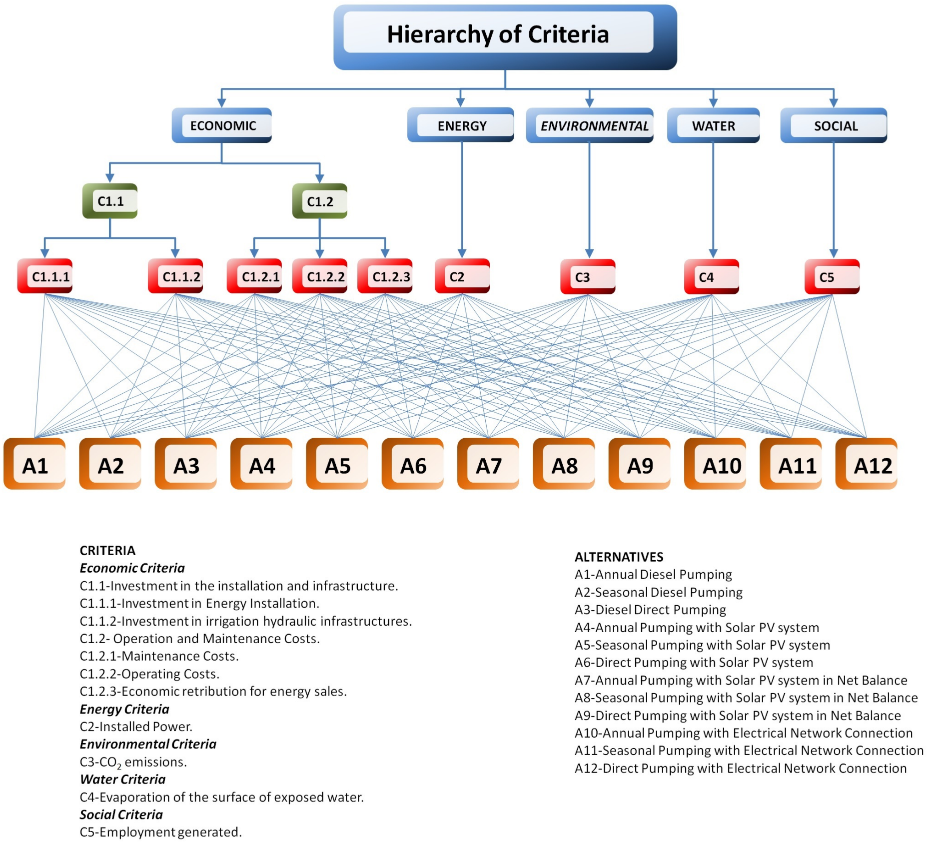

Figure 4: Hierarchy of Criteria: energy resources and water storage option alternatives (A_i).

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

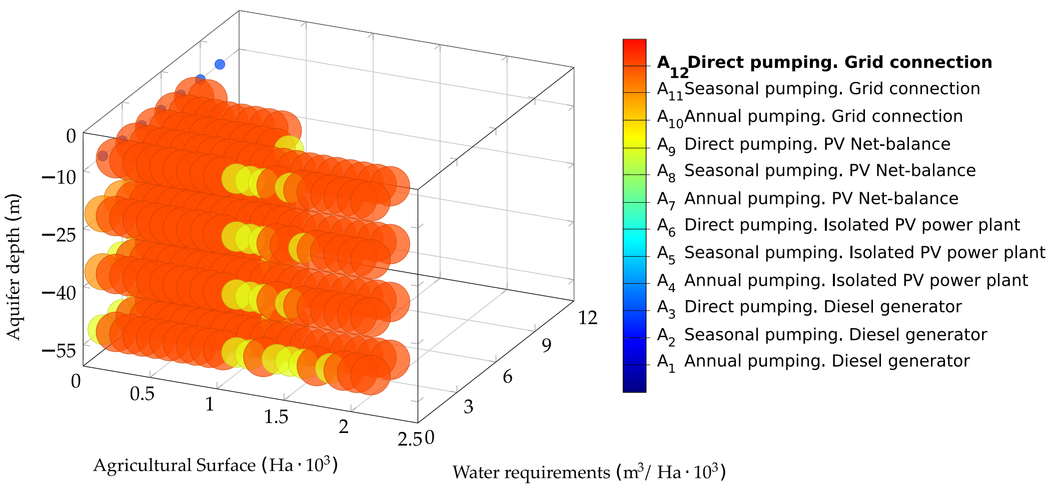

Figure 5: First optimal alternatives selected by the experts.

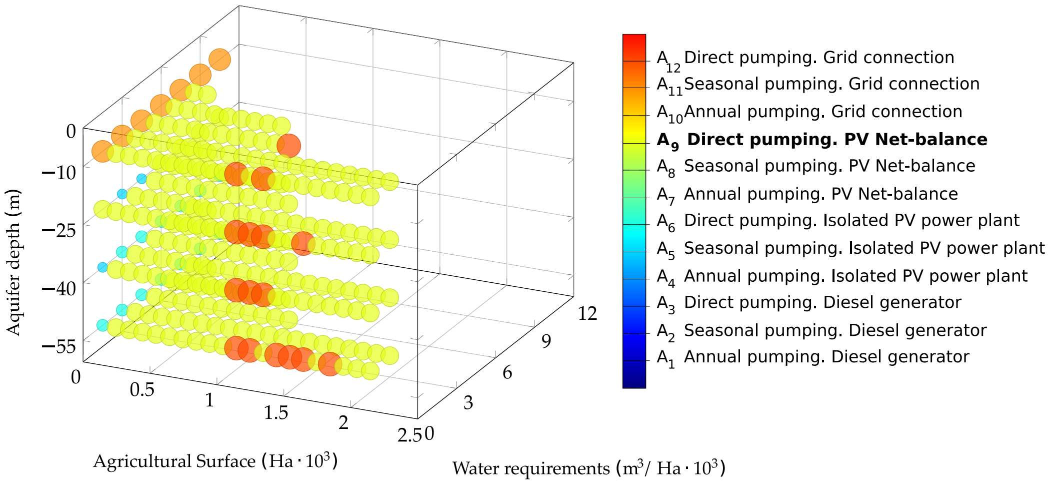

Figure 6: Second optimal alternatives selected by the experts.

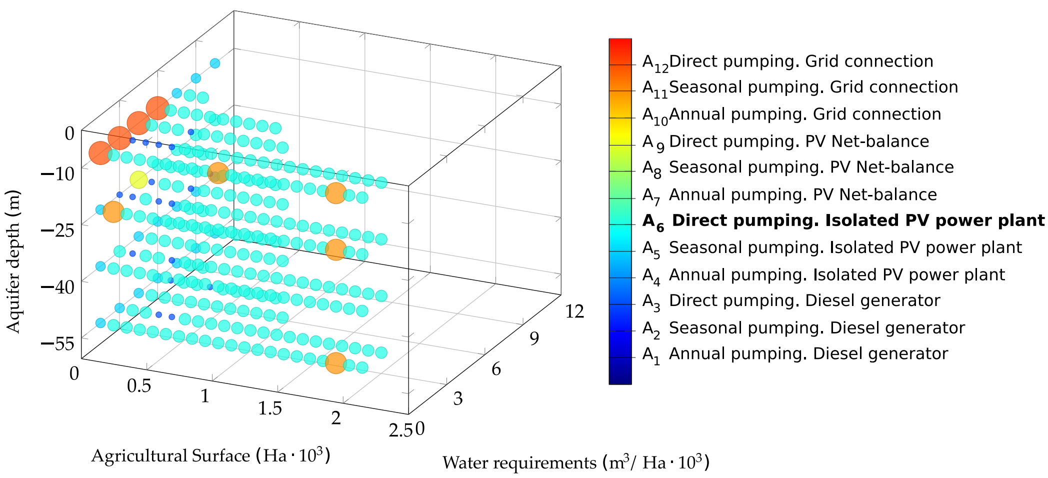

Figure 7: Third optimal alternatives selected by the experts.

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 homogeneous 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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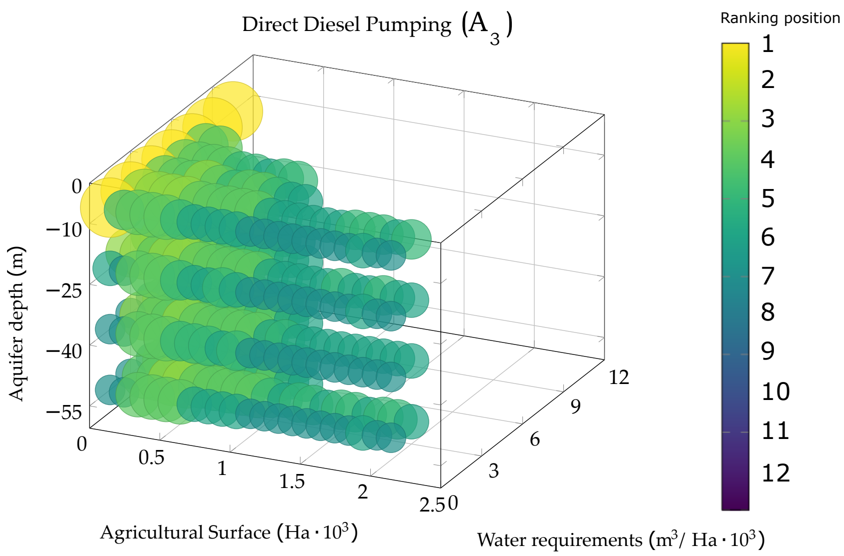

Figure 8: Diesel direct pumping (A_3): ranking position based on the depth of the aquifer and the aggregated agricultural and water crop requirement configurations.

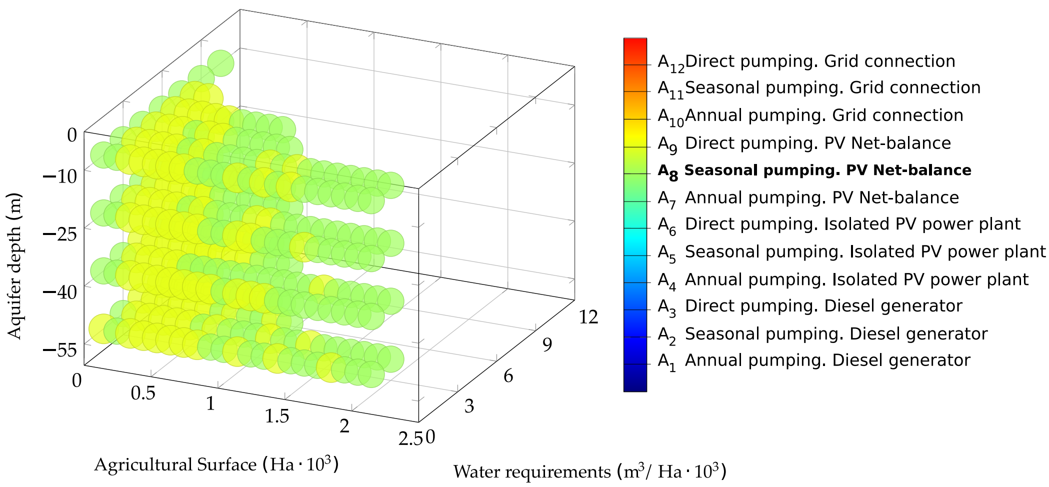

Figure 9: First optimal alternatives selected by the homogeneous weight vector.

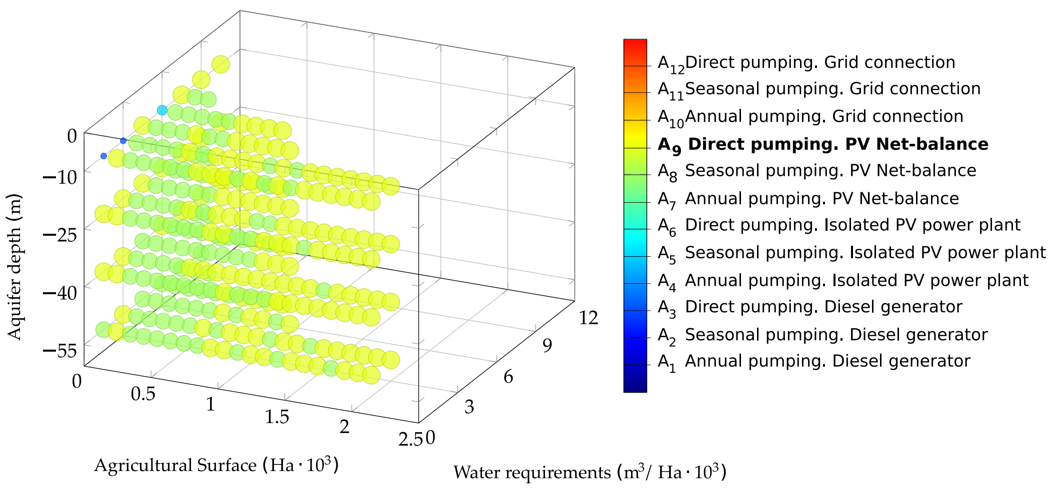

Figure 10: Second optimal alternatives selected by the homogeneous weight vector.

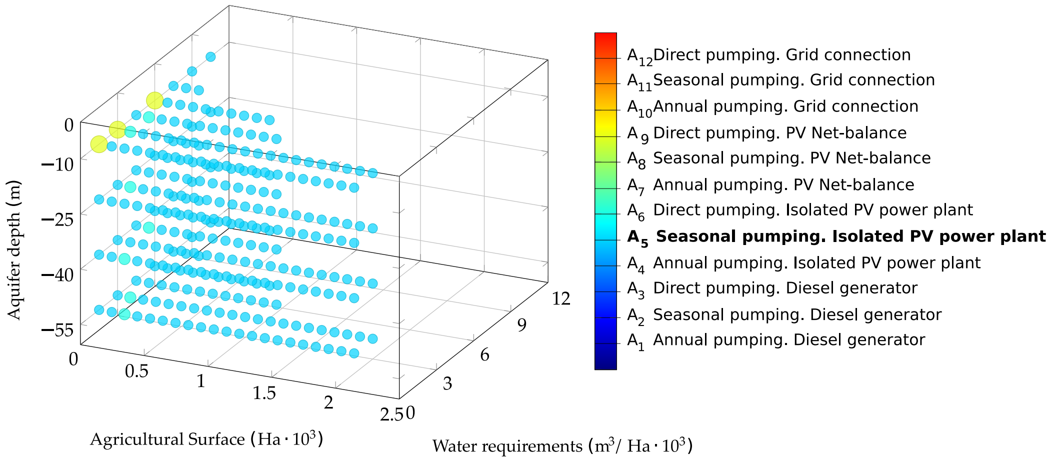

Figure 11: Third optimal alternatives selected by the homogeneous weight vector.

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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"La patience est la clé de la solution".
Proverbe arabe

6. Conclusions et Contributions

6.1 Conclusions

Dans ce chapitre, les conclusions obtenues dans le développement de cette recherche seront présentées et résumées.

6.1.1 Conclusions relatives à la Méthodologie

C01. La conjonction entre un Système d'Information Géographique (SIG), le processus d'aide à la décision multicritère (MCDM) et un processus de génération et de caractérisation d'alternatives avec visualisation 4D, a été satisfaisante, permettant de filtrer et de classer les configurations qui pourraient offrir de plus grands avantages, et de représenter tant graphiquement que géographiquement son fonctionnement à travers différents indicateurs.

C02. La génération d'alternatives en combinant les options de configuration permet d'étudier toutes les alternatives potentiellement viables avant la caractérisation et la prise de décision multicritères, parvenant à la conclusion que l'utilisation d'un schéma de réseau de neurones pour la génération d'alternatives est utile car il permet d'aborder toutes les configurations possibles qui pourraient être appliquées.

C03. La méthodologie proposée a abordé la caractérisation unifiée des alternatives du point de vue économique, énergétique, environnemental, hydrique et social. Cela n'avait été fait dans aucune étude antérieure, loin de la caractérisation économique et environnementale réalisée par certains auteurs. Ce processus de caractérisation permet d'aborder la caractérisation des alternatives à partir d'une approche plus large conforme à la réalité.

C04. Pour visualiser les résultats numériques du processus de caractérisation, un nouveau type de graphique a été choisi, les graphique 4D. Parce qu'ils permettent de représenter un réseau tridimensionnel de valeurs discrètes se référant à un problème avec trois dimensions, la quatrième dimension étant celle qui stocke et représente une valeur thématique, par la taille ou la couleur. L'utilisation de ce type de graphique dans l'étude a été satisfaisante car il remplit la fonction d'illustrer une série de données thématiques qui serait fastidieux d'analyser numériquement.

6.1.2 Conclusions relatives aux résultats de l'Étude de Cas

C05. Il est conclu que le Système d'Information Géographique a représenté un outil très utile dans l'analyse multidimensionnelle et la comparaison des données thématiques liées à la mise en place d'alternatives sur le territoire, ainsi que l'étude hydrogéologique, concrètement celle des besoins énergétiques et celle du potentiel de la ressource solaire incidente. Le SIG a permis d'analyser différentes variables et conditions initiales associées au cas d'étude de l'Aquifère 23 et plus particulièrement au pompage, dont certaines à caractère innovant, telles que: l'Indice d'Applicabilité qui fournit des informations sur les zones, parcelles ou groupes de parcelles de l'aquifère dans lesquelles il est plus facile d'extraire 1 m^3 d'eau et l'Indice de Couplage, qui analyse le potentiel solaire incident et les besoins énergétiques totaux, afin de mieux déterminer la surface du système PV nécessarie à mettre en place.

C06. L'étude montre que la méthodologie privilégie (dans cet ordre) les systèmes alimentés par le système électrique, les systèmes alimentés en énergie solaire photovoltaïque raccordés au réseau électrique et les systèmes photovoltaïques isolés. Cela est dû au fait que les alternatives énergétiques qui couvrent la demande énergétique de la pompe à partir du réseau électrique présentent une série d'avantages par rapport aux autres alternatives, tels que la sécurité d'approvisionnement et le faible entretien, par rapport à la dépendance énergétique à l'électricité comme principal inconvénient.

C07. En ce qui concerne la source d'énergie à utiliser, le résultat donne un score inférieur dans le classement final du processus de prise de décision multicritère (MCDM) des alternatives aux systèmes énergétiques à base de combustibles fossiles, parce qu'ils présentent des valeurs élevées en coûts d'entretien et d'exploitation, en émissions de CO_2, alors qu'ils ont à peu près les mêmes coûts d'investissement en infrastructures d'eau et d'énergie que les autres alternatives.

C08. Dans la même ligne, l'analyse MCDM a également effectué une analyse de la taille optimale des installations de pompage pour les trois alternatives résultantes. De ce processus, il a été déduit que la plage d'extension idéale pour l'Alternative 9 est de 100 ha à 500 ha, dans une plage entre 100 ha et 500 ha pour l'Alternative 6 et, enfin, pour l'Alternative 12 cette plage est comprise entre 300 et 600 ha.

C09. De la conclusion précédente, il s'ensuit qu'en appliquant et en généralisant la possibilité pour les exploitants des eaux souterraines de s'organiser en groupe en coopératives ou en communautés d'irrigation dans le double but de produire des aliments et de l'énergie dans ce qu'on pourrait appeler des coopératives ou des communautés agro-énergétiques, un certain nombre d'avantages importants pourraient être réalisés à petite et à grande échelle. Parmi ces bénéfices pourraient être listés: une meilleure gestion des ressources énergétiques et économiques, la possibilité d'une seconde source de revenus localisée en milieu rural, la réduction de la dépendance énergétique de ce type d'agriculture et la réduction des émissions de CO_2.

C10. Pour permettre le développement de systèmes en bilan net ou en autoconsommation dans les installations de pompage pour l'irrigation telles que celle étudiée, il est nécessaire de disposer d'un système électrique flexible permettant d'étendre le réseau électrique aux zones rurales et d'une régulation énergétique stable qui accueille et promeut les communautés énergétiques dans l'agriculture.

6.2 Contributions

L'étude menée tout au long de la présente Thèse de Doctorat a supposé une série de contributions d'une grande importance pour l'état de l'art du domaine du pompage pour l'irrigation dans l'agriculture et qui étaient à la fois innovantes et originales et qui ont été pertinentes. l'importance de la recherche et de l'analyse de l'intégration des énergies renouvelables dans le pompage des eaux souterraines.

Les principales contributions qui ont été apportées au cours de cette recherche peuvent être résumées comme suit:

A01. Analyse et détermination des principaux impacts et conséquences de l'agriculture liée au pompage d'eaux souterraines d'un point de vue multiple, en examinant comment les impacts environnementaux, socio-économiques, sur l'eau et l'énergie affectent l'objet de l'étude. L'article *I05* du congrès est à l'origine de cette contribution.

A02. Proposition d'analyses techniques, statistiques et géographiques lors du dimensionnement d'une installation photovoltaïque de pompage d'eaux souterraines pour l'irrigation, en tant que comparaison entre petites installations et grandes installations collectives. L'analyse statistique comprend l'étude de la ressource solaire incidente, tandis que l'étude géographique inclut à la fois l'analyse de la ressource solaire sur la surface et la profondeur de l'aquifère. Suite à cette contribution l'article *I01* du congrès (primé) et l'article *P01* ont été publiés.

A03. Formulation d'une méthodologie SIG appliquée au pompage des eaux souterraines pour l'agriculture, en visualisant les conditions initiales (météorologique, hydrogéologique, énergétique, parmi d'autres) et en analysant différentes alternatives ou solutions énergétiques pour le pompage à travers le génération et représentation géographique des valeurs thématiques résultantes, montrant l'adéquation de ladite alternative au cas d'étude. Cette contribution a conduit à la rédaction et à la publication des articles du congrès *I01* et *I03* et à la rédaction d'un chapitre du livre *L01*.

A04. Proposition d'utilisation d'une nouvelle méthodologie permettant de caractériser de manière multidimensionnelle (à travers des graphiques 4D) et d'un point de vue multi-focaux (économique, environnemental, énergétique et hydrique) les alternatives énergétiques pouvant être implantées dans l'agriculture pour répondre à la demande de pompage des eaux souterraines pour l'irrigation. Cette proposition inclut la conception d'un réseau de configuration de solution (réseau neuronal de génération d'alternative) qui inclut différentes options dans la conception de l'installation (type de pompage, individuel ou collectif, système isolé ou connecté, types de sources d'énergie et autres options plus spécifiques). Et d'autre part, l'utilisation de graphiques 4D (conditions initiales 3D + variable thématique 1D), non utilisés auparavant dans la résolution de ce type de problèmes, qui structurent les données résultantes dans le cadre des conditions initiales et en même temps, cela facilite la visualisation des résultats thématiques de chaque alternative. Sur la base de la contribution décrite, un article de congrès *I04* et un article *P02* ont été publiés.

A05. La mise en ouvre du processus de décision multicritère (MCDM) pour distinguer les alternatives proposées de pompage des eaux souterraines à des fins d'irrigation, en fonction de différents aspects ou critères liés aux valeurs thématiques résultant de la caractérisation des solutions de pompage. Le processus a montré qu'il est possible de connaître l'alternative qui correspond le mieux à la situation idéale, en tenant compte des conditions initiales de l'étude. Ce qui a prouvé qu'il est possible d'utiliser d'autres différentes et plus avantageuses que celles des solutions actuellement utilisées. À travers les résultats obtenus dans le cadre de cette contribution, l'article *P04* a été écrit, et la collaboration dans les publications *D01* et *D02*.

A06. Analyse et proposition d'intégration de systèmes coopératifs photovoltaïques à pompage direct connectés au réseau électrique dans la configuration du net balance ou autoconsommation, avec une méthodologie évolutive et exportable, comme solution à appliquer dans l'agriculture, permettant de produire des ressources économiques à l'agriculture par la vente d'énergie excédentaire comme deuxième source de revenu. Cette proposition de configuration constitue une coopérative ou communauté agroénergétique, en tant que moyen d'exploiter efficacement le potentiel énergétique offert par l'agriculture, et qui rejoint le concept, à l'étude déjà faite par d'autres auteurs, de Agro SmartGrid ou Rural SmartGrid en tant que forme d'interconnexion et du gestion efficace de l'énergie en milieu rural et agricole. Conformément à l'objectif de cette contribution l'article *P03* et l'article de congrès *I06* on été publiés.

6.3 Autres publications et congrès

D'autres publications et activités réalisées au cours du processus de recherche seront énumérées ci-dessous.

- Liste des congrès, conférences et séminaires auxquels on a participé au cours du développement de la recherche:

I05. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2015, July). Geographic information systems for optimization and integration of photovoltaic solar energy in agricultural areas with energy deficiency and water scarcity. In *International Congress on Project Management and Engineering* (CIDIP'15, Granada (Spain)).

I06. A. Rubio-Aliaga, A. Molina-García, J.M. Sánchez-Lozano, M.S. García-Cascales (2016, May). Integration of Solar Energy Resource into Agro-Energy Cooperative Districts: A Case Study based on Solar Powered Irrigation Pumps. In *International Conference on Renewable Energies and Power Quality* (ICREPQ'16). Article primé.

I07. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2016, July). Analysis of solar resource for agriculture pumping applications: environment and energy impact. In *International Congress on Project Management and Engineering* (CIDIP'16, Cartagena (Spain)).

I08. Molina-García, A., Rubio, A., García-Cascales, M. S., & Sánchez-Lozano, J. M. (2017, December). An Approach to Multidimensional Analysis for PV Solar Energy Integration into Groundwater Pumping Solutions. In *2017 International Renewable and Sustainable Energy Conference (IRSEC)* (pp. 1-6). IEEE.

I09. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2018, April). Multi-focusing Analysis and Impact of PV-Solar Resource in Groundwater Pumping Agriculture Applications. In *Renewable Energy International Conference* (ICREN'18, Barcelona (Spain)).

I10. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2018, July). Economic analysis of net-zero energy balance applied to solar pumping facilities in agriculture. In *International Congress on Project Management and Engineering* (CIDIP'18, Madrid (Spain)).

Il est nécessaire de signaler la participation à de nombreuses conférences, réunions et séminaires organisés pendant la période de développement de cette Thèse de Doctorat, notamment la participation aux les Journées Doctorat VII (2017), VIII (2018) y IX (2019) de l'Université de Castilla-La Mancha (UCLM), l'assistance au IV Réunion d'ingénierie énergétique du Campus Mare Nostrum (2018), l'assistance au I Conférence doctorale en énergies renouvelables de l'Université de Jaén (2018), l'aide aux IV Journées Doctorales de l'Université de Murcia (2018) et au I Conférence doctorale de l'Université Polytechnique de Carthagène (UPCT) dans 2018 et aux IV Journées Doctorales Campus Mare Nostrum (2022).

- Les chapitres de livres qui ont été developpés sont également indiqués ci-dessous:

L01. Rubio-Aliaga, Á., García-Cascales, M. S., Molina-García, Á., & Sánchez-Lozano, J. M. (2017). Geographic Information System for Optimization and Integration of Photovoltaic Solar Energy in Agricultural Areas with Energy Deficiency and Water Scarcity. In *Project Management and Engineering Research* (pp. 181-197). Springer, Cham.

- Enfin, il a également impliqué la collaboration avec d'autres publications et conférences telles que:

D01. García-Cascales, M. S., Molina-García, Á., Sánchez-Lozano, J. M., Rubio-Aliaga, Á., & Munier, N. (2020, June). Assessment of Groundwater Pumping Alternatives for Irrigation Purposes based on the SIMUS Method. In *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

D02. García-Cascales M.S., Molina-García, Á., Sánchez-Lozano, J.M., Mateo-Aroca, A., Munier, N. (November 2021). Multi-criteria analysis techniques to enhance sustainability of water pumping irrigation. *Energy Reports*, Volume 7, Pages 4623-4632. Journal International Open Access, Q1 avec un facteur d'impact de 6 870 (2021).

6.4 Conclusiones

En este capítulo, se mostrarán, y se resumirán las conclusiones obtenidas en el desarrollo de la presente investigación.

6.4.1 Conclusiones relativas a la Metodología

C01. La conjunción entre un Sistema de Información Geográfica (SIG), el proceso de toma de decisiones multicriterio (MCDM) unida a un proceso de generación y caracterización de alternativas con visualización 4D, ha resultado satisfactorio permitiendo filtrar y clasificar aquellas configuraciones que pudieran ofrecer mayores ventajas y representar tanto gráfica como geográficamente su funcionamiento a través de diferentes indicadores.

C02. La generación de alternativas por combinación de las opciones de configuración permite estudiar todas las alternativas potencialmente viables previo a la caracterización y a la toma de decisión multicriterio, lo cual aporta como conclusión que el uso de un esquema de Red Neuronal de Generación de Alternativas resulta de utilidad ya que permite abordar todas las posibles configuraciones que pudieran ser de aplicación.

C03. La metodología propuesta ha abordado la caracterización unificada de las alternativas desde el punto de vista económico, energético, ambiental, hídrico, y social. Lo cual no se había realizado en ningún estudio anterior, lejos de la caracterización económica y ambiental realizada por algunos autores. Este proceso de caracterización permite abordar la caracterización de las alternativas desde un enfoque más amplio y ajustado a la realidad.

C04. Para visualizar los resultados numéricos del proceso de caracterización se ha optado por un tipo de gráfica novedosa, las gráficas 4D. Debido a que permiten representar una red tridimensional de valores discretos referentes a un problema con tres dimensiones, siendo la cuarta dimensión la que almacena y representa un valor temático, a través del tamaño o bien por su color. El uso de este tipo de gráficas en el estudio ha resultado satisfactorio ya que cumple la función de ilustrar una serie de datos temáticos que numéricamente seria tedioso de analizar.

6.4.2 Conclusiones relativas a los resultados del Caso de Estudio

C05. Se concluye que el Sistema de Información Geográfica ha representado una herramienta muy útil en el análisis multidimensional y comparación de datos temáticos relativosa la implantación de las alternativas en el territorio, conjuntamente con el estudio hidrogeológico y energético de los requerimientos de energía y del potencial del recurso solar incidente. El SIG ha permitido analizar diferentes variables y condiciones iniciales asociadas al caso de estudio del Acuífero 23 y concretamente al bombeo, algunas de ellas de carácter innovador como son: el Índice de Aplicabilidad que aporta información de las zonas, parcelas o grupos de parcelas del acuífero en las que resulta más fácil elevar 1 m^3 de agua y el Índice de Acoplamiento, el cual relaciona el potencial solar incidente y los requerimientos energéticos totales aproximando la superficie del sistema PV a implantar.

C06. El estudio demuestra que la metodología prioriza (en este orden) sistemas abastecidos por el sistema eléctrico, sistemas abastecidos con energía solar fotovoltaica conectados a la red eléctrica y sistemas fotovoltaicos aislados. Esto es debido a que las alternativas energéticas que cubren desde la red eléctrica la demanda de energía de la bomba poseen una serie de ventajas respecto de las otras alternativas, como es la seguridad de suministro y un bajo mantenimiento, frente a la dependencia energética de la electricidad como principal inconveniente.

C07. En cuanto a la fuente energética a utilizar el resultado otorga una menor puntuación en la clasificación final del proceso de Toma de Decisiones Multicriterio (MCDM) de alternativas a aquellos sistemas energéticos basados en los combustibles fósiles, debido a que presentan valores altos en costes de mantenimiento y operación, en emisiones de CO_2, mientras que tiene aproximadamente los mismos costes de inversión en infraestructuras hídricas y energéticas que otras alternativas.

C08. En la misma línea, el análisis MCDM también ha realizado un análisis del tamaño óptimo de las instalaciones de bombeo para las tres alternativas resultantes. De este proceso se ha deducido que el rango de extensión idóneo para la Alternativa 9 es de 100 ha a 500 ha, en un rango comprendido entre 100 ha y 500 ha para la Alternativa 6 y, por último, para la Alternativa 12 este rango se ciñe entre 300 ha y 600 ha.

C09. De la anterior conclusión se deriva que aplicando y generalizando la posibilidad que los agricultores de aguas subterráneas pudieran organizarse en agrupaciones, cooperativas o comunidades de regantes con el doble fin de producir alimentos y energía en lo que podría llamarse cooperativas o comunidades agroenergéticas, se podrían obtener una serie importante de beneficios tanto a pequeña como a gran escala. Entre estos beneficios se podrían enumerar: una mejor gestión de la energía y de los recursos económicos, la posibilidad de una segunda vía de ingresos localizado en el ámbito rural, la reducción de la dependencia energética de este tipo de agricultura y la reducción de las emisiones de CO_2.

C10. Para permitir el desarrollo de sistemas en balance neto o en autoconsumo en instalaciones de bombeo para riego como el estudiado, se requiere de un sistema eléctrico flexible con la capacidad de extender la red eléctrica a áreas rurales y una regulación energética estable que acoja, de cabida y potencie las comunidades energéticas en la agricultura.

6.5 Contribuciones

El estudio realizado a lo largo de la presente Tesis Doctoral, ha supuesto una serie de aportaciones al Estado del Arte del ámbito del bombeo para el riego en la agricultura y han puesto de relevancia la importancia de la búsqueda y análisis de la integración de las energías renovables en el bombeo de aguas subterráneas.

Las principales aportaciones que se han realizado durante esta investigación, se pueden resumir en la siguiente forma:

A01. Análisis y determinación de los principales impactos y consecuencias entorno a la agricultura de bombeo de aguas subterráneas desde un punto de vista multienfoque, estudiando cómo afectan al objeto de estudio los impactos ambientales, socioeconómicos, hídricos y energéticos. De dicha aportación se originó el artículo de congreso *I05*.

A02. Propuesta de análisis técnico, estadístico y geográfico a la hora del dimensionamiento de una instalación fotovoltaica de bombeo de aguas subterráneas para el riego como comparativa entre instalaciones pequeñas y grandes instalaciones colectivas. Incluyendo el análisis estadístico y geográfico tanto del recurso solar disponible como del recurso hídrico. A raíz de esta aportación han sido publicados, el artículo de congreso *I01* (premiado) y el artículo de revista *P01*.

A03. Formulación de una metodología SIG (exportable y escalable) aplicada al bombeo de aguas subterráneas para su uso en la agricultura, mediante la visualización de las condiciones iniciales (meteorológicas, hidrogeológicas, energéticas, entre otras) y el análisis de diferentes alternativas o soluciones energéticas al bombeo a través de la generación y representación geográfica de valores temáticos resultantes, que muestren la adecuación de dicha alternativa al caso de estudio. Esta aportación ha propiciado la redacción y publicación de los artículos de congreso *I01* e *I03*, y un capítulo de libro *L01*.

A04. Propuesta para el uso de una nueva metodología para caracterizar multidimensionalmente (a través de las gráficas 4D) y desde un punto de vista multienfoque (económico, ambiental, energético e hídrico) las alternativas energéticas capaces de implantarse en la agricultura para abastecer la demanda del bombeo de aguas subterráneas para el riego. Esta propuesta incluye el diseño de una red de configuración de soluciones (Red neuronal de generación de alternativas) que comprende diferentes opciones en el diseño de la instalación (tipo de bombeo, individual o colectivo, sistema aislado o conectado, tipos de fuentes de energía y otras opciones más específicas). Y por otro, la utilización de las gráficas 4D (3D condiciones iniciales + 1D variable temática), no utilizadas anteriormente en la resolución de este tipo de problemas, que aporta una estructura a los datos resultantes en el marco de las condiciones iniciales y al mismo tiempo facilita la visualización de los resultados temáticos de cada alternativa. Fundamentados en la aportación descrita se publicaron: un artículo de congreso *I04* y un artículo de revista *P02.*

A05. La implementación del proceso de toma de decisiones multicriterio (MCDM) para elegir entre las alternativas propuestas para el bombeo de aguas subterráneas para el riego, en función de diferentes aspectos o criterios relacionados con los valores temáticos resultantes de la caracterización de las soluciones de bombeo. El proceso ha demostrado que es posible conocer la alternativa que mejor se ajusta a la situación ideal, tomando en cuenta las condiciones iniciales del estudio. Lo cual ha resultado que es posible utilizar otras soluciones diferentes y más ventajosas que las utilizadas en la actualidad. A través de los resultados obtenidos en relación de esta aportación se ha publicado el artículo de revista *P04*, y surgió la colaboración en las publicaciones *D01* y *D02*.

A06. Análisis y propuesta de integración de los sistemas cooperativos fotovoltaicos de bombeo directo conectados a la red eléctrica en la configuración de balance neto o autoconsumo, con una metodología escalable y exportable, como una solución a aplicar en la agricultura, permitiendo dirigir recursos económicos a la agricultura por la venta de la energía excedente como una segunda vía de ingresos. Esta propuesta de configuración, una Cooperativa Agroenergética, constituye una forma de aprovechar eficientemente el potencial energético que ofrece la agricultura, y que se une al concepto de la Agro SmartGrid o Rural SmartGrid como una forma de interconexión y gestión eficiente de la energía en entornos rurales y agrarios. Cumpliendo con el objetivo de esta aportación, se publicó el artículo de revista *P03*, y el artículo de congreso *I06*.

6.6 Otras publicaciones y congresos

A continuación, se enumeran otras publicaciones y actividades realizadas durante el proceso de investigación.

- Relación de congresos, jornadas y seminarios, a los que se ha asistido durante el desarrollo de la investigación:

I05. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2015, July). Geographic information systems for optimization and integration of photovoltaic solar energy in agricultural areas with energy deficiency and water scarcity. In *International Congress on Project Management and Engineering* (CIDIP'15, Granada (Spain)).

I06. A. Rubio-Aliaga, A. Molina-García, J.M. Sánchez-Lozano, M.S. García-Cascales (2016, May). Integration of Solar Energy Resource into Agro-Energy Cooperative Districts: A Case Study based on Solar Powered Irrigation Pumps. In *International Conference on Renewable Energies and Power Quality* (ICREPQ'16). Article primé.

I07. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2016, July). Analysis of solar resource for agriculture pumping applications: environment and energy impact. In *International Congress on Project Management and Engineering* (CIDIP'16, Cartagena (Spain)).

I08. Molina-García, A., Rubio, A., García-Cascales, M. S., & Sánchez-Lozano, J. M. (2017, December). An Approach to Multidimensional Analysis for PV Solar Energy Integration into Groundwater Pumping Solutions. In *2017 International Renewable and Sustainable Energy Conference (IRSEC)* (pp. 1-6). IEEE.

I09. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2018, April). Multi-focusing Analysis and Impact of PV-Solar Resource in Groundwater Pumping Agriculture Applications. In *Renewable Energy International Conference* (ICREN'18, Barcelona (Spain)).

I10. Rubio-Aliaga, A., Molina-Garcia, A., & Garcia-Cascales, M. S. & Sánchez-Lozano, J. M. (2018, July). Economic analysis of net-zero energy balance applied to solar pumping facilities in agriculture. In *International Congress on Project Management and Engineering* (CIDIP'18, Madrid (Spain)).

Es necesario señalar la participación a numerosas jornadas, encuentros y seminarios realizados en el periodo de desarrollo de la investigación: la asistencia a las VII (2017), VIII (2018) y IX (2019) Jornadas Doctorales de la Universidad de Castilla-La Mancha (UCLM), la asistencia al IV Encuentro de Ingeniería de la Energía del Campus Mare Nostrum (2018), la asistencia a las I Jornadas Doctorales en Energías Renovables de la Universidad de Jaén (2018), asistencia a las IV Jornadas Doctorales de la Universidad de Murcia (2018), a la I Jornada Doctoral de la Universidad Politécnica de Cartagena (UPCT) en 2018 y a las VII Jornadas Doctorales Campus Mare Nostrum (2022).

- A continuación, se muestran también los capítulos de libro que se han realizado:

L01. Rubio-Aliaga, Á., García-Cascales, M. S., Molina-García, Á., & Sánchez-Lozano, J. M. (2017). Geographic Information System for Optimization and Integration of Photovoltaic Solar Energy in Agricultural Areas with Energy Deficiency and Water Scarcity. In *Project Management and Engineering Research* (pp. 181-197). Springer, Cham.

- Finalmente, también ha supuesto la colaboración en otras publicaciones y congresos como:

D01. García-Cascales, M. S., Molina-García, Á., Sánchez-Lozano, J. M., Rubio-Aliaga, Á., & Munier, N. (2020, June). Assessment of Groundwater Pumping Alternatives for Irrigation Purposes based on the SIMUS Method. In *2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

D02. García-Cascales M.S., Molina-García, Á., Sánchez-Lozano, J.M., Mateo-Aroca, A., Munier, N. (November 2021). Multi-criteria analysis techniques to enhance sustainability of water pumping irrigation. *Energy Reports*, Volume 7, Pages 4623-4632. Journal International Open Access, Q1 con un factor de impacto de 6 870 (2021).

Annexes

I. Lignes de recherche futures

Après avoir terminé cette recherche, des questions à résoudre surgissent à partir de la base créée dans cette étude, ouvrant un large éventail de futures lignes de recherche.

La transversalité et les synergies potentielles entre les disciplines de l'agriculture et de l'énergie, permettent sans aucun doute un large développement et laissent place à une grande infinité d'études sur l'agro-énergie. C'est à ce stade que surgit le premier groupe de nouvelles pistes de recherche, à partir de l'**analyse de l'intégration des ressources énergétiques renouvelables dans l'agriculture**.

Bien que cette étude se concentre sur le pompage des eaux souterraines pour l'irrigation avec un apport d'énergie renouvelable, il est possible d'étendre l'analyse de l'utilisation de l'énergie et l'étude de l'application du potentiel énergétique des sources d'énergie renouvelables présentes dans les zones rurales, non seulement au pompage mais aussi à d'autres processus agricoles et le secteur de l'élevage. Cela permettra d'entreprendre des études sur l'optimisation et l'utilisation des ressources énergétiques en agriculture, permettant de réduire les coûts énergétiques de la production agricole et sa dépendance aux énergies fossiles. Et donc enfin, créer de nouvelles opportunités économiques et d'emplois dans les milieux agricoles et ruraux dans una gestion durable de l'énergie.

- L01. Étude de l'utilisation de la méthodologie proposée afin d'intégrer des systèmes d'énergies renouvelables alternatives (mini-éolien, équipement de générateur dont la source d'énergie est basée sur des biocarburants, du biodiesel, du bioéthanol ou du biogaz, etc.) ou des systèmes hybrides de deux ou plusieurs sources d’énergies renouvelables dans le domaine agricole du pompage des eaux souterraines, pour caractériser et déterminer la configuration optimale de l'installation.

- D'ailleurs, la méthodologie décrite permet d'apporter différentes contributions jusqu'à atteindre un degré de développement supérieur. Par conséquent, il est possible de générer de nouvelles lignes de recherche en termes de **contributions méthodologiques**:
- L02. Analyse de sensibilité permettant de connaître l'influence des différentes variables dans les résultats finaux, dans l'intention de simplifier le processus en éliminant les variables qui n'affectent pas de manière significative.
- L03. Exécution du processus de décision multicritère (MCDM) en utilisant des méthodologies différentes de celle utilisée dans la présente étude (Fuzzy, SIMUS, et autres).
- L04. Intégrer un plus grand nombre de critères dans le processus de décision multicritère MCDM, dans le but d'évaluer les alternatives de manière plus précise et en tenant compte d'autres facteurs.

Enfin, les **systèmes énergétiques coopératifs dans l'agriculture, les communautés ou les coopératives agroénergétiques**, comme dans ce cas un système d'irrigation par pompage avec une installation photovoltaïque connectée au réseau électrique, présentent de grands avantages dans ce secteur. D'une part, il permet de réduire les coûts d'investissement et les coûts d'entretien, tout en permettant une utilisation plus rationnelle de l'eau, de l'énergie et des ressources économiques. Et, d'autre part, il gère le potentiel énergétique inexploité pendant la période d'absence d'irrigation, pour permettre une deuxième voie de revenu économique dans l'économie agricole à partir de la vente d'électricité.

- L05. Analyse et étude des coopératives agroénergétiques: cadre réglementaire et figure juridique. Avantages et inconvénients de son implantation à partir de l'analyse 3E: énergétique, socio-économique et environnemental.
- L06. Etude des sources d'énergies renouvelables adaptées, de manière autonome ou par des systèmes hybrides, dans des Coopératives ou des Communautés Agroénergétiques.

II. Líneas futuras de investigación

Una vez finalizada esta investigación surgen cuestiones a resolver desde la base creada en el presente estudio, abriendo un amplio abanico de futuras líneas de investigación.

La transversalidad y las potenciales sinergias entre las disciplinas de la agricultura y la energía, sin duda alguna permiten un amplio desarrollo y da cabida a una gran infinidad de estudios en materia agroenergética. Es en este punto donde surge el primer grupo de nuevas líneas de investigación, desde el análisis de la **integración de los recursos energéticos renovables en la agricultura**.

Aunque este estudio se centra en el bombeo de aguas subterráneas para el riego con aporte energético renovable, es posible extender el análisis del uso de la energía y el estudio de aplicación del potencial energético de las fuentes de energía renovables presentes en el ámbito rural, no solo al bombeo sino también al resto de procesos agrícolas y al sector ganadero. Lo cual permitirá acometer estudios acerca de la optimización y aprovechamiento de los recursos energéticos de la agricultura, permitiendo reducir los costes energéticos de la producción agrícola y su dependencia de los combustibles fósiles. Para así finalmente crear nuevas oportunidades económicas y laborales en entornos agrícolas y rurales en una gestión sostenible de la energía.

- L01. Estudio del uso de la metodología propuesta con la finalidad de integrar sistemas energéticos renovables alternativos (mini-eólica, equipos electrógenos cuya fuente de energía esté basada en biocombustibles, biodiésel, bioetanol, o biogás, etc.) o sistemas híbridos de dos o más fuentes de energía renovable en el ámbito agrícola de bombeo de aguas subterráneas, para caracterizar y determinar la configuración óptima de la instalación.

Por otro lado, la metodología descrita permite realizar diferentes aportaciones hasta alcanzar un mayor grado de desarrollo. Por lo tanto, permite generar nuevas líneas de investigación en lo que **aportaciones metodológicas** se refiere:

- L02. Análisis de sensibilidad que permita conocer la influencia de las diferentes variables en los resultados finales, con la intención de simplificar el proceso eliminando aquellas variables que no afectan significativamente.
- L03. Ejecución del proceso de Toma de Decisiones Multicriterio (MCDM) mediante metodologías diferentes a la usada en el presente estudio (Fuzzy, SIMUS, etc.).
- L04. Incorporar un número mayor de criterios en el proceso de toma de decisiones multicriterio MCDM, con el objetivo de evaluar las alternativas de una forma más precisa y atendiendo a más factores.

Finalmente, los **sistemas energéticos cooperativos en la agricultura, comunidades o cooperativas agroenergéticas**, como en este caso un sistema de riego por bombeo con una instalación fotovoltaica conectada a la red eléctrica, poseen grandes ventajas dentro de este sector. Por un lado, permite la reducción de los costes de inversión y de gastos en mantenimiento, al mismo tiempo que logra un uso más racional del agua, de la energía y de los recursos económicos. Y, por otro lado, gestiona el potencial energético no aprovechado durante el tiempo en el que no se riega, para permitir una segunda vía de ingresos económicos en la economía agrícola por la venta de energía eléctrica.

- L05. Análisis y estudio de las Cooperativas Agronergéticas: Marco Regulatorio y Figura Jurídica. Ventajas e inconvenientes de su implantación desde el análisis 3E: energético, socio-económico, y ambiental.
- L06. Estudio de las fuentes de energía renovable que se adaptan de forma independiente o mediante sistemas híbridos a la implantación de las Cooperativas Agroenergéticas.

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III. Documentation accréditant sur le quartile

Ensuite, les documents qui certifient le facteur d'impact et sa classification dans les revues dans lesquelles les articles qui composent cette Thèse par Compendium ont été publiés, sont présentés.

Article 1 | GIS based solar resource analysis for irrigation purposes: Rural areas comparison under groundwater scarcity conditions.

SOLAR ENERGY MATERIALS AND SOLAR CELLS

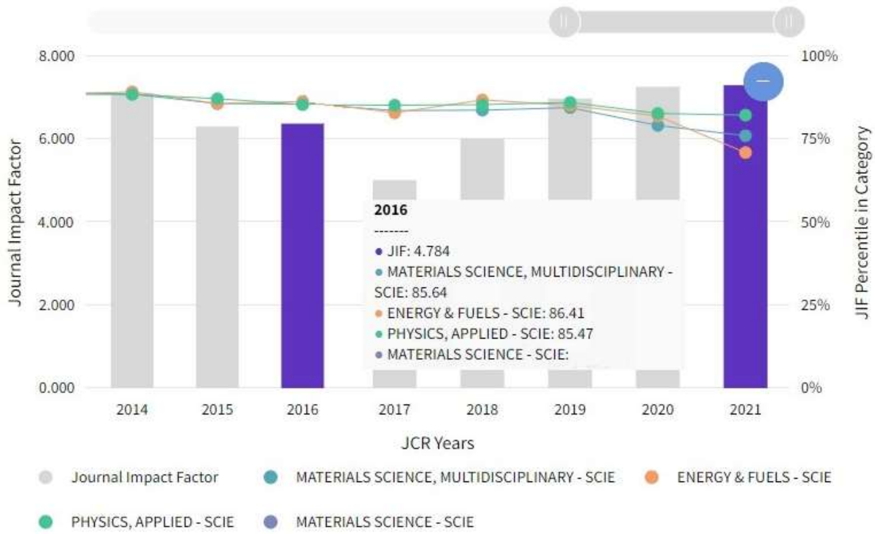
2016 JOURNAL IMPACT FACTOR & PERCENTILE RANK IN CATEGORY

The Journal Impact Factor (JIF) is a journal-level metric calculated from data indexed in the Web of Science Core Collection. It should be used with careful attention to the many factors that influence citation rates, such as the volume of publication and citations characteristics of the subject area and type of journal. The Journal Impact Factor can complement expert opinion and informed peer review. In the case of academic evaluation for tenure, it is inappropriate to use a journal-level metric as a proxy measure for individual researchers, institutions, or articles.

4.784

2016 Journal Impact Factor

SOLAR ENERGY MATERIALS AND SOLAR CELLS



Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

13/92

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2021	35/119	Q2	71.01
2020	21/114	Q1	82.02
2019	17/112	Q1	85.27
2018	14/103	Q1	86.89
2016	13/92	Q1	86.41

Article 2 | Multidimensional analysis of groundwater pumping for irrigation purposes: Economic, energy and environmental characterization for PV power plant integration.

RENEWABLE ENERGY

2019 JOURNAL IMPACT FACTOR & PERCENTILE RANK IN CATEGORY

The Journal Impact Factor (JIF) is a journal-level metric calculated from data indexed in the Web of Science Core Collection. It should be used with careful attention to the many factors that influence citation rates, such as the volume of publication and citations characteristics of the subject area and type of journal. The Journal Impact Factor can complement expert opinion and informed peer review. In the case of academic evaluation for tenure, it is inappropriate to use a journal-level metric as a proxy measure for individual researchers, institutions, or articles.

6.274

2019 Journal Impact Factor

RENEWABLE ENERGY

Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

19/112

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2021	25/119	Q1	79.41
2020	16/114	Q1	86.40
2019	19/112	Q1	83.48
2018	17/103	Q1	83.98
2019	19/112	Q1	83.48

Article 3 | Net-Metering and Self-Consumption Analysis for Direct PV Groundwater Pumping in Agriculture: A Spanish Case Study.

Applied Sciences-Basel

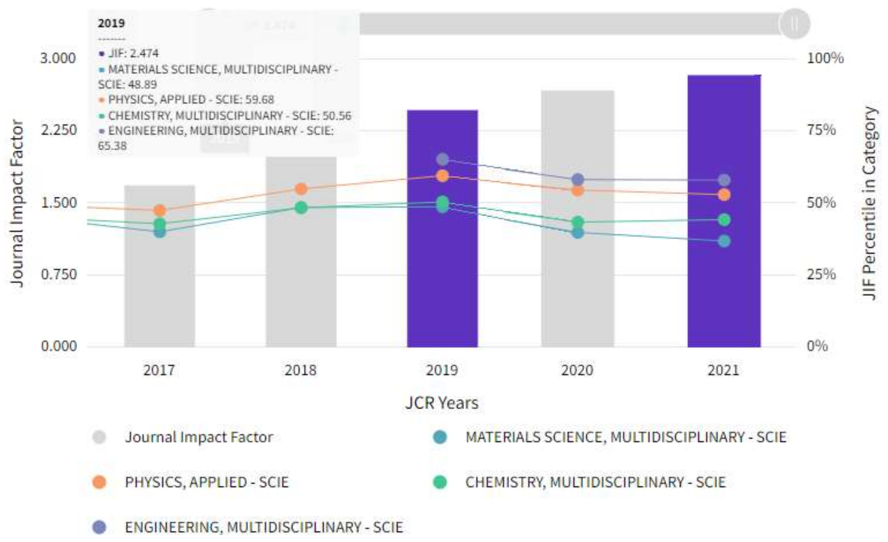
2019 JOURNAL IMPACT FACTOR & PERCENTILE RANK IN CATEGORY

The Journal Impact Factor (JIF) is a journal-level metric calculated from data indexed in the Web of Science Core Collection. It should be used with careful attention to the many factors that influence citation rates, such as the volume of publication and citations characteristics of the subject area and type of journal. The Journal Impact Factor can complement expert opinion and informed peer review. In the case of academic evaluation for tenure, it is inappropriate to use a journal-level metric as a proxy measure for individual researchers, institutions, or articles.

2.474

2019 Journal Impact Factor

Applied Sciences-Basel



Rank by Journal Impact Factor

Journals within a category are sorted in descending order by Journal Impact Factor (JIF) resulting in the Category Ranking below. A separate rank is shown for each category in which the journal is listed in JCR. Data for the most recent year is presented at the top of the list, with other years shown in reverse chronological order. Learn more

EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENGINEERING, MULTIDISCIPLINARY

32/91

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2021	39/92	Q2	58.15
2020	38/90	Q2	58.33
2019	32/91	Q2	65.38
2018	N/A	N/A	N/A
2019	32/91	Q2	65.38

Article 4 | MCDM-based multidimensional approach for selection of optimal groundwater pumping systems: Design and case example.

RENEWABLE ENERGY

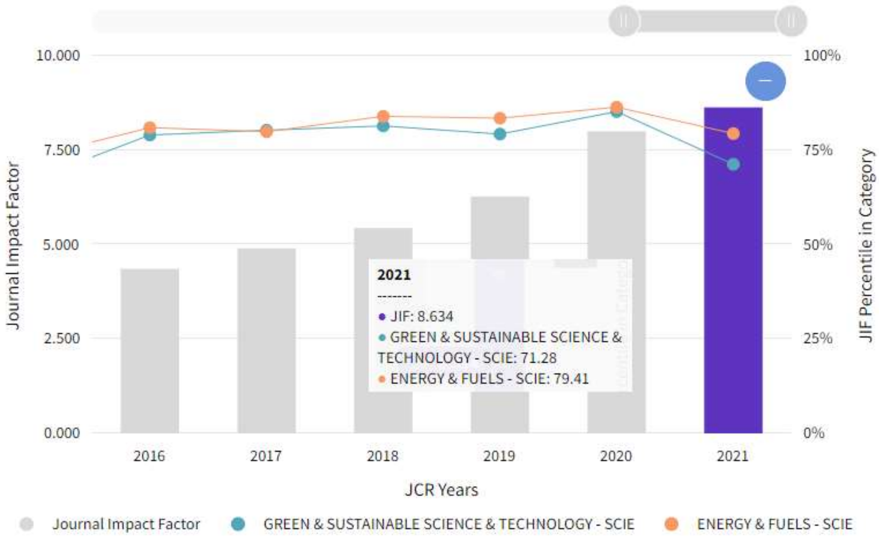
2021 JOURNAL IMPACT FACTOR & PERCENTILE RANK IN CATEGORY

The Journal Impact Factor (JIF) is a journal-level metric calculated from data indexed in the Web of Science Core Collection. It should be used with careful attention to the many factors that influence citation rates, such as the volume of publication and citations characteristics of the subject area and type of journal. The Journal Impact Factor can complement expert opinion and informed peer review. In the case of academic evaluation for tenure, it is inappropriate to use a journal-level metric as a proxy measure for individual researchers, institutions, or articles.

8.634

2021 Journal Impact Factor

RENEWABLE ENERGY



Rank by Journal Impact Factor

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EDITION

Science Citation Index Expanded (SCIE)

CATEGORY

ENERGY & FUELS

25/119

JCR YEAR	JIF RANK	JIF QUARTILE	JIF PERCENTILE
2021	25/119	Q1	79.41
2020	16/114	Q1	86.40
2019	19/112	Q1	83.48
2018	17/103	Q1	83.98
2017	20/97	Q1	79.90