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A comprehensive analysis based on GIS-AHP to minimise the social and environmental impact of the installation of large-scale photovoltaic plants in south Spain

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A R T I C L E I N F O

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A B S T R A C T

This article aims to propose a methodology to assess and prioritise the territorial factors considered when selecting the location of large-scale photovoltaic plants. It therefore seeks to answer the current social conflict problem regarding their installation, particularly in the rural context. The territory zoning is conducted from a holistic perspective, taking into account its social and environmental impact.

Therefore, a series of analysis and restriction parameters are established and the Analytic Hierarchy Process by Geographic Information Systems is used. Those criteria are superimposed on the landscape of the Jimena Depression. Located in the south-west of Spain, it is coastal landscape countryside where energy companies currently exert great pressure to expedite applications for photovoltaic projects.

A mapping characterization is thus produced that determines which areas should be considered excluded, along with the zones of greater or lesser environmental and social awareness. Assessing this zoning, along with the energy demands and the location of the existing plant projects leads to a series of questions to be considered in the planning of those municipalities. They respond to the need to conduct an overall study, and ones on land protection, the cumulative impact regulation, and on implementing social measures to offset the changes caused.

1. Introduction

The **population's growing interest** in the dubbed "clean energy" can be traced back to the fossil fuel crisis in the 1970s. However, despite the initial acceptance of those emerging energy landscapes, the impact on the territory - together with the citizen perception - began to be considered in countries such as Sweden as early as 1979. Even though the timeline of the early assessment work in that regard varied according to the location, impetus to the initial general research can be found in the mid-1990s and which would be consolidated with the turn of the century [1]. In the last decade, much research reflected this **paradox** that is underpinned by social **rejection** of **large-scale renewable energy** production when in prized or inhabited territories [2–6].

In Spain, this movement has led to the **#Renovablesíperonoasí** [#Renewablesyesbutnothere] slogan, which owes much to the **#Notinmybackyard**[1] **(NIMBY) coined in the United States** [7,8]. The explanation, as numerous authors have asserted, is based on the population's attachment to the countryside ([2]:201); while opposition to the conventional energy systems is on public health and environmental grounds, it is down to the territorial impact in the case of renewables do ([1]:129).

In tandem to this social context, the **renewable energy sector is**

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[1] While there is controversy around the NIMBY phenomenon due to its lack of solidarity, the Spanish slogan does not reject the implementation of renewables, but it does question their location.

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expanding in Spain at a breakneck speed. Fig. 1 shows the **European planning context** for renewable energy in a diagram from 2018 when Directive 2018/2001 on the promotion of energy use from renewable sources was approved. It can be seen how the conflict in Ukraine has boosted energy sovereignty policies, a strategy in which Spain can play a crucial role. In 2022, the EU adopted the REPowerEU Plan to make the Union independent from Russian fossil fuels well before 2030. That new strategy increases the average deployment rate of renewable energy capacity by 2030 by the modifications included in Directive 2023/2413. So in that context, Council Regulation (EU) 2022/2577 and the last Council Regulation 2024/223 of December 22, 2023 introduce exemptions from certain assessment obligations set in Union environmental legislation for renewable energy projects that are necessary for the integration of renewable energy into the electricity system.

As one of the most southerly countries of Europe, the submitted projects far exceed the targets of 50 GW of wind and 39 GW of photovoltaic power established by the Spanish National Integrated Energy and Climate Plan (PNIEC) by the end of this decade ([9]:12).[2] According to Solar Power Europe, the country is on track to achieve a potential of installed solar capacity of 179 GW by 2030 [61]. Despite exceeding the installed capacity forecasts, the **PNIEC** 2030 shows certain shortcomings. The main ones include the lack of indications regarding the way to plan and organise the implementation of these macro-infrastructures at territorial level, and the lack of disaggregated self-consumption and distributed renewable generation targets, as required by the European directives of the Winter Package [10]. Shortcomings that -apart from jeopardising Spain's valuable biodiversity-seem detached from the growing focus on recognising the landscape as an asset to be enhanced and conserved as established by the European Landscape Convention, ratified by Spain in 2008 [11].

This lack of specific regulations allows large developers to look for cheaper land and closer to the connection points, with power lines, and without questioning the cultural and environmental value of that land. This problem affects the generation of **photovoltaic power** to a greater extent, as, given its solar irradiance conditions, **Spain** offers large cost-effective areas for its installation. Furthermore, its extensive occupancy of the space is greater than that of wind power, and its receptors imply -in the majority of cases-greater exclusivity of the use of the land compared to air turbines, despite being less visible from further away. Moreover, its costs allow for different sizes of investors, compared to the large developers that wind power requires.

Currently, the large photovoltaic projects in Spain only require the assessment of their **Environmental Impact Statement** to ensure the suitability of their location [12], which means **no** holistic territorial assessment, as no spatial planning experts are involved in this decision. As far as the authorities are concerned, only **zoning maps and visors** exclusively for **environmental protection** have been prepared, and which, however, are not binding. At state level, they include the creation of the Environmental Sensitivity Index that resulted in the Environmental Zoning Tool for renewables in Spain, consisting of a document and a map [13]; and at regional level, the Environmental Awareness Map of the Autonomous Region of Murcia [14], the Environmental Criteria Manual for the Implementation of Photovoltaic Power Plants in Catalonia [15], the Environmental Zoning Map for Priority Projects in Castilla La Mancha [16], and the Spatial Data Infrastructure Visors that include zoning for renewables in the Basque Country [17] and Castilla y León [18].

Despite being a great step forward, the visors do not include information on the occupancy of the existing plants or the location and the sizing of the new projects; it is therefore not possible whether those aspects have been taken into consideration. This **need for transparency** has only been embraced by certain autonomous regions and is not problem free. It has been addressed in Catalonia, where there is an environmental visor and with renewable energy data for public consultation[3] [19], while other regions such as Valencia or Andalusia seem to be reluctant to publish. According to its Spatial Data Infrastructure, the former has a public layer entitled "Photovoltaic Facilities in the Pipeline"; however, its visor is currently inactive [20]. In 2020, the latter prepared a guide to analyse the location of the photovoltaic solar plant projects and a zoning map that were withdrawn a month after being published in January 2021 [21]. As proof of the highlighted need, the Climate Observatory of the SEO/BirdLife NGO has a map of the specific planning instruments existing in Spain for the deployment of windfarms and photovoltaic plants at regional level [58]. According to that map, only five (Basque Country, Castilla y León, Castilla La Mancha, Autonomous Region of Valencia, and Catalonia[4]) of the 17 autonomous regions have binding planning or regulations approved, which include zoning criteria, even though we always speak of exclusively environmental parameters.

That is, the emphasis seems to have been on the natural risks throughout this process in Spain, overlooking the **territorial changes** that have been taken into account in this growth of large-scale renewables in countries such as Germany, France, Portugal, the United Kingdom, Denmark and Sweden [1]. It is also a country in which **landscape is increasingly seen as cultural heritage**, but there is still work to be done. Even though there are designations such as the recognition of the Cultural Landscapes of Spain or the registers of cultural landscapes in some autonomous regions, they do not have legal status.

As a result of the scenario set out in this state of play, the stakeholders ignored in the political debate in this regard, including ecologist groups, residents, farmers and land owners, constitute a growing social **rejection scenario** in the Spanish regions where the plan is to install or increase those projects.

Those groups consider all those energy production facilities to be exogenous, as they increase the social and salary gap between large and small land owners, and do not allow for citizen **participation** information measures, or the economic aspects that involve and flow back into the affected populations. In the last five years, headlines have been common in the press and hundreds of social protest **citizen platforms** have been set up in this regard [22–24]. That all contributes to a situation that jeopardises the **necessary energy transition** towards energy from renewable sources.

Given the lack of transparency of some communities regarding the territorial data of the projects in the pipeline, many of these citizen **platforms** or associations are progressing in the data gathering, and some even in their cartography or in simulating the changes to the landscape caused by those megaprojects. With developments in the Autonomous Region of Madrid, Aragón, Andalusia, Galicia, Autonomous Region of Valencia, and Catalonia, ALIENTE, the State Energy and Territory Alliance, has published the main ones on its website [54]. Particularly noteworthy is the case of the Valle Natural Río Grande Association that – after reviewing the rulings published in the Spanish Official Gazette (BOE) and of the Autonomous Government of Andalusia (BOJA) – has prepared a mapping visor that now progressively and collectively covers the whole of the Autonomous Region of Andalusia [25].

In view of the alarming situation described above, the aim of this research is to propose a **zoning method** for the installation of large

[2] These targets have been revised in the PNIEC update that will be sent to the European Commission. The new targets are 62 GW for wind and 78 GW for PV.

[3] Layers of zones not compatible with the generation of different types of energy are established; information is available on the dimensions and constraints of the envisaged projects and the approximate location of the active projects, and technical information can be downloaded on each as a report.

[4] Catalonia is currently working on drafting a Renewal Energies Sectoral Territorial Plan. As of May 2023, it was at the public consultation stage and will, probably, be the first spatial planning instrument in the field in Spain [52].

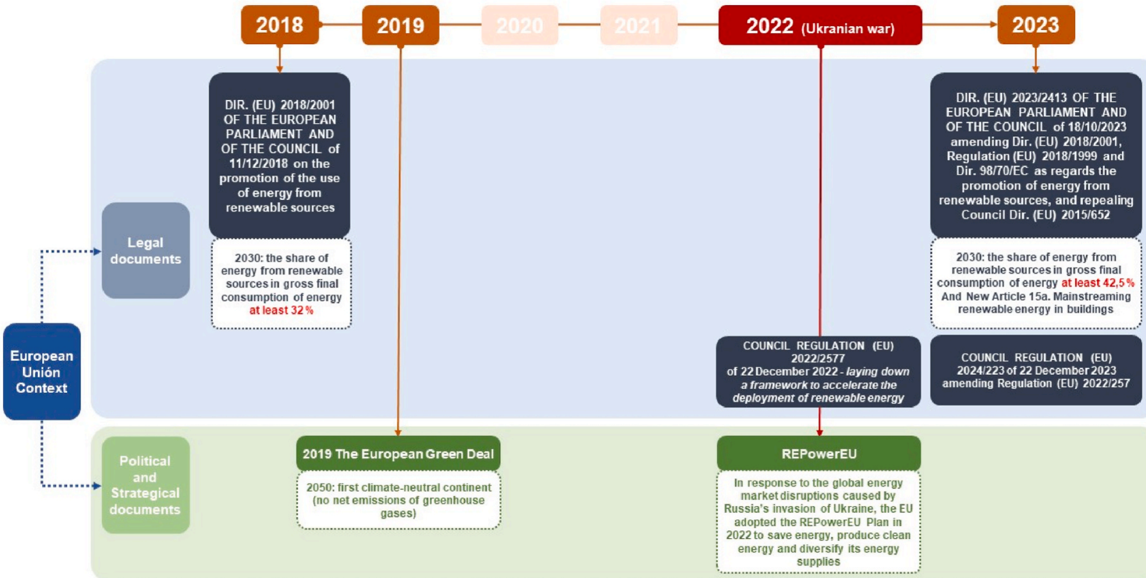

Fig. 1. European Union Context for renewable energy. Source: Authors (2024).

photovoltaic plants which implements the use of **socio-economic**, **environmental** and **cultural criteria**, as well as a greater **specificity** for each territory. The goal is to use this zoning method as a tool to help technicians in small communities who are currently overwhelmed by the number of projects proposed in their areas by large energy companies. As a test case, the situation in the southernmost region of **Spain**, **Andalusia**, with undoubted photovoltaic potential due to its high levels of solar radiation, will be analysed. Within this region, the landscape of the **Jimena** Depression is chosen as a representative area for the extreme accumulation of PV projects that, without the necessary zoning tools, will drastically change the **land use** and **economy** of the entire region.

Thus, this paper analyses the shortcomings of the traditional application of the **AHP methodology** to this zoning in other **related works** (section 2), establishes a set of **restrictive** and **analytical criteria** (section 3) based on the contextualization of the **case study** (section 4), and **results** in the **mapping** of exclusion areas and zoning (sections 5.1 and 5.2). This leads to the **discussion** and **conclusions** (sections 5.3 and 6), which focus on the occupation of inappropriate and prohibited areas, the high concentration of photovoltaic plants in certain zones, the changes in land use and the lack of links between the predominant socio-economic activity and the new energy use.

2. Literature review

Multi-criteria methodologies and **Geographic Information Systems** have been widely used to assess all the different parameters that come into play for the implementation of photovoltaic energy plants. The main advantage of using **Geographic Information Systems** for this task is that they generate a mapping result by allowing the assessment of multiple attributes. That means that the analysis of each pixel can be viewed jointly and superimposed on other mapping, which allows conflictive areas and overlaps to be detected. Furthermore, they provide a database to support the decision making.

In turn, the **multicriteria methodology** chosen to conduct this research is the **Analytic Hierarchy Process** or **Saaty Method** (hereinafter **AHP**). This is one of the most widely used tools in decision-making with multiple criteria [26], which also has a proven track record in international research into environmental zoning of wind and photovoltaic power at municipal, regional and even national level [27–33].

Multicriteria methodology and AHP allow to jointly analyse several parameters and to determine the weights of each parameter (or criteria) using a pairwise comparison matrix. For instance, the photovoltaic site suitability in **Oman** has been assessed using GIS and multicriteria evaluation with the tool Fuzzy Logic Ordered Weight Module [34]. They have proposed to use technical criteria (solar radiation and accessibility land use), economical (grid proximity, land slope and load poles) and environmental (sensitive areas, hydrographic line, sand/dust risk). With their proposed methodology, only a small area of the country has a high suitability level while very large areas have moderate suitability.

The spatial suitability for large solar systems in **Tanzania** (country level) has been analysed using GIS and MCDM using AHP [35]. They have identified six exclusion criteria: protected areas, land cover, topography, water bodies, urban expansion, and low solar radiation; and seven ranking criteria: amount of solar radiation received, water availability, proximity to roads, proximity to utility grid, proximity to cities with over 250.000 inhabitants and with 100.000–250.000 inhabitants, and proximity to mines. They have evaluated two technologies: CSP power plants and PV plants. They have obtained the km^2 suitable for each technology.

A map of the most suitable locations for photovoltaic systems in **Malatya** (province of **Turkey**) has been built using AHP and GIS [36]. They have used the following factors: solar energy potential, roads, energy transmission lines, transformer centres, slope, aspect, location of dams and rivers, natural gas pipelines, fault lines, land cover, and residential areas. They have found 34 suitable areas that could be reduced when the conditions of the existing lands are considered. They have proposed as a positive criteria the areas that are close to the solar PV power plants that were being built because they have considered this fact as evidence that these areas are quite suitable. Similar methodology has also used for **Çanakkale** province, also in **Turkey** [37]. After using exclusion criteria, they have identified the best locations for installing PV plants using several location, climatic, and orography criteria and for these locations they have estimated the potential power capacity and payback period and selected those with lower payback period.

Noorollahi Y. et al. [38] have studied the photovoltaic solar power plant's potential in **Khuzestan** province of **Iran**, using Fuzzy-Boolean logic and Analytical Hierarchy Process (AHP) decision analysis based on GIS. The main criteria for selecting optimal locations include climate, economics, orography and land use. They have concluded that only 0.12% of the total area of the province has excellent suitability to install a photovoltaic system.

AHP and Multi-Criteria Decision Analysis (MCDA) in a GIS environment have been used to select optimal sites for solar energy plants in **Bangladesh** [39]. They have used the following factors: solar radiation, air temperature, slope, orientation, land aspect, distance from urban areas, distance from roads, and distance from power line. They have concluded that in Bangladesh about 19 % of the surface is "very high" suitable for installing solar energy plants, being this area dispersed throughout the country.

However, all the studied references are limited to **environmental zoning**. They can be seen not to consider those **social** and **intangible** attributes, such as **landscape perception** or **heritage issues** as this contribution does. Furthermore, they seem to give preference to terrain and climate criteria (they are weighted as the most influential factors) that ensure greater productivity of the installation, over environmental or location ones. The **discussion** addressed in this paper is the need to respond **holistically** to the impact that the concentration of photovoltaic plants currently generates in rural environments, by incorporating and prioritising the qualitative analysis of socioeconomic criteria. Therefore, contribution of this article is the use of this methodology with new priorities: the determinants for this study will be legal, location, environmental and terrain,[5] in that order of priority. The underlying premise is that, even though **environmental criteria** – such as the type of existing crops – will not influence the performance of the plant, they will affect the **local economy** radically. The same is true of the **location** criteria, based on the distances to the historical sites or the transformation centres, which will guarantee logical and respectful **urban**, **landscape** and **energy** planning measures. In contrast, the **terrain** criteria – orientation and slopes – will focus directly on locating the optimal areas to **lower the investment** required due to fewer earth movements and **to increase the production** of the plant by following the most efficient orientation. The **legal criteria** mean restrictions and will therefore not form part of the hierarchy.

3. Objectives and methodology

Accordingly, the main objective of this research has been to define and test a **classification methodology of the ideal territorial areas** to locate photovoltaic plant projects in rural environments. Heeding the environmental and cumulative impact of these power facilities, the methodology has used scientific criteria that consider social, territorial and environmental characteristics of the case study used for the testing, along with incorporating its energy demand and its potential to implement self-consumption systems by means of the saturation state of its grid points.

Therefore, the research has led to the development of a **zoning map** that allows the territory to be classified into areas of greater and lesser **cultural, landscape and environmental sensitivity** to the installation of solar farms. The idea is for that zoning, transferred to **planning tools**, to allow the saturation of the grid capacity to be avoided and to make a more sustainable implementation model possible, which prioritises self-consumption and local energy communities, thus avoiding the mortgaging of the future development of their economic activities.

The aim is also to facilitate and foster the **active participation of the inhabitants** in the development of photovoltaic plant projects in the territories in question and to provide objective data on the possible impact of renewables projects on their values. This active involvement of the locals will help to introduce the matter of protecting the landscape, taken as a common construct based on the perception and activity of those living in a territory. In other words, to be useful for **energy companies** and investors alike, and for the municipalities and the technicians involved in the **processing** of photovoltaic energy projects.

The work process is divided into five successive phases, which are shown in Fig. 2:

- The study area is established in the first phase**.** This phase consists of justifying the work zone and establishing its constraints, in accordance with landscape, territorial and administrative criteria.
- The multicriteria analysis methodology known as Analytic Hierarchy Process (hereinafter AHP) is applied using Geographic Information Systems in the following phases. The **second** phase identifies the territorial specific characteristics of the area according to two groups, restrictive criteria and analysis criteria. The **third** establishes an initial type of weighting or gradient for those attributes. These characteristics, that have already been weighted to the territory using a general constraint or value percentage among the different analysis criteria groups, are applied in the **fourth** phase. The result is the geographic projection of a scale of values that allows each area of the territory studied to be classified according to its suitability as a site for the installation of photovoltaic plants.
- Finally, in the **fifth** phase, the location and surface area of the photovoltaic plant projects existing in the work zone are superimposed on that result, and compared to the energy consumption data for those municipalities and the saturation state of their grid points. The aim of the latter is to show how this research can become a tool for the local councils of small municipalities that are currently overwhelmed with proposals from large companies given the lack of planning regulations as regards renewable energies at state and regional level. Using the tool would allow them to foresee how the territory would be affected if permission were given to construct the projects in the pipeline.

The **restricted areas** for the installation of power plants will be those where it is prohibited by current legislation and whose surface area is outside the assessment areas. Namely, highways and roads and their immediate environs, areas protected for their environmental values such as publicly-owned woodland or natural areas, river basins or aquifers and their respective limits of the hydraulic public domain, and sites of cultural interest, along with their established protected environments. Those areas can be grouped into three families following the themes of the source of the geographical data used for all of them, the Benchmark Spatial Structure in Andalusia (hereinafter DERA) attached to the Andalusian Institute of Statistics and Cartography. Table 1 sets out the differentiated layers that represent those areas, the legislation that establishes the restriction criterion and the measurement of the extra buffer perimeter, as applicable. The three **data** families and its layers are: **transport networks** (roads and drove-roads), **natural and cultural heritage** (public forests, biosphere reserves, special protection areas, Natura 2000 Network, protected natural areas and sites of cultural interest) and **hydrography** (rivers and aquifers).

On the other hand, the **analysed areas** will be those likely to receive new photovoltaic plants. Therefore, those areas are assessed according to their greater or lesser suitability for the installation of power plants. Therefore, a more or less appropriate zone value gradient is applied by means of reclassification geoprocessing. The criteria to assess them, i.e., the analysis inputs, could be quantitative or qualitative. While the slopes, orientations and distances to transformation centres from a certain point will be quantitative values as they will affect the higher or lower performance of the power plants; their distance to the population centres or the changes to land uses will be qualitative values as they will imply a greater or lesser socioeconomic impact on the inhabitants and on their perception and participation regarding the landscape. Table 2 classifies the type of criteria used for these analysed areas and breaks down the selected layers for their graphic representation and the gradients applied to each. It also incorporates the weighting applied to each group and layer as established for the AHP methodology. The DERA is again the source of the data, even though the land uses come from the state-owned Agricultural Plots Geographic Information System (hereinafter SIGPAC), under the Ministry of Agriculture, Fisheries and Food.

[5] Climate criteria such as irradiance and temperatures have not been considered in this specific case, as there is uniformity throughout the study area according to Spanish Meteorological Office data.

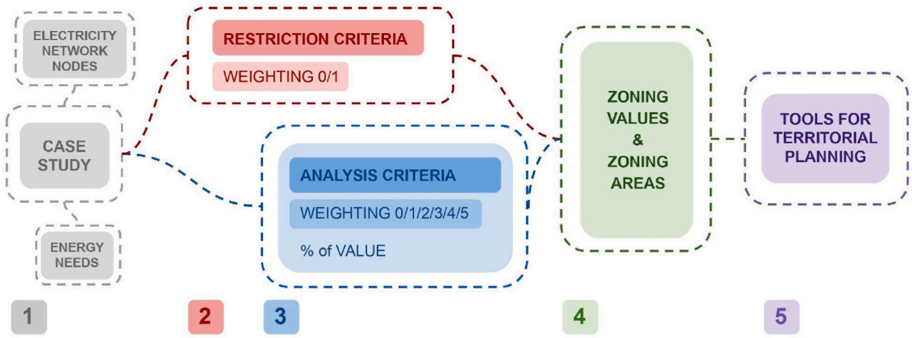

Fig. 2. Methodological scheme. Source: Authors (2023).

Table 1
Criteria, layers and buffer zones of restriction areas. Source: Authors (2023).

Restriction layers				
Group	Criteria	Layer		Buffer zone (m.)
Transport networks	Ley 8/2001, de 12 de julio, de Carreteras de Andalucía	R1	Roads	High-capacity roads 100 Remaining roads 50
	Ley 3/1995, de 23 de marzo, de Vías Pecuarias	R2	Drove-roads	*Cañadas* 75 *Cordeles* 37.5 *Veredas* 20
Natural and cultural heritage	Ley 43/2003, de 21 de noviembre, de Montes	R3	Public forests	–
	Ley 42/2007, de 13 de diciembre, del Patrimonio Natural y de la Biodiversidad	R4	Biosphere Reserves	–
	Decreto 493/2012, de 25 de septiembre, por el que se	R5	Special protection areas	–
	declaran determinados lugares de importancia comunitaria como Zonas Especiales de Conservación de la Red Ecológica Europea Natura 2000 en la Comunidad Autónoma de Andalucía	R6	Natura 2000 Network	–
	Ley 2/1989, de 18 de julio, por la que se aprueba el Inventario de Espacios Naturales Protegidos de Andalucía y se establecen medidas adicionales para su protección	R7	Protected Natural Areas	–
	Ley 14/2007, de 26 de noviembre, del Patrimonio Histórico de Andalucía	R8	Sites of Cultural Interest	Declared surroundings of the Site
Hydrography	Real Decreto Legislativo 1/2001, de 20 de julio, por el que se aprueba el texto refundido de la Ley de Aguas	R9 R10	Rivers Aquifers	105 –

In these areas two **data** families are applied: **socio-economic** and **landscape** data and **orographic** data. The first group is based on land use, population centres distance, power grid distance and plot of land size. The second one is based on slopes and orientation layers.

This **analytic hierarchy process** is based on a **ranking by criteria pairs** that start from a square matrix in which the number of rows and columns is defined by the number of parameters to be weighted. Following the mathematical procedure established by the **AHP** [40] and the priority order decided for this specific case, the percentage hierarchy will distribute 80% on the socioeconomic and landscape factors, 40% distributed for the environment and a further 40% for the location, while the terrain accounts for 20%. Thus, the resulting paired comparison matrix is expressed in Table 3 and the matrix of ranking with auxiliary vector value appears in Table 4.

4. The case study: the Jimena Depression landscape area in Spain

The Jimena Depression Landscape Area located in the **Autonomous Community of Andalusia** was selected as the test case for this methodology. Andalusia is located in the south of the Iberian Peninsula, this region comes under one of the most significant pressures from energy companies and investors in Spain, given its geography and the presence of resources; photovoltaic energy production increased by 35% between 2021 and 2022, according to the data of the Andalusian Energy Infrastructures Report [41]. Fig. 3 shows the active projects, which include 5 plants with over 50 MW of installed capacity and 60 with power of between 10 and 50 MW.

Even though it is not possible to know the percentage of growth of **rural land occupancy** by the power plants, as the regional government does not provide visors for the projects in the pipeline, the headlines show a sharp increase in the presence of macro-plants in the region in 2023 [42]. In that regard, the Autonomous Region does not currently have any guide for the zoning, mapping of the surfaces of the existing projects or those in the pipeline, or spatial planning linked to the facilities with capacity under 50 MW.[6] It should also be noted that, in April 2022, 93 local councils submitted a legislative bill to the Andalusian Parliament, to defend the protected areas and calling for renewable energy planning, and which was rejected in February 2023 [43].

However, public information can be obtained on the projects in the pipeline that are the remit of the General **Administration of the State,** i.e., those with over 50 MW of installed capacity. In that regard, the Industry and Energy Division of the Sub-Delegation of the Government in Seville has prepared a map of the processing and authorisation of renewable generation facilities in the autonomous region [59]. Based on that map, Fig. 4 shows that 116 **photovoltaic macro-plant projects**

[6] As has been set out in the State of Play, the public information advances in that regard, Map and Guide, were withdrawn a month after their publication in February 2021.

Table 2
Layers, criteria and gradients applied in the analysis areas, W = weight; QL = qualitative criteria; QN = quantitative criteria, Gradients, 5 = optimal area; 0 = restricted area. Source: Authors (2023).

Analysis layers							
Group + Weight		Criteria		Layer + Weight		Gradient	
Socio-economic and Landscape W = 0,80	**Environmental** W = 0,40	QL	Considers the economic and environmental impact that the plant could generate by changing agricultural land uses	A11 W = 0,40	Land use	5	Grassland Shrub pasture Unproductive
						4	Wooded pasture
						3	Arable land Fruits & Nuts Fruit trees
						2	Citrus Citrus-fruit trees Greenhouses
						1	Vineyard - Olive groves Olive grove Vineyard Vineyard - Fruit trees
						0	Forestry
	Location W = 0,40	QL	Considers the possibility of the urban growth in the face of a reduction in the number of transport routes	A14 W = 0,13	Population centres distance	2	1–5 km
						1	>5 km
						0	<1 km
		QN	Considers simplification of layouts and reduction of transport losses	A15 W = 0,13	Power grid distance	4	<1 km
						3	1–2 km
						2	2–3 km
						1	3–5 km
						0	>5 km
		QN	Considers more useable areas based on average plot size (61.430,15m^2)	A16 W = 0,13	Plot of land	2	>60.000 m^2
						1	<60.000 m^2
Orographic W = 0,20		QN	Considers the damage that could be caused by soil movement and accessibility issues	A12 W = 0,10	Slopes	5	<3 %
						4	10-3 %
						3	10–20 %
						2	20–25 %
						1	25–30 %
						0	>30 %
		QN	Considers solar radiation values depending on orientation	A13 W = 0,10	Orientation	5	South
						4	South-east
						3	South-west
						2	East
						1	West North-east North-west
						0	North

Table 3
Criteria paired comparison matrix. Source: Authors (2023).

Criteria	Environmental	Terrain	Location
Environmental	1.00	2.00	1.00
Terrain	0.50	1.00	0.50
Location	1.00	2.00	1.00
Addition	2.50	5	2.50

Table 4
Criteria Paired Comparison Matrix with auxiliary vector value. Source: Authors (2023).

Criteria	Environmental	Terrain	Location	Wj
Environmental	0.40	0.40	0.40	0.40
Terrain	0.20	0.20	0.20	0.20
Location	0.40	0.40	0.40	0.40

have been filed so far, 55 of which are still pending processing (blue dots on the Figure) and 61 are being processed. As regards the latter, the perimeters can be established using the projects or impact statements for the 6 with administrative authorisation for construction and declaration of public interest (in blue on the Figure), the 8 with favourable Environmental Impact Statements (in green on the Figure) and the 34 with prior administrative authorisation (in yellow on the Figure). However, the mapping visor only locates them, without including their constraints or morphology, and preventing their georeferenced extension from being known. Nonetheless, the presence of areas of great concentration can be seen in the eight provinces. Other relevant information that is included, in addition to a provincial boundary layer, the demarcation of the **Territorial Units** included in the Spatial **Plan of Andalusia.**[7]

As the geographer M. J. Prados already forecast over a decade ago, large-scale solar energy production has become the largest *invader* of landscapes in this region; however, the different **Andalusian Energy Plans** (1995–200, 2003–2006, 2007–2013) did not fully recognise the territorial impacts of the large solar parks [57]. That is also the case of the subsequent Andalusian **Energy Strategies** (2015–2020 and 2021–2030). Those documents only mention environmental aspects,

[7] In accordance with its current Spatial Plan, Andalusia is administratively divided into 8 provinces and 785 municipalities. Those municipalities are in turn grouped into 34 Territorial Units that reflect their "functional and physical uniformity, as well as having common opportunities and problems in areas related to the economic use of the territory and the management of their heritage resources" (Consejería de Obras Públicas y [53]:32). These Units are, therefore, the benchmark to determine the areas of the subregional planning spheres, known as Subregional Plans.

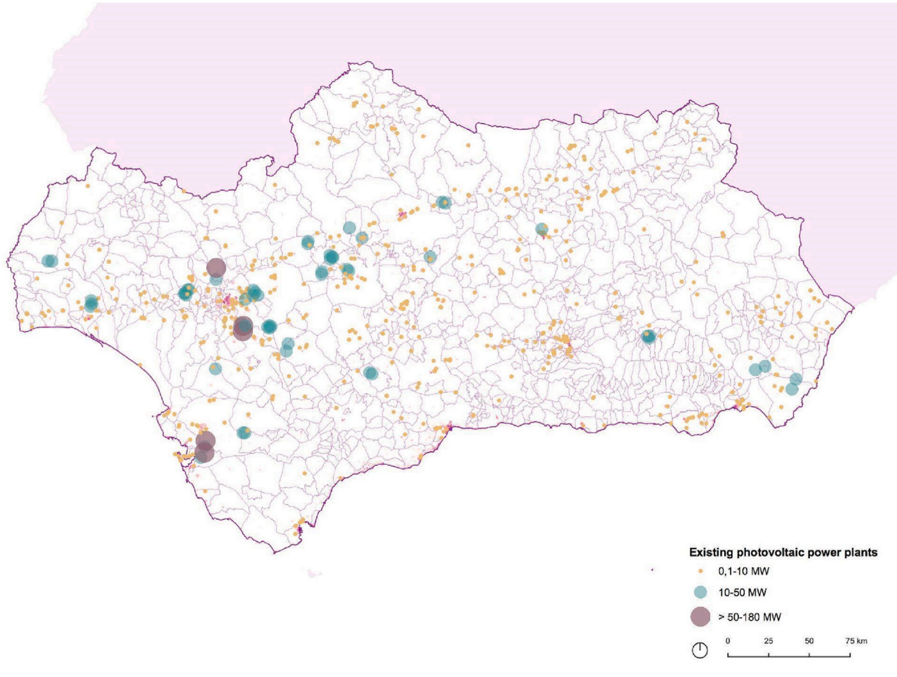

Fig. 3. Location of active photovoltaic plants in Andalusia. Source: Authors (2023) based on Benchmark Spatial Data Infrastructure in Andalusia.

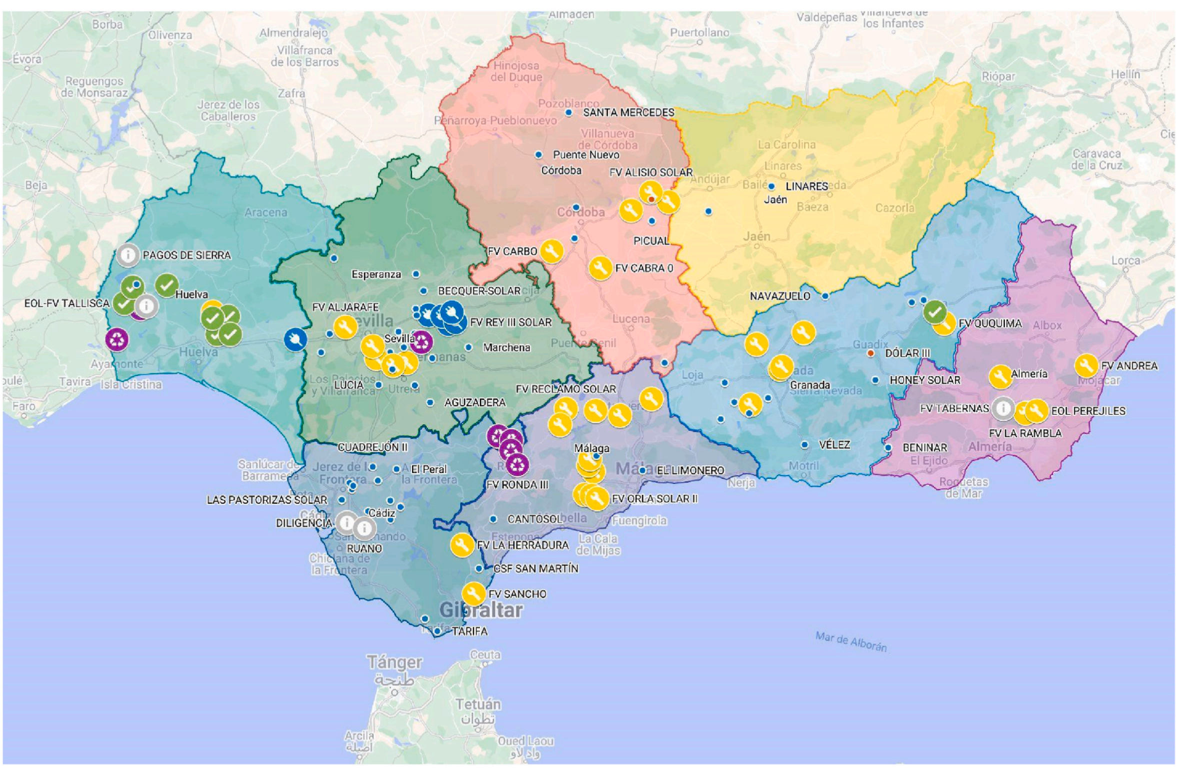

Fig. 4. Approximate location of projects in the pipeline for state-owned photovoltaic plants in Andalusia (>50 MW). Source: Industry and Energy Area of the Government Sub-delegation in Seville (2023) retrieved from: https://www.google.com/maps/d/u/0/viewer?mid=1_BgYOb7yda-vTpaKPBxHPK98G2X4tCE&ll=37.25952672937669%2C-4.747560231445318&z=8.

mainly based on risks for birdlife, and overlook social & cultural, landscape and economic factors. Their closest link to the territorial aspects is based on referencing the Spatial Plan of Andalusia (2006) as an instrument for their planning, even though that document published in 2006 did not establish protections in that regard and is obsolete given the current expansion of the sector.

This **growth** in energy farms in Andalusia – **lacking standardisation** at territorial levels and **unbalanced** in its concentration – affects many economic sectors, including agriculture, livestock farming and tourism, as well as the environment. In tandem, it jeopardises the progress made in recent decades for the **enhancement and conservation of the landscape,**[8] taken to be a collective cultural construct in constant evolution and where citizen participation is essential in its decision making.

The scope chosen to analyse and check the proposed methodology is the geographical area made up by **four Andalusian municipalities**: Jimena de la Frontera, San Martín del Tesorillo, Casares and Gaucín. The four are part of the **Jimena Depression,**[9] as established by the Map of the Landscapes of Andalusia (2003). This **landscape area** consists of coastal rural landscape that, as can be seen in Fig. 5, is surrounded by highland ranges to the north, cliff-lined coast to the east and a coast with coastal mountains to the west.

Given its appropriate **geographical characteristics**, orientation and slopes, this countryside area is under greater pressure from energy companies and investors, making it an area at great risk of being **impacted** by the **cumulation of photovoltaic plants** with less than 50 MW of power, in other words, those that are the remit of the Autonomous Region. Specifically, the area currently has, at least, **21** photovoltaic plants in the pipeline according to the data provided by the Environmental Department of Casares Local Council.

This rural landscape, located between Cadiz and Malaga, is a Mediterranean **coastal zone** characterised by hills and ridges crossed by the valleys and terraces of the lower sections of the Genal and Guadiaro rivers. According to the Autonomous Government of Andalusia's Regional Ministry of Agriculture, Fisheries and Sustainable Development, much of its surface is wild, while it also has areas used for rainfed crops and irrigated fruit trees [55]. It also has a specific climate and geological formation, thanks to which it is home to a remarkable variety of fauna and flora; as well as being in a strategic geographical location in the south of the Iberian Peninsula and close to the Strait of Gibraltar and neighbouring Africa; that meant the landscape played a defensive role in the past and is dotted with fortifications dating back to the Al-Andalus period [44]. It is also a crossing point for migrating species, and is of particularly interest for watching the birds that migrate in summer to the Mediterranean forests to nest by the rivers, in the forests or on the crags. Therefore, the study of this area reveals the potential impacts on a mainly untouched territory, with important **landscape, historical** and **environmental values**.

Apart from these riches, this type of coastal rural landscape is only found in Andalusia along the Atlantic coast, the western coastline of Huelva, and in the Mediterranean, El Poniente, Campos de Níjar and Almanzora in Almeria. However, while the former focuses on growing irrigated fruit trees and has large areas of pine trees, the latter prioritises greenhouse crops. Nevertheless, the **Jimena Depression** is the only **coastal agricultural stronghold** in the Strait of Gibraltar, occupied by a **continuous built environment**. This restricted area still has forest ground cover of scrub and grassland, some flood plains and areas of irrigated fruit trees and woody crops, located along the Guadiaro **and Genal watercourses** [45]. The final section of the agricultural corridors that run down both valleys, **important enclaves** currently at risk, are the key feature of this **agricultural landscape** with centuries of history, as shown in Fig. 6.

As regards the **municipalities** to be found there, Jimena de la Frontera and San Martín del Tesorillo form part of the far eastern part of the province of Cadiz and, within that, the Campo de Gibraltar administrative district. They have 6681 and 2797 inhabitants respectively. In turn, Casares, with 7700 inhabitants, and Gaucín, with 1,608[10], are on the south-western edge of the province of Malaga, in the Costa del Sol administrative district. Despite its small size, this last municipality is exceptionally located as it is the nexus between both administrative districts and the Serranía de Ronda, and is a fundamental point in interprovincial communications.

5. Results and discussion

5.1. Mapping characterisation of the excluded areas

A **final layer of restricted areas** is thus obtained and is the result of the sum of R1 to R10 vector layers, including the established buffer zones, after submitting them to Reclass geoprocessing as raster layers. The sum is defined by a system of binary values: value "1″ determines those pixels that belong to zones where photovoltaic facilities can be installed, while value "0″ represents the areas where that is forbidden. The **restriction mapping** is shown below.

The **transport network** and its buffer zones, Fig. 7, account for just **7.4%** of the restricted surface. Special mention only therefore needs to be made of the A-7 dual-carriageway and the AP-7 Mediterranean Motorway through the Municipality of Casares, while the other highways running north-south through the landscape are local and regional roads connecting population centres. However, there is a dense register of different types drove-roads, classified in descending hierarchical order as *cañadas, cordeles, veredas* and *coladas* in Spanish, that structure and connect this agricultural territory.

On the other hand, the **hydrology,** Fig. 7, accounts for **22%** of the excluded areas. The main river basins from east to west are those of the Genal, the Guadiaro and Hozgarganta, even though there are also many streams from the nearby mountains. Furthermore, these converge with detritic aquifers of the Campo de Gibraltar and Marbella river basin districts.

As regards the **natural** and **cultural heritage**, Fig. 8, which accounts for nearly **60%** of the restricted area, particularly noteworthy are: over 22 areas of publicly-owned woodland in the municipalities of Casares, Gaucín and Jimena de la Frontera, with the latter being the most rugged; the area belonging to the International Biosphere Reserve of the Mediterranean established by UNESCO in 2006, which stretches to the North of Morocco; the Special Protection Areas of the Guadiaro and Genal River Valleys and Groves, the Aljibe, Bermeja and Crestellina mountain ranges, all of which belong to the Natura 2000 network and Los Alcornocales Natural Park, and the Protected Natural Landscapes of the Sierra Crestellina and Los Reales de Sierra Bermeja mountain ranges. As far as the Sites of Cultural Interest are concerned, special mention should be made of the rocky shelters and caves in Jimena de la Frontera, fortified architecture such as ramparts, towers and castles throughout the area, the Historical Sites of Casares and Jimena, and the Sima de las Hediondas caves and the Archaeological Area of the Roman city of Lacipo, both in Casares.

The **result** is Fig. 9, a surface area of 14,755 Ha where plants could be installed and which accounts for 25% for the whole area studied. In other words, 75% of the territory has been excluded, fundamentally due to the cultural and environmental value of this landscape that, as has been stressed, results in large expanses of protected areas and river basins where it is not possible to install the plants or the ensuing industrialisation of that land. Thus, the municipal district with the largest percentage of restricted areas is Jimena de la Frontera (87%); followed by Gaucín (82%), Casares (60%), and, finally, San Martín del Tesorillo (34%).

[8] From the Map of the Landscapes of Andalusia that shows its biophysical values [45], to the Landscape Strategy [56] or the Provincial Catalogues that ends with the classification of its cultural values in the first Register of Landscapes of Cultural Interest of Andalusia [44].

[9] The landscape of the Jimena Depression also partially includes the municipalities of San Roque, Manilva and Estepona. However, the coastal and urban areas occupy a large part of the surface area while the rural zone is very limited. Therefore, there is a lower risk of occupation by energy companies and investors, and which have not been taken into account in this study.

[10] The 2022 census data, according to the Andalusian Institute of Statistics and Cartography.

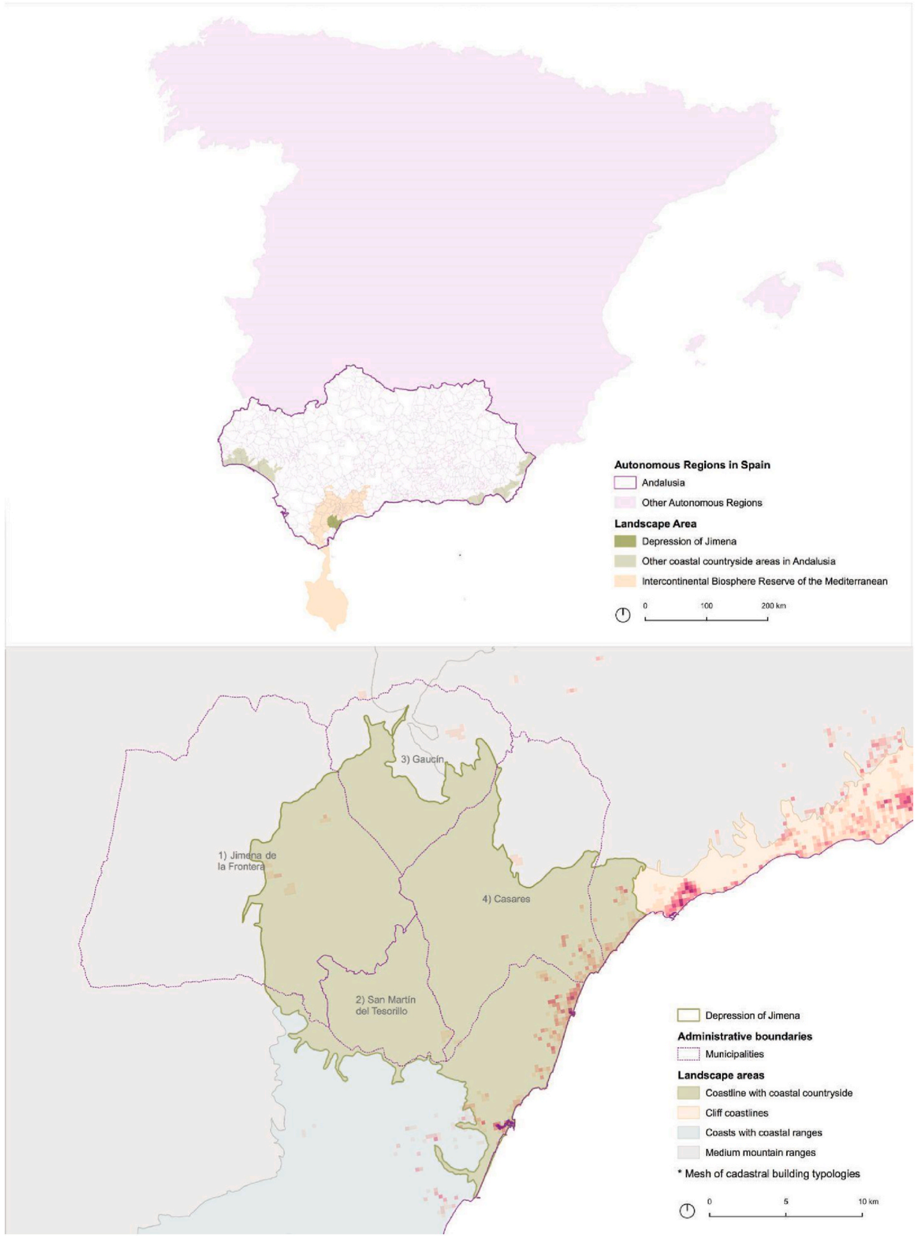

Fig. 5. Location of the case study area. Source: Authors (2023).

5.2. *Mapping characterisation of the analysed areas*

In tandem, the **final layer of analysed surfaces** is obtained from the sum of the A11 to A16 vector layers, after classifying them according to the established values and subsequently submitting them to Reclass geoprocessing as raster layers. In this case, the sum contains a system of values that range from "0″, restricted areas, to "1″, less appropriate areas, "2″, more appropriate areas, and "3″, optimal areas. The analysed mapping includes, in hierarchical order, those relating to environmental, terrain, location and size of plot.

Among the non-urban **land uses** analysed, Fig. 10, in relation to the zoning described above, optimal areas have been established as those where there is a predominance of pastureland, shrub pasture and unproductive uses of the land; those occupied by wooded pasture as highly appropriate; arable land and growing of fruit and nuts as appropriate; the land used for citrus fruit and fruit trees as rather inappropriate; finally, the land occupied by olive groves, vineyards, fruits and greenhouses as inappropriate. This decision seeks to protect the main economic and productive systems of the location.

As regards location, Fig. 11, the **distance to population centres of** over 5 km, considered the least appropriate, coincides with river basin land that is already excluded. Conversely, the presence **of connection points to the electricity grids** does steer the location of the plants towards the municipality of Casares, where the three electricity substations for La Jordana, Casares and Los Llanos are located, which is at odds with the presence of certain Sites of Cultural Interest. Lastly, plots over 60,000 m^2 predominate, even though there are fewer in the areas where the substations are located.

Finally, as regards **terrain**, Fig. 12, even though the less steep areas coincide with the excluded watercourses, the rest of the viable area has gentle slopes that do not exceed 20% and that, therefore, allow the plants to operate. However, **orientation** does further limit the areas, with those facing south, south-east and south-west considered to be the most appropriate.

The **result** is Fig. 13, where the least favourable, the adequate and the optimal are shown using a gradient of colours, and according to all

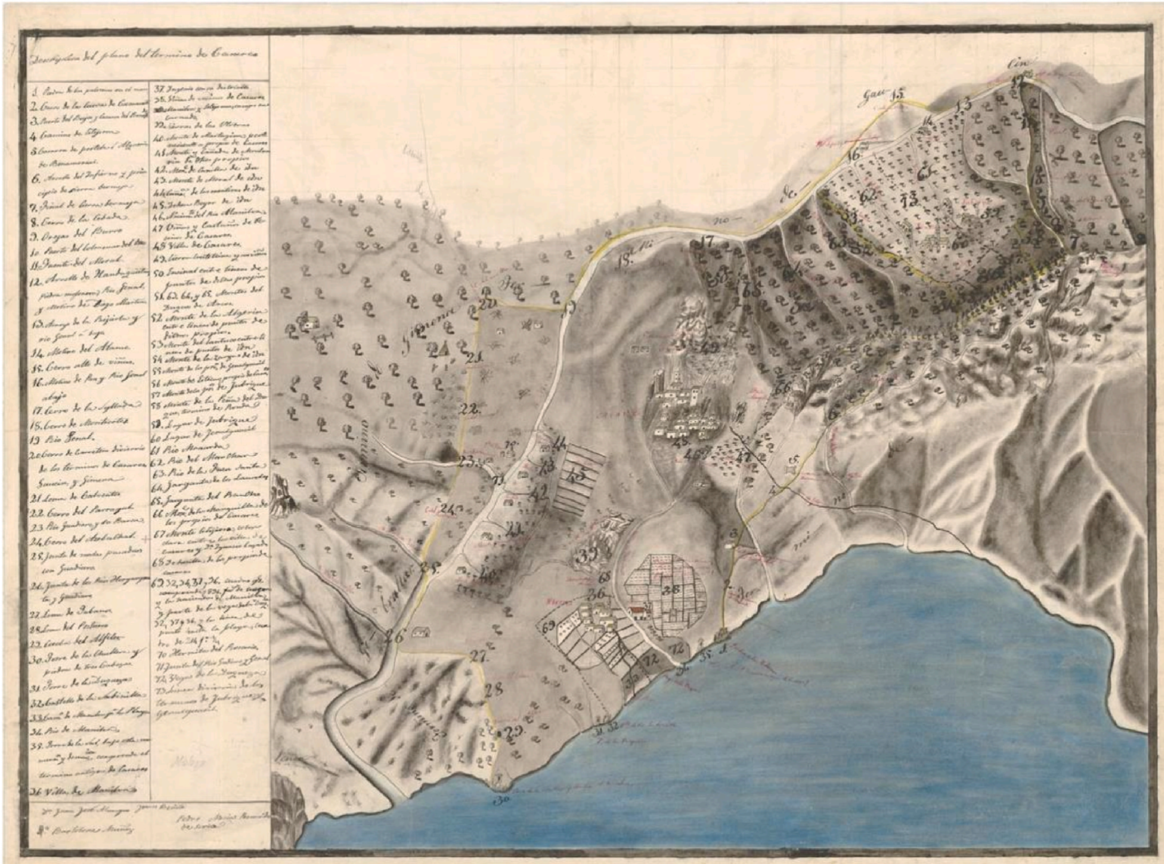

Fig. 6. Almagro, J. J., Muñoz, B., Benítez, J. and Benavide de Soria, P. M. Map of the Municipal District of Casares in the 18th century. The map shows the gallery forest around the river Genal, while the slopes are covered in tree crops, particularly chestnut trees. Source: Casares Town Hall, retrieved from: https://www.turismocasares.com/mirador-de-casares/.

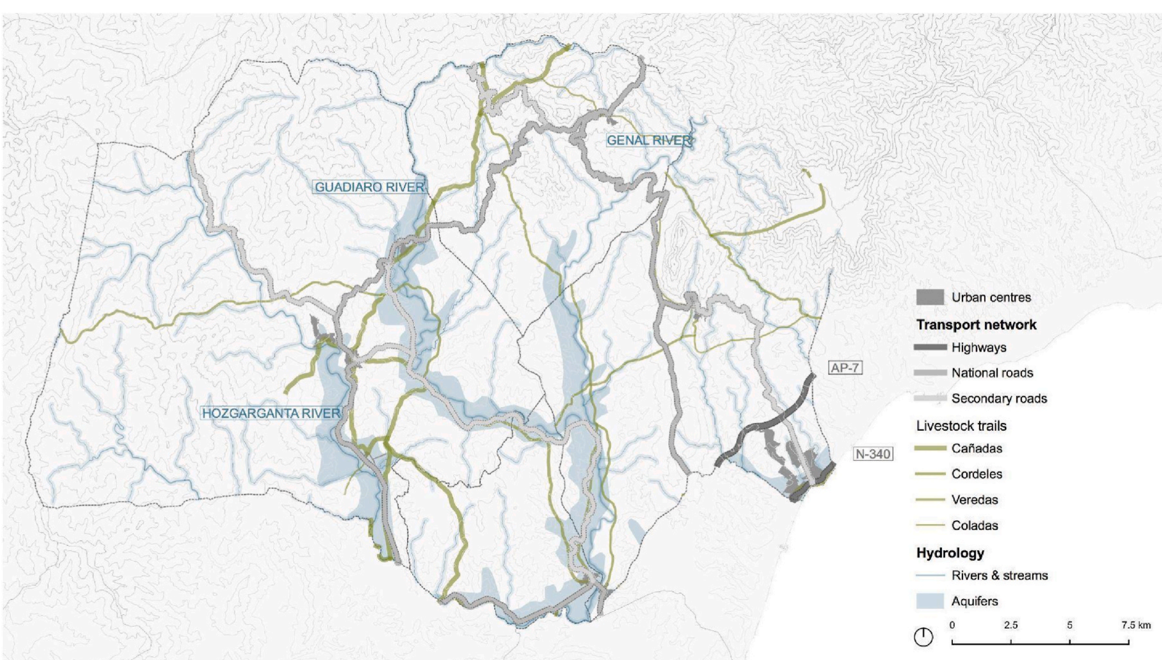

Fig. 7. Mapping restriction layers: transport network & hydrology. Source: Authors (2023).

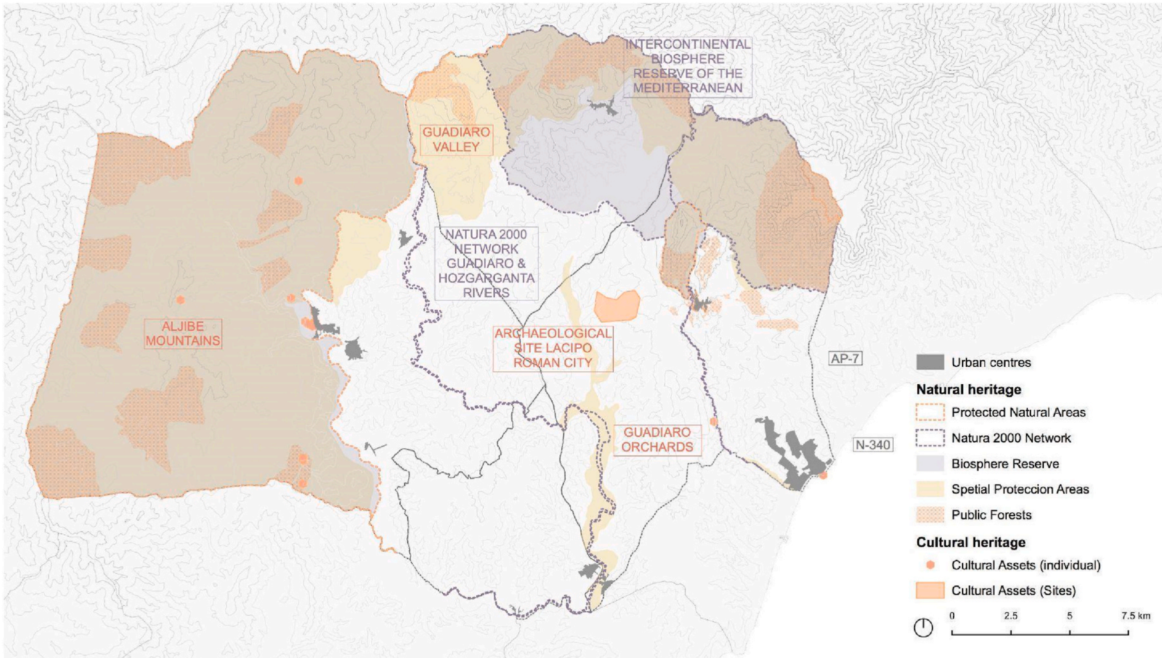

Fig. 8. Mapping restriction layers: natural and cultural heritage. Source: Authors (2023).

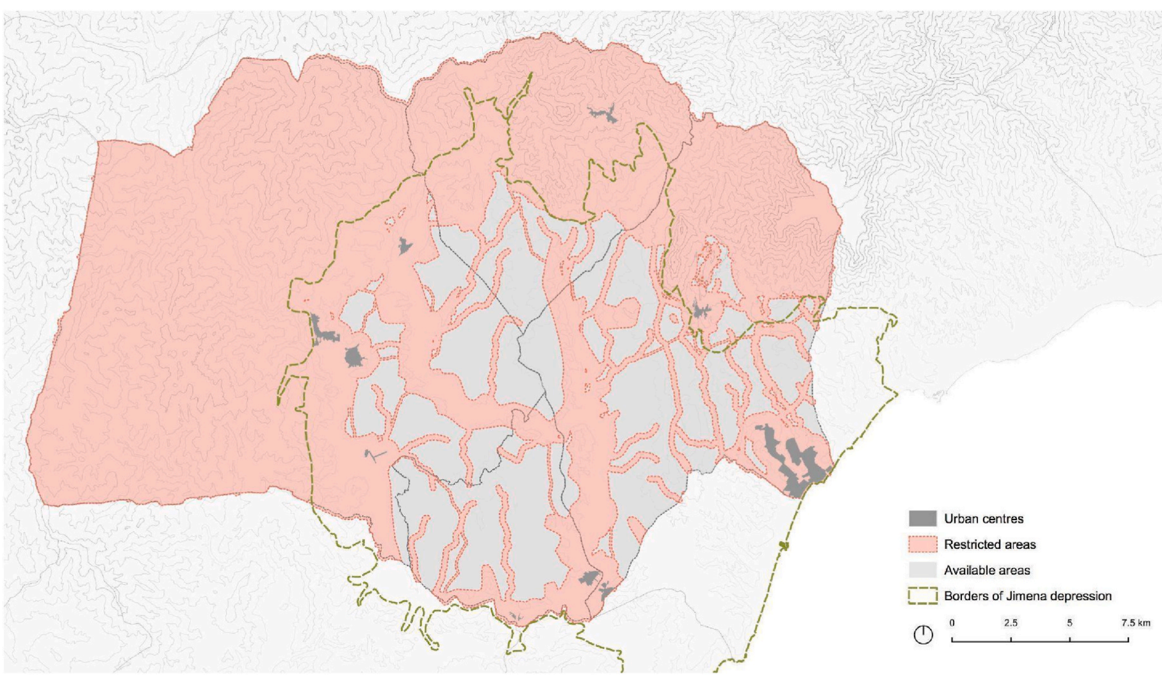

Fig. 9. Final mapping: restricted areas. Source: Authors (2023).

the parameters analysed and the hierarchy established for the different groups. Thus, the surface areas considered to be optimal account for 2% (924 Ha) of the total of the four municipalities and are located in the municipality of Casares, compared to those considered adequate that are present in the four municipal districts and account for 19% (11,126 Ha), or to the least favourable, 3% (1278 Ha).

5.3. Discussion

The choice of the case study was justified by the presence of at least 21 power plants in the pipeline for the landscape of the Jimena Depression. Even though, as has been stressed in the first section of this article, the Autonomous Region of Andalusia does not provide an open-data visor to facilitate the mapping information of the renewable energy projects coming under its remit, thanks to the cooperation of Casares Local Council, the extension and location of those projects could be known.

The locations and extension were superimposed on the zoning performed, Fig. 14**,** in order to understand whether or not their Environmental Impact States takes into account territorial factors such as those analysed in this study. Should all the projects be approved, this exercise shows that their **location**, their **extension** and their **concentration**

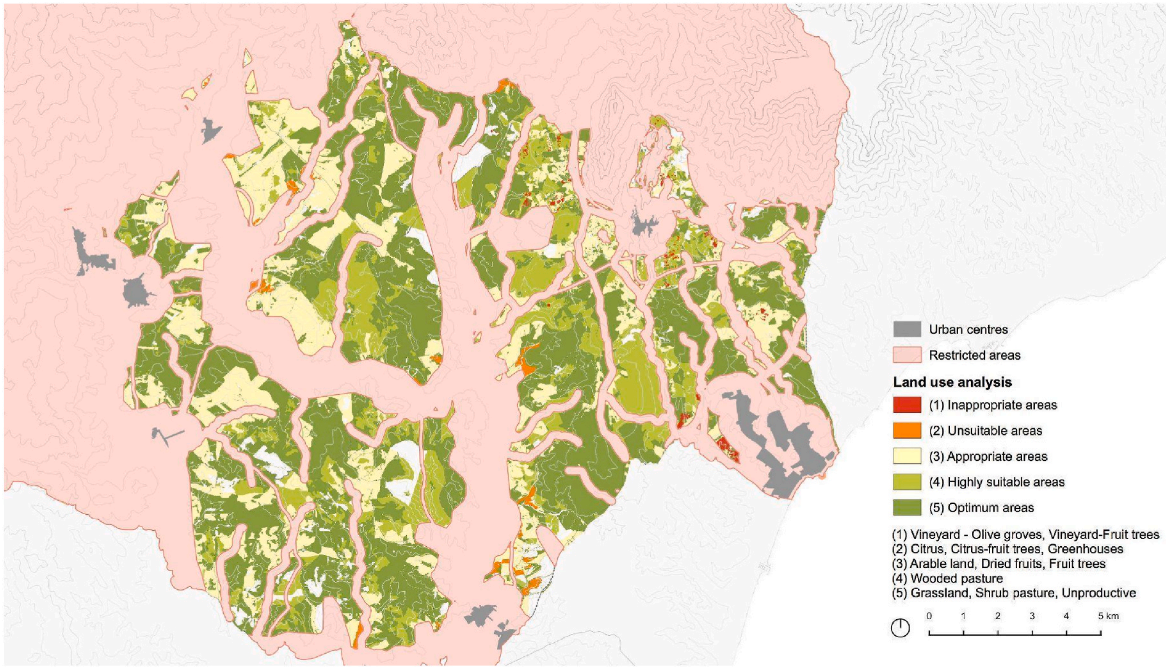

Fig. 10. Mapping socio-economic and landscape analysis layers: environmental criteria via land use. Source: Authors (2023).

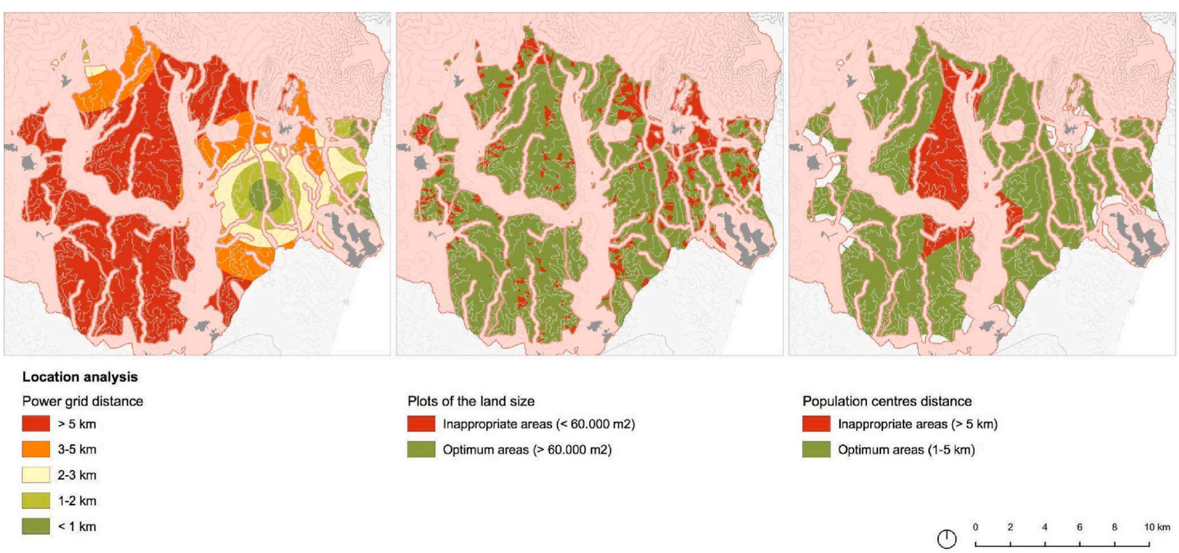

Fig. 11. Mapping socio-economic and landscape analysis layers: power grid distance (left), land size plots (centre) and population centre distance (right). Source: Authors (2023).

would lead to significant disputes.

First, the **occupied land** would be distributed in the following way on the generated model: 21% of the occupied area by photovoltaic projects is encroaching on **excluded** zones where the existing jurisdiction forbids the installation of this type of facilities; 11% is in unfavourable areas; 64% adequate ones; and merely 4% would be located in areas considered to be optimal. Some of those first 21% would occupy part of the transport network, others would alter the connectivity of green corridors such as the drove-road or the river basins, and others would annex unique agricultural landscapes and areas of special protection. Thus, that would all contribute to the loss of native and socio-economic dynamic landscapes, and the alteration of the ecosystemic services.

Secondly, that location would not be uniform and would lead to landscape **disequilibrium** problems due to **concentration**. Out of the total of the projects located in this rural area, 50.5% are clustered in the Casares municipal district and the 21.4% in Jimena de la Frontera are in the small part of the municipal district that does not have environmental protection, less than 15% of its territory. This imbalanced occupancy means that the land uses of those municipalities are greatly altered, leading to well-founded social rejection. Furthermore, their technicians are faced with complex impact assessment tasks, both due to the occupancy of the photovoltaic modules and to the layout of evacuation lines.

Finally, this concentration idea spirals into the debate on their need and their **link to the place** in which they are installed. The installed power would be around 1000 MW on the basis of the surface area occupied by the photovoltaic energy projects, around 2000 Ha. However, according to the data of the Andalusian Multiterritorial Information System, the electricity consumption of this area is very small, where around 60% is for residential consumption [60]. The data can be used to

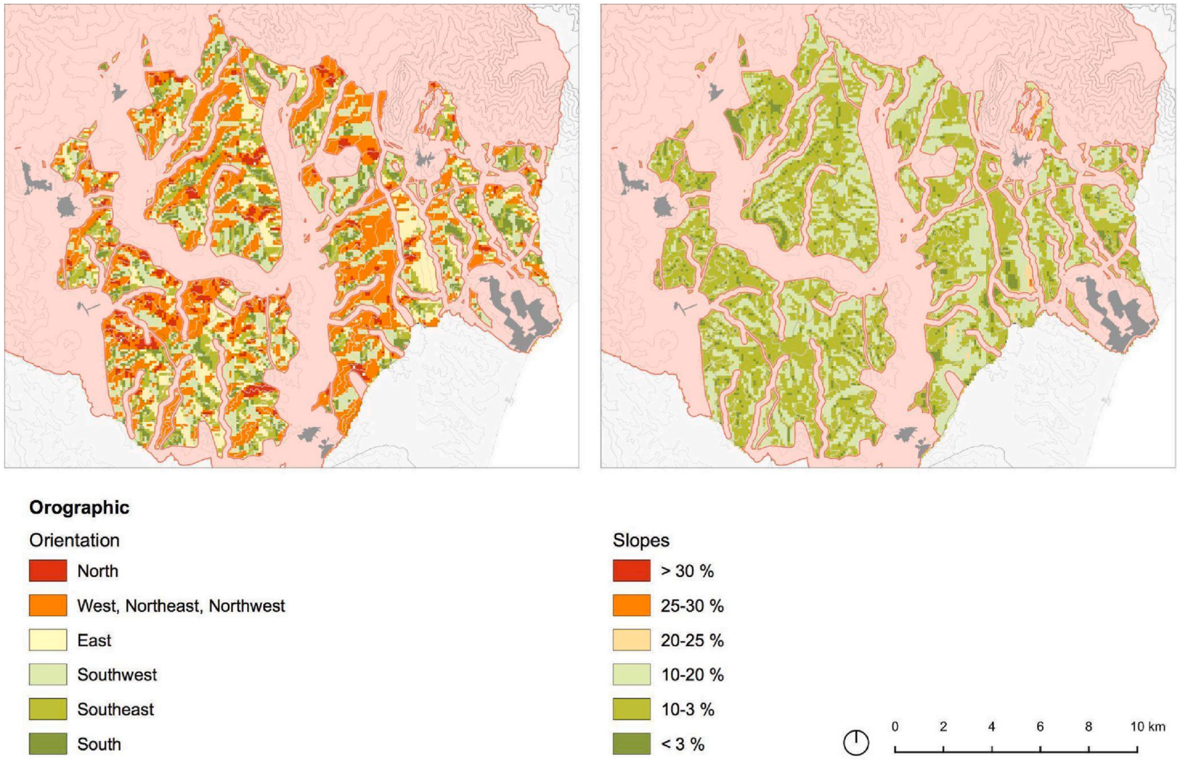

Fig. 12. Mapping orographic analysis layers via orientation (left) and slopes (right). Source Authors (2023).

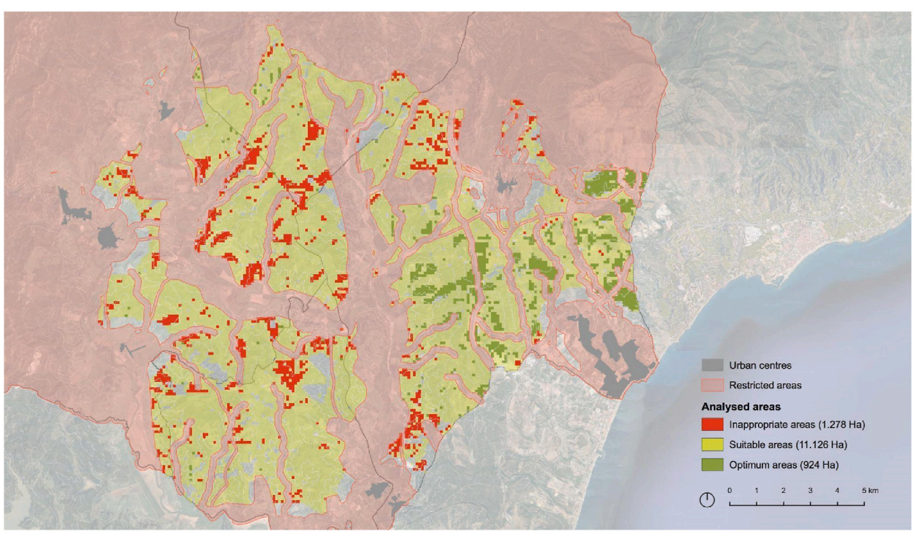

Fig. 13. Final mapping: analysed areas. Source: Authors (2023).

calculate the occupancy of a photovoltaic system whose annual production is equal to 100% of the electricity demand for those four municipalities. Taking into account the average irradiance in each of them, that would not exceed 43.5 MWp and, therefore, 87 Ha of photovoltaic occupancy. That is to say, it can be acknowledged that generating as much energy as electricity demand, using medium-sized photovoltaic facilities, is feasible in this territory. Around 30% could be self-consumption systems installed on erected roofing, thus reducing the additional need for land to 30 MWp and 60 Ha.

The fact that **concentration decoupled from the territory** exhausts the capacity of the access points to the grid is added to the calculation. Specifically, the area has two **distribution grid hubs**, the Corchado substations in Gaucín and Casares, apart from 5 nearby (one in Manilva, one in Sotogrande, one in Cortes de la Frontera and two in Estepona). According to the data updated monthly by Endesa, none currently have connection capacity [46].

The following results can be extracted from analysing the case study:

- Nearly 76% of the analysed territory is excluded from the possible installation of power stations on cultural and environmental grounds. However, 21% of the total area occupied by all the photovoltaic projects is protected. A figure that shows the alarming **non-compliance of cultural and environmental legislation** by the **companies or investors** behind the projects.
- Even though the roads, paths or rivers have **buffer zones**, the case of the Jimena Depression shows how the perimeters of Special

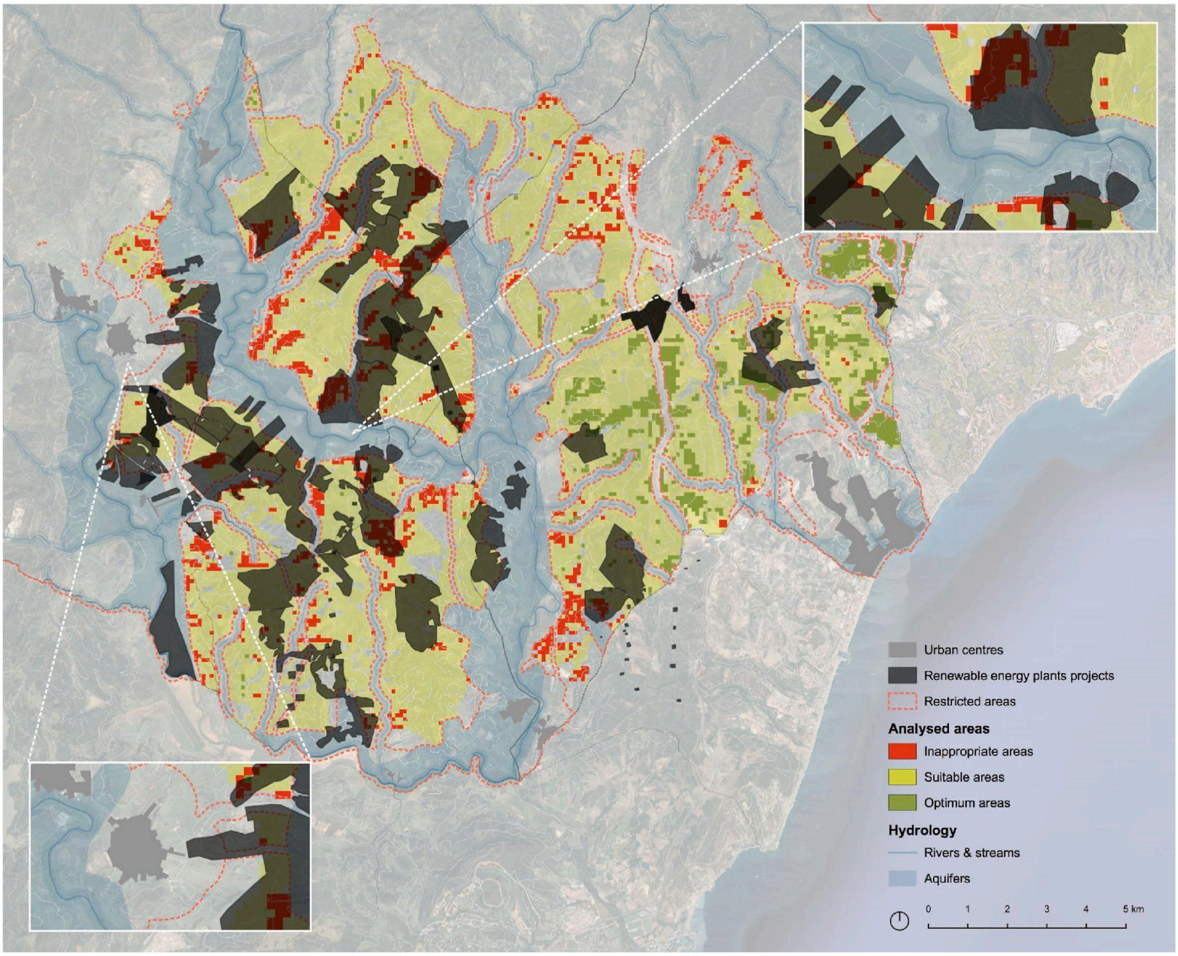

Fig. 14. Final mapping: areas occupied by renewable energy power plant projects overlapping the areas analysed and zooms of some of the most stressed areas. Source: Authors (2023).

Protection Areas, Natural Parks or Publicly-owned woodland are becoming besieged by the energy plant projects. This situation should be included in the relevant planning, thus avoiding the **isolation** of these protected areas and the change in citizen perception.

- As can be seen from the specific problem of Jimena de la Frontera, in the municipalities with large protected areas given their cultural and environmental wealth, the zones where plants could be installed must have a **reduction coefficient** that avoids the **great concentration** of large renewable plants.
- The analysis of the **uses of agricultural land** for the landscape studied has highlighted the need to understand the **social risks** that lead to the disappearance of certain crops or pastureland. Therefore, the proposal is that the impact statements of the power plants should be based on the analysis and specific prior zoning of the territory in question.
- Despite **complying with the constraints established** by this research, different types of **compensation would have to be devised,** if restricting the surface area likely to be the site of such installations only to the optimal or more favourable areas. On the one hand, **economic and labour** compensation for the change of land use, both for the land owners and their workers, and the municipalities. On the other hand, **social and cultural** compensation, which fosters greater knowledge, enhancement and protection of the transformed territories and ensures documentary visors of the altered land uses and the ensuing changes to the landscape.
- The calculation of the **energy demand** for those four municipalities have shown that the installed **capacity** restricts the possibility of a **decentralised energy transition** in the municipalities of the question. The saturation of the access nodes to detected grids prevents the capacity reserve for **photovoltaic self-consumption** and the creation of **local energy communities.**

In addition to identifying which areas of this territory are excluded and which are the most suitable for the location of future power plants, this study focuses on illustrating the real challenge of the region: the imminent installation of numerous projects already in the process of being approved. The novelty of the results is therefore based on the overlap of these projects in the area under study (Fig. 14). This makes it possible to measure the high percentage that would occupy both legally excluded and unsuitable land, as developed above.

From an international perspective, these results are innovative since the most recent research on the subject, detailed in the Literature Review section, does not include projects under development as a factor of analysis. Specifically, those that develop a provincial scale, such as the cases of Oman [38], Turkey [36,37] or Bangladesh [39] focus only on the suitability gradient designation. In the cases of Oman and Bangladesh, 59.46% and 31.18%, respectively, assess suitability as inappropriate. These results highlight the important differences depending on the specificity of each territory. The studies in the Turkish regions of Çanakkale and Malatya go a little further, analysing the location of some existing plants and proposing alternative locations for them, but they do not study the projects that are about to be approved.

There are no similar specific studies in the national context of the selected case study. However, there have been many recent reflections on impacts such as massive land use change [47,48], landscape impacts [49] or data scarcity [50]. All of these, complement and confirm the importance and unprecedented contribution of the results of this research.

6. Conclusions

Following the problem set out in the state of play, the deployment of this research has made clear the **need for spatial planning of** the large renewable energy plants in Spain and, specifically, in Andalusia, and the utility, in that regard, of the multicriteria analysis; not only due to the **environmental impact** risk, but also for its **landscape** and **sociocultural** implications.

Given that energy in Spain is a devolved power of the Autonomous Regions, it seems necessary that the social and environmental zoning criteria for the new large-scale renewable energy generation are contained in the autonomous regional **planning** of the territory. As can be seen from the data already given, only converting them into legislative criteria can curb the uncontrolled expansion of the large-scale renewables over fragile territories with cultural and environmental values. That would guarantee the equilibrium of the productive surfaces, thus avoiding the excessive concentration of plants and the ensuing jeopardising of the arable and livestock sector in certain regions. Thus, the zoning must be directly linked to the **sub-regional or spatial planning figures of each Autonomous Region**. That being the case, the Environmental Impact Statement, which is mandatory in order to process these facilities, would have an objective legislative framework, and the established territorial assessments and restrictions would have to be met as the first step towards the project implementation.

As the case study has shown, that **planning** must be based on holistic **zoning** and impact the **legislative framework**, as it is essential in the regional, autonomous and municipal **decision-making systems.** It will be fundamental to accomplish the **overall landscape scale** and avoid the partial analysis, as only thus will it be possible to understand the **energy, social, geographic and ecological dynamics** of the territory, along with taking into account the **cumulative impact** of the projects.

Only thus, by means of a **collective construct** based on **planning**, **transparency** and **active participation**, the mass conversion of agricultural into industrial land that is currently taking place in regions such as Andalusia could be planned in a balanced way, without jeopardising the future of the districts involved or of their inhabitants.

To conclude, it should be noted that this work has had two **added difficulties** to be developed. The first one has been the scarcity of public open data by the institutions of the Andalusian government, something that has already been reviewed in the national and regional contextualization. Secondly, the difficulty of defining the working area, as the installation of power plants does not follow administrative boundaries such as municipalities, but rather areas with a suitable landscape due to their orientation and slope conditions. For this reason, a particularly stressed area was chosen due to the accumulation of future projects. Likewise, the specificity of the established criteria demands the **application** of this analysis in other areas to develop it through a **broader spectrum** of **cases.** For this reason, it is an ongoing research that is being applied to other Andalusian zones in order to obtain comparably conclusions and a greater adjustment of the methodology.

On the other hand, the application of the results obtained depends on the applicability of this study at the municipal level, through the General Municipal Management Plans. This is because the Land Use Plan currently in force in Andalusia (2006) does not regulate the siting of this type of power plants. In any case, its **usefulness** seems remarkable since, for the moment, these first results have already been taken into account by the City Council of Casares. Based on the data obtained, this municipality has made a modification of its General Urban Development Plan, which is awaiting approval.

The results of this project can help national and regional governments achieve European legislation. Specifically, in article 15b of the European Directive, 2018/2001, *on the promotion of energy from renewable sources,* the need for Mapping of areas necessary for national contributions towards the overall Union renewable energy target for 2030 appears. Member States have to carry out a coordinated territorial mapping for the deployment of renewable energy to identify the domestic potential and the available land surface areas. Identifying these lands is necessary to install renewable energy plants and their related infrastructure and to achieve the Union's renewable energy target for 2030. These maps must be developed by May 21, 2025. Beside, by February 21, 2026, Member States must develop a specific plan designating the renewables acceleration areas (article 15c). This research offers a methodology to identify the most suitable areas to develop photovoltaic plants, observing economic, social, and environmental aspects.

Finally, its development can therefore be applied to zoning studies for other energies, such as wind or solar thermal. In both cases, new specific criteria would have to be added; in particular, in the case of solar thermal, the availability and proximity of water would be a fundamental criterion. In any case, this is a conflict on the rise, so careful analysis of every area will be a must in the near future.

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CRediT authorship contribution statement

Celia López-Bravo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Llanos Mora-López:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Mariano Sidrach-deCardona:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **María José Márquez-Ballesteros:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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