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Landscape-based spatial energy planning: minimization of renewables footprint in the energy transition

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Landscape transformations derived by renewable energy sources exploitation may induce public resistance and loss of quality of the existing environment. Integrated approaches are needed to inform and guide transformation processes, relying on empirical evidence regarding spatio-technological feasibility, acceptance by the community, and integration in the landscape. To address this issue, the paper aims to propose a methodological procedure for the development of local spatial plans to implement photovoltaic systems at the local level. The procedure is spatially explicit, combining qualitative considerations of inhabitants and experts with quantitative data on energy potentials, and associating site selection with solar integration strategies. The outcome is a planning framework combining spatial areas with quality requirements for the implementation of solar power plants, thereby allowing for the envisioning of future scenarios. The application of the method is tested in Arcos de la Frontera, Spain, considering both on-ground and on-roof distributed energy systems.

Keywords: renewable energy landscapes; solar power plants; landscape integration; sustainable energy planning; social acceptance

1. Introduction

The transition towards low-energy and carbon neutral paths is one of the primary challenges that our society must face. The latest European Climate Energy strategy sets a carbon neutral vision by 2050 (European Commission 2018). In this vision, the use of Renewable Energy Sources (RES) is a major contributor. Such extensive deployment requires an understanding of the site characteristics and implies a concertation between landscape protection, energy, and spatial planning, matching energy needs while preserving site identity (Mérida-Rodríguez, Lobón-Martín, and Perles-Roselló 2015). In this view, the (inter)national agreements need to be turned into regional and local targets guiding these transformations (Dobravec *et al.* 2021). However, currently local energy plans are rarely adopted and lack some important considerations. Spatial energy plan outlines often neglect landscape considerations and stakeholders' involvement (Prados 2010)

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*Corresponding author. Email: anna.codemo@unitn.it hindering the translation of energy targets into collaborative scenarios that incorporate local landscape knowledge (Leal and Azevedo 2016). Another critical aspect is the alignment of the energy strategy with other land-use and spatial issues (Pasqualetti and Stremke 2018; Kempenaar *et al.* 2021) and the introduction of policy changes, such as decision-making tools and new institutional capabilities (Kempenaar *et al.* 2021; Droege 2018). Planning for energy transition, therefore, involves several challenges: landscape integration of energy systems in urban and rural areas (Pasqualetti and Stremke 2018), institutional and societal innovation for planning and integrating energy systems (Kempenaar *et al.* 2021), integration with other challenges and consideration of ecosystem services (Picchi *et al.* 2019; Roth *et al.* 2018; Frolova, Prados, and Nadaï 2015). Moreover, the landscape transformations due to RES deployment can lead to barriers related to social acceptance (Selman 2010). Current methodologies for this issue include a-posteriori landscape impact assessment, such as visibility analysis (Ioannidis *et al.* 2022), but often do not directly include stakeholders' considerations within the planning tools.

To incorporate landscape considerations and public perception in the energy transition discourse, there is a call to include the concept of landscape, as defined in Article 1 of the European Landscape Convention (Council of Europe 2000), in the definition of energy targets, policies and projects. While in recent years landscape has been widely discussed in relation to wind energy (e.g. Pasqualetti, Gipe, and Righter 2002; Stremke and Schöbel 2019; Thayer and Freeman 1987), hydropower energy (e.g. Ferrario and Castiglioni 2017; Frolova 2010; Rodriguez 2012) and high-voltage powerlines (e.g. Batel and Devine-Wright 2015), the relationship between landscape and solar energy has received less attention (e.g. Bevk and Golobič 2020; Munari Probst & Roecker 2019; Oudes & Stremke 2018; Scognamiglio 2016). Indeed, most of the studies assessing feasible locations for solar energy include environmental and economic criteria excluding considerations on landscape (e.g. Rios and Duarte 2021; Suuronen *et al.* 2017; Guaita-Prada *et al.* 2019). Moreover, the literature focusing on landscape transformations and stakeholders' perception is carried on at the territorial scale (e.g. Spyridonidou *et al.* 2021; Gutiérrez *et al.* 2022; Kempenaar *et al.* 2021). For example, Spyridonidou *et al.* (2021) determined suitable locations of wind turbines and photovoltaic plants in Israel combining sustainable siting analysis (economic, social, and environmental) with local experts', stakeholders', and inhabitants' considerations. Recently, the growing attention to the local scale favoured the development of urban and regional methodological frameworks for solar siting (Clarke, McGhee, and Svehla 2020; Florio *et al.* 2018; Oudes and Stremke 2018; Thebault *et al.* 2022; van den Dobbelsteen, Broersma, and Stremke 2011; Weinand, McKenna, and Mainzer 2019).

Some of these studies propose the inclusion of suitable locations for solar energy within local planning tools. For example, Clarke, McGhee, and Svehla (2020) developed a tool to identify feasible areas for Solar Power Plants (SPPs) in Glasgow taking into account environmental, land use, and visual criteria. Oudes and Stremke (2018) combined biophysical and technical constraints with stakeholders' and inhabitants' perceptions to envision climate neutral scenarios. Their work draws on energy potential mapping, a method to quantify and spatially represent technical energy potential. Hence, spatial energy planning has received growing attention in overcoming planning challenges related to the implementation of Renewable Energy Technologies (RET) (e.g. Liu *et al.* 2018; Hussain Mirjat *et al.* 2018; Terrados, Almonacid, and PeRez-Higueras 2009). In addition, visibility analysis and site sensitivity are considered main factors for urban energy planning and for establishing required levels of photovoltaic (PV) integration by Florio *et al.* (2018). These studies point out important features of spatial energy planning tools: they are spatially-explicit, evidence-based, and informed by qualitative considerations of stakeholders, and include levels of RES landscape integration. Due to the lack of methodological frameworks for energy spatial plans, this research simultaneously emphasizes sustainability criteria, qualitative considerations of stakeholders, and landscape-integration levels at the local scale.

The aim of the study is, therefore, to close this gap by presenting and discussing an integrated approach that can be used to develop local spatial plans that simultaneously incorporate qualitative considerations, landscape-integration and sustainable criteria for solar energy. For this purpose, the proposed work ought to be spatially explicit and evidence based, inclusive of local experts' and inhabitants' preferences, and focused on the integration of SPPs in the context. The effort is achieved by associating different levels of site suitability with requirements of innovative design solutions. In particular, the specific objectives of the present study are: i) assessing and mapping suitable locations for PV implementation; ii) including public opinion in the assessment of suitable locations; iii) proposing a workflow that combines innovative design requirements to levels of suitable locations. For this research, literature studies have been conducted, and a case study has been carried out in Arcos de la Frontera (Spain).

2. Conceptual framework

Several concepts, methods and approaches form the basis for the study presented here. These concepts underpin the theoretical framework and inform the investigation of existing methods and procedures with spatial implications.

The first concept is the "energy landscape" (Apostol *et al.* 2017; Frolova, Prados, and Nadaï 2015), employed to define sustainable energy transition planning and design. It denotes the part of the physical environment affected by energy transition (Pasqualetti 2013; Selman 2010) originating from one or more elements of the energy chain and combining technical and natural energy sources (PEARLS 2019). However, multiple societal needs entail transformation of landscapes causing land use conflicts (Marques-Perez *et al.* 2020). In this view, Stremke (2015) pointed out that four dimensions should be considered for a sustainable transition: environmental, socio-cultural, economic and technical. These dimensions are linked to the potential ecological impacts of photovoltaic installations. The environmental aspects refer to the potential impacts on land, such as biodiversity change and fragmentation, soil and water. Socio-cultural considerations are related to visual impact and multifunctionality. Economic factors encompass synergies or conflicts with other land uses, such as urban development (Sánchez-Pantoja, Vidal, and Pastor 2018a). Given these considerations, a large number of criteria can be taken into account for the installation of SPPs. For the framework of the study, only criteria with spatial implications in the spatial planning tools have been considered. Therefore, economic criteria linked to solar farm design (solar cells, types of panels, grid connection), initial capital cost, discount rates, lifetime of the project, retail price have not been included.

The second concept is the social acceptance of landscape transformations (Wüstenhagen, Wolsink, and Bürer 2007; Delicado, Figureueiredo, and Silva 2016; Smardon and Pasqualetti 2017). Several factors are associated with social acceptance, including those linked to aesthetics, environmental impacts, economic benefits, temporal scale, people's attitude (Roddis *et al.* 2020; van den Berg and Tempels 2022). Within these factors, landscape impacts are rarely considered in energy planning through mitigation strategies, becoming one of the major causes of opposition against new projects

(Frolova, Prados, and Nadaï 2015; Ioannidis and Koutsoyiannis 2020). Landscape impacts can be objectively quantified, for instance, in relation to land use, or qualitatively addressed, such as through public perception investigation (Ioannidis and Koutsoyiannis 2020). As local context and civil society (Roth *et al.* 2018) and procedural aspects (Wolsink 2007; Devine-Wright 2011) play an important role in reaching energy targets, public participation becomes a key element for social acceptance (Marot and Kruse 2018) supporting decision-making through information sharing, transparent communication, consensus-building and informed decision-making (Koirala, van Oost, and van der Windt 2018). This aspect is currently not widely considered in existing urban environments (Stober *et al.* 2021; Florio *et al.* 2018). Besides procedural issues, local perception is affected by SPPs visual impact, and specifically by the number of panels, location, spatial distribution, and characteristics of the site (Ioannidis *et al.* 2022; Florio *et al.* 2018). Such aspects are addressed in visual impact assessments (Bishop 2003; Sánchez-Pantoja, Vidal, and Pastor 2018b; Frantál *et al.* 2018), evaluating both factors related to the object and subjective experience and both for on-ground and buildings' photovoltaic applications (e.g. Florio *et al.* 2018; Kosoric, Wittkopf, and Huang 2011). Moreover, social acceptance can be investigated through surveys with the inhabitants. Studies focusing only on social acceptance and landscape perception mostly use visual stimuli to interview inhabitants: real landscape stimulus (Bevk and Golobič 2020), photographs (Torres-Sibille *et al.* 2009; Sánchez-Pantoja, Vidal, and Pastor 2018b; Salak *et al.* 2021; Spielhofer *et al.* 2021; Lu, Lin, and Sun 2018; Naspetti, Mandolesi, and Zanoli 2016). Other studies including public perception in energy planning workflows used questionnaires (Oudes and Stremke 2018; Spyridonidou *et al.* 2021). For the framework of the study, we adopt the visibility analysis, established as the best practice for landscape impacts (Spielhofer *et al.* 2021), and we include the perception of the inhabitants and experts (Oudes and Stremke 2018) through surveys.

Landscape- and building-photovoltaic integration is the third main concept of the study. The concept of photovoltaic integration is well-known for buildings, especially in relation to Building Integrated Photovoltaic (BIPV) systems (Farkas and Horvat 2012; Maturi and Adami 2018; Santos and Rüther 2012; Jelle, Breivik, and Drolsum Røkenes 2012). However, recently it has been extended for on-ground solar plants by Scognamiglio (2016) to open the discussion about the design of SPPs through a landscape-based approach. Indeed, high architectural integration can support solar deployment and establish positive responses by local inhabitants or users (Farkas *et al.* 2013; Oudes and Stremke 2021). An integrated system is coherent with the context and an integral part of the architecture or of the landscape by its visual characteristics (e.g. collectors' field size, position, density; visible materials) (Munari Probst and Roecker 2019). Photovoltaic integration has been linked to urban planning through the concept of "criticity" (Farkas *et al.* 2013; Frontini *et al.* 2012). The term has been used by Munari Probst and Roecker (2015) to combine the value of the urban context (i.e. sensitivity) and the visibility from public space (i.e. visibility) with design requirements to facilitate local acceptance. Specifically, the level of criticity of an area sets a required degree of architectural integration of the energy infrastructure (Munari Probst and Roecker 2019).

3. Methodological procedure

The present section aims to briefly describe the methods and techniques used to elaborate on the planning framework. The overall methodological procedure is illustrated

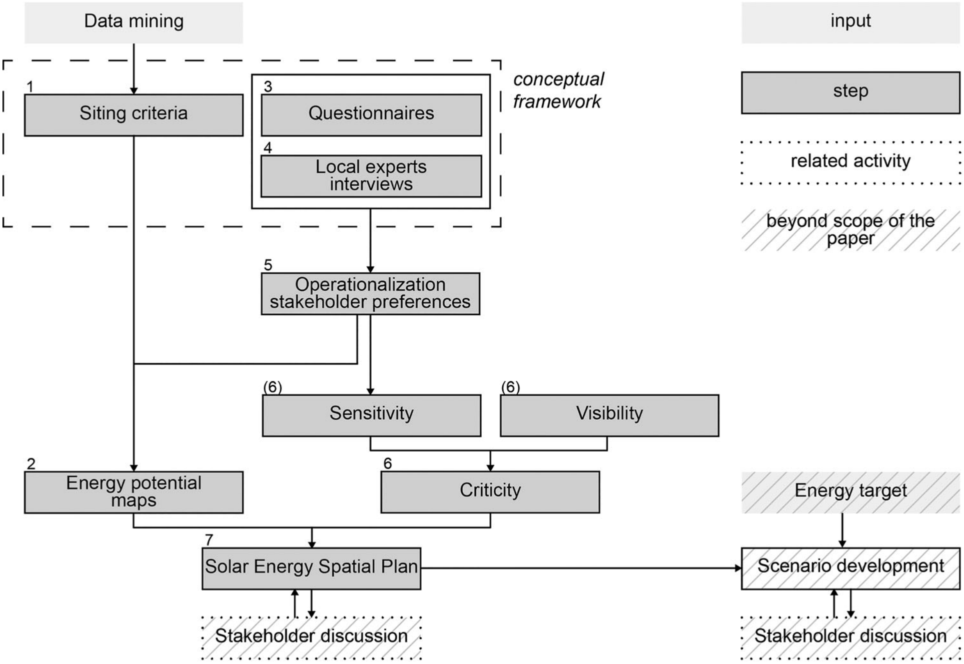

Figure 1. Methodological workflow.

in Figure 1. The structure of the proposed energy planning workflow is derived from the insights gained from the literature review and considerations on the current planning tools that emerged from consultation with local experts involved in various working fields in the Andalusian context. According to the conducted interviews, the role of local authorities is important to manage energy-related landscape transformations. However, the interviewees highlighted a lack of planning tools to control land use and landscape transformations. The study presented here connects the three main concepts of sustainable energy landscapes, social acceptance and landscape-integration with planning and design strategies by adopting recognized procedures from the literature (Figure 2). The research process was iterative and structured according to the comments received by the local experts. In the following subsections, aim, general techniques and methods, input and output are described for each step. The results of each step are spatially explicit, to develop a solar energy plan in line with common urban planning tools. The maps have been created with the open-source Geographical Information System (GIS) software QGIS version 3.20 “Odense”. GIS technology is combined with multicriteria decision making techniques to identify levels of suitability for solar energy development. This methodology allows the combination of geographical data with qualitative considerations to obtain information adequate for spatial planning.

3.1. Siting criteria

The aim of Step One is to collect and visualize potentials and constraints for the implementation of SPPs. A set of Assessment Criteria (AC) has been collected by similar studies focusing on solar siting at the local level. According to the studies (e.g.

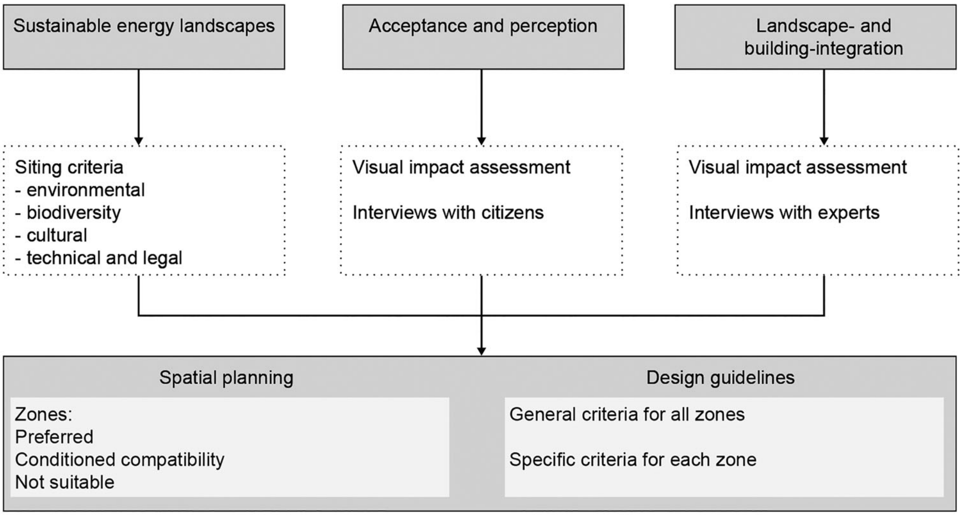

Figure 2. Procedures and methodologies to define the sustainable energy planning tool based on the conceptual framework.

Clarke, McGhee, and Svehla 2020; Oudes and Stremke 2021; Spyridonidou *et al.* 2021), a list of AC has been created (Appendix A [online supplementary material]), and subsequently reduced considering only those relevant to the specific case study. While the threshold of technical requirements can be determined by the literature studies, the type of restrictions and limits for cultural and environmental aspects should take into account legal considerations and local stakeholders' reflections. Each AC has been defined as a single layer, edited, organized, and visualised, to inform a GIS dataset containing spatially explicit information about AC, for example areas with heritage status or natural protected sites. The output of Step One is a GIS model including thematic maps with the information for potentials and constraints of photovoltaic implementation.

3.2. Energy potential maps

The aim of Step Two is to define energy potential maps for the implementation of SPPs. The maps are based on the combination of potential SPPs and the thematic maps developed in Step One. The potential solar sites include on-ground and on-roof solar panels, in residential, commercial, industrial areas as well as open spaces. The selection of suitable locations for SPPs is very important, and it constitutes the result of stakeholder discussions and energy planning through several scales. The thematic maps may include different levels of restrictions, defined in accordance with local experts and stakeholders. For example, environmental and biodiversity conservation areas with high percentages of canopy cover could be removed from potential SPP implementation sites as they are valuable for the provision of ecosystem services. In other cases, specific design solutions could be required to produce solar energy while enhancing nature conservation (Blaydes et al. 2021; Oudes, van den Brink, and Stremke 2022; Randle-Boggis *et al.* 2020). Similarly, cultural heritage areas could constitute potential solar sites if adequate integration is provided. Further consideration of this aspect will be made in Step Six. The output of Step Two is a GIS model of the potential areas for solar power production.

3.3. Citizens' survey

The aim of the survey is to explore the general perception of the inhabitants of the case area towards energy transition and on the related landscape transformations. The methodology used to investigate the opinion of the inhabitants is the visual Q methodology (Brown 1979; Stephenson 1980), since it relies on the evaluation of pictures (Grosswiler 1992) and it allows the assessment of shared points of views, rather than statistical considerations (Watts and Stenner 2014). The selected pictures included SPPs in different urban and rural land uses with different degrees of landscape or architectural integration quality (integrated, semi-integrated and non-integrated). The level of integration is evaluated according to the capacity of the system to be designed as part of its landscape, specifically in relation to its geometry, materiality, and pattern (Munari Probst and Roecker 2019). Respondents were citizens of Arcos de la Frontera. Brown (1980) suggested that participants should be selected to express a particular point of view. Thus, our recruitment strategy included two main groups: non-experts with awareness of the existence of PV systems, experts in landscape planning or in solar energy (Naspetti *et al.* 2016; Lu *et al.* 2018). A total of 21 people responded to the survey, among whom 12 were experts and 9 non-experts. The number of participants in Q methodology is not crucial, as the aim is not to generalize an opinion but rather to assess different viewpoints, called factors (Watts and Stenner 2014). These factors are derived from a factor analysis carried on PQ Method software which generates a correlation matrix between responses extracted with the centroid method and rotated with varimax. For the extraction of the factors, we followed the guidelines of Watts and Stenner (2014). The survey was conducted between February and March 2022 in Arcos de la Frontera. Residents were approached in public places or in their workplaces. Since Q methodology does not aim to provide a statistical analysis of the results, the number of participants is considered suitable for the purpose. The considerations of the inhabitants are operationalized in Step Five and inform Step Six as an input.

3.4. Interviews with experts

The aim of Step 4 is to investigate the opinion of local experts on the landscape transformations due to photovoltaic applications and on the tools to manage them. The interviews were conducted between February and March 2022, online and onsite, and involved five local experts: two university professors, a representative of the regional government, a representative of Municipal government, and a consultant for large scale photovoltaic plant implementation. The interviews were well structured and lasted between 30 min and one hour. Interviews with local experts provide useful information on potentials and constraints for RES deployment, specifically on the stakeholder preferences and aversions regarding RET and the current model of renewable energy development in Andalusia. Furthermore, they contribute to understanding the constraints related to local energy planning and define specific requirements that could improve the current situation. Finally, the experts assessed the AC for the specific case study of Arcos de la Frontera, through a correspondence matrix. The stakeholders' preferences are operationalized in Step Five and inform Step Six.

3.5. Operationalization of public preferences

The aim of Step Five is to operationalize qualitative criteria and to make them spatially explicit, to prevent land use conflicts, and provide accepted solutions (Oudes and Stremke 2018). The data used as input in this phase are the results of the survey of the inhabitants (Step Three) and the interviews with experts (Step Four). The results can be used as inputs in the spatialization of critical areas (Step Six) and in the solar energy spatial plan (Step Seven). The output is a series of spatially explicit considerations in the GIS model.

3.6. Criticity

The aim of Step Six is to consider socio-cultural values of the local context and public perceptions of the definition of suitable areas. The concept of criticity was introduced by Munari Probst and Roecker (2015) to define the impact of modifications of urban surfaces on their global quality. This concept was outlined to manage architectural transformations due to photovoltaic installations, but we extend it to larger scales. The "criticity" of the areas is associated with specific quality and integration requirements according to their visibility and sensitivity. The output of Step Six is a map of zones of the municipal area divided by criticity levels, combining sensitivity and visibility, as a tool for decision makers to set quality requirements. Specifically, sensitivity sets levels of socio-cultural value of the urban context (Munari Probst and Roecker 2015), defined by land-use zones, blocks of buildings that are protected, local documents identifying areas of importance, such as landmarks, considerations from the interviews with experts and inhabitants. Visibility is used to reverse visual impact assessments to an a-priori assessment of visible areas (Ioannidis *et al.* 2022). In this study, visibility is geometrically assessed through GIS tools, defining the visibility of the ground and roof surfaces from a set of viewpoints. Visibility of building roofs mainly depends on geometric factors and reciprocal obstructions. The geometric indicator of visible areas for GIS applications is the "viewshed" (Llobera 2003), defining how many times a surface is seen from selected viewpoints. The visibility of ground surfaces mainly depends on the topographical configuration of the area. At this stage of the research, it is important to define whether areas or roofs are visible from many points of view, rather than defining the physical perception from each viewpoint. Considering the relationship between social acceptance and visibility, several viewpoints were taken into consideration: the view from the supra-urban roads (Sun *et al.* 2021; Fernandez-Jimenez *et al.* 2015), the view from urban streets and public spaces (Florio *et al.* 2018), the view from walking paths, viewpoints and touristic routes (Cassatella 2014; Fernandez-Jimenez *et al.* 2015).

3.7. Solar energy spatial plan

The aim of Step Seven is to define an energy spatial plan dividing the Municipality areas into zones according to the level of integration required to implement SPPs. The map combines the criticity zones (Step Six) with the energy potential map (Step Two).

The output consists of a synthesis map of the Municipality divided into criticity zones and quality requirements for the implementation of SPPs, including general ones as well as zonal specific. In some areas, SPPs will not be allowed; in others they will be allowed under certain conditions or without conditions. The conditions should guarantee the SPPs' integration into the landscape, for a sustainable, accepted and landscape-inclusive energy transition. The type of output is in line with the urban planning tools (e.g. General Urban Plan). By integrating the spatial plan in the local planning tools, it is possible to develop scenarios for the Municipality as well as to evaluate the possible development of proposed projects (as a landscape impact assessment tool).

4. Case study application

Arcos de la Frontera is a Municipality in Andalusia, Spain. It is a small city located in the inland of the Province of Cadiz, with a surface of 526.81 km^2 and 30,741 inhabitants. It is characterized by a peculiar topography: the historic center and the urban area are located on a sandstone hill, while the peri urban and agricultural areas lay in the surrounding flat areas, along the Guadalete river and the reservoir. The following subsections will present the steps of the methodological procedure for the specific case study, in accordance with Section 3. The city has been selected as a case study as it includes an historical centre, agricultural areas and natural areas within the municipality borders. For computational reasons, the selected area for the study includes the main urban area, the reservoir and the surrounding peri-urban areas (Figure 3). However, the study can be extended for the whole municipal area. The selected area is representative of small cities characterized by a main urban nucleus and surrounding rural fields. The case study offers the opportunity to think of rural and urban areas as one system, solving the ambiguity of structural changes (Poggi, Firmino, and Amado 2020).

4.1. Siting criteria

To assess siting criteria, georeferenced data were collected from public datasets (Instituto de Estadística y Cartografía de Andalucía – DERA, local cadastre, Red de Información Ambiental de Andalucía), appropriately digitized/pre-processed and used to create the relevant thematic maps in a GIS model. Urban planning data (such as General Urban Plan, Regeneration strategy) are not available, or are out-of-date (1994), so they have not been considered for this study. The relevant AC, presented in Table 1, belonged to five categories: (a) environment, (b) biodiversity, (c) land use and cultural, (d) technical and (e) legal aspects.

To assess the environmental and biodiversity constraints, policy constraints have been identified from European, national, regional and local regulations (e.g. Natura 2000 areas) as well as limitations that are not formalized in legislation, but could reflect the concerns of stakeholders and could protect the value of landscape (e.g. green corridors). Environmental and biodiversity parameters mostly affect the implementation of PV panels on-ground. Land use and cultural parameters reflect the type of land use and the heritage status of the areas, thus affecting sensitivity as well as limiting the implementation of PV panels, because of local legislation (e.g. landmarks) or recognized cultural value (e.g. non protected monuments). Land use parameters have an impact in the implementation of PV panels both on roofs and on-

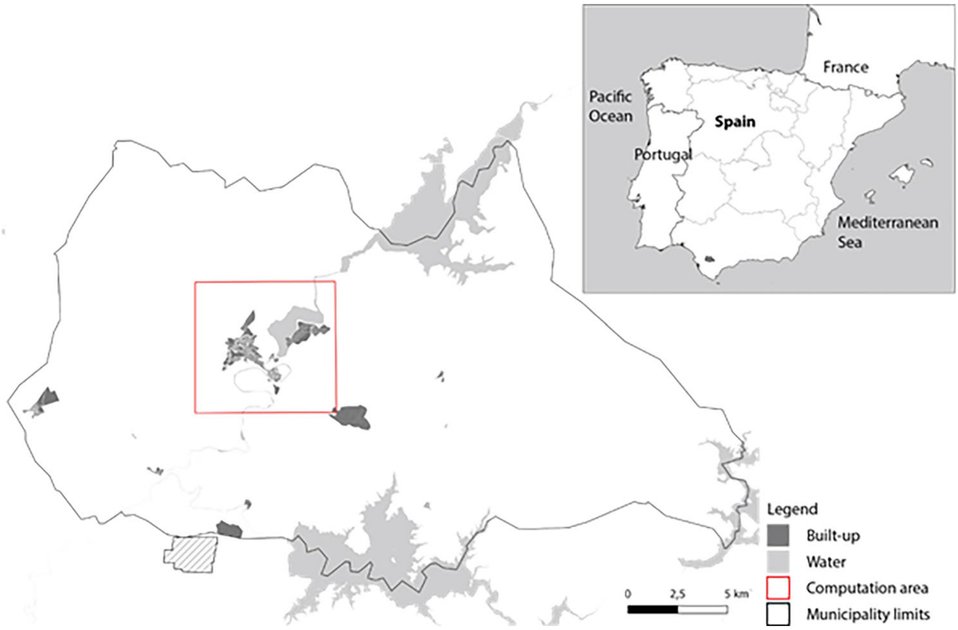

Figure 3. Case study: Arcos de la Frontera, Spain. Location in Spain and definition of computational area.

ground. Technical parameters represent objective parameters that influence the efficiency of a solar plant, and they depend on terrain and climatic characteristics, as well as on the connection and the congestion of the grid. Legal parameters ensure a certain distance of the SPPs from urban components. Three thematic maps have been created resuming the AC by typology (Figure 4): environmental and biodiversity, land use and cultural, technical and legal. A more detailed list of source data and methodologies to make them spatially explicit is available in Appendix B (online supplementary material).

4.2. Energy potential maps

AC have been mapped to assess solar energy potential and constraints and combined with the types of SPP suitable for the municipal area. The potential solar sites include on-ground and on-roof farms, in residential, commercial, industrial areas as well as open spaces. A complete list of potential locations is available in Table 2. Considering the scale of the study, PV panels in facades have not been considered. The thematic maps have been simplified according to their information. Values not suitable for energy production in relation to technical criteria have been removed from the potential sites. Areas mapped according to environmental and biodiversity criteria have been excluded from potential sites, since they provide benefits for other environmental and ecological issues. Areas derived from cultural and land use criteria have been highlighted but not removed from potential sites, since the development of SPPs in such areas has an impact only on humans and could be mitigated by architectural/landscape integration. Figure 5 shows the overall map created for solar energy potential.

Table 1. Criteria to identify suitable siting locations.

Criteria	Parameter	Description	Suitable values
Environmental	Green corridor	Ecological infrastructures along water courses	Unsuitable
	Local nature reserves	Land use classified as coniferous and evergreen species (80%), deciduous trees (70%)	Unsuitable
	Conservation areas	Areas classified as environmental protected areas	Unsuitable
	Areas important for nature conservation	Natura 2000 areas	Unsuitable
Biodiversity	Local protected species-corridors	Areas protected for biodiversity conservation	Unsuitable
Land use and cultural	Heritage status	Historical centre	Required mitigation
	Urban green	Land use classified as gardens and parks	Unsuitable
	Protected landscapes and landmarks	Buildings or areas listed as cultural heritage	Required mitigation
	Agrologic value	Analysis of soil fertility and land cover	Olive and other woody crops, vineyards unsuitable; arable farming, scrubland, bare soil and meadows suitable
Technical	Slope	Analyses of terrain flatness	< 10°
	Orientation of land	Aspect analysis of terrain	East-west
	Orientation of building	Aspect analysis of roof surfaces	East-west
	Shade from objects	Analysis of shaded surfaces (included in irradiation analysis)	Non shaded objects
	Access power grid	Distance from the nearest electricity network connection, power line, or transformer substation.	1 km from power grid
	Flood risk areas	Environmental risk analysis	Areas without risk
	Irradiation	Radiation Analyses	> 800 kWh/m2y
	Temperature	Analyses of the mean annual temperature	< 40 °C
Legal	Distance from streets of first and second order	Buffer from streets	> 35 m
	Distance from streets of third order	Buffer from streets	> 115 m
	Distance from the urban areas	Buffer from urban core	> 200 m

4.3. Citizens' survey

The respondents offered a view on the perception of the inhabitants of landscape transformations due to solar photovoltaic installations. The results of the survey consist of

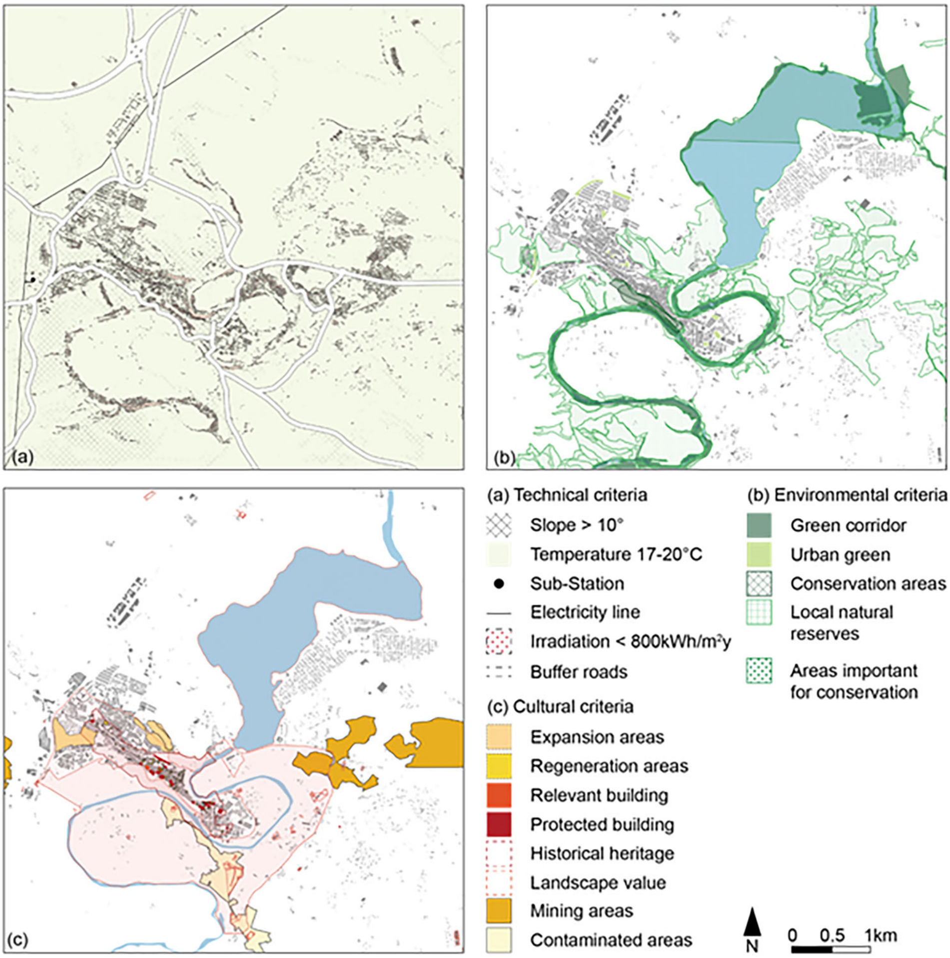

Figure 4. Map of environmental constraints; map of land use and cultural constraints; map of technical and legal constraints.

Table 2. Applications of SPPs suitable for the urban area.

Type of PV	Location
On-roof	Rooftop of building
On-ground	Agricultural land Abandoned land Sand mining area Landfill Surface water

four points of view of the inhabitants (Factors), which are depicted in Figure 6. In general, positive feedback on the efforts for energy transition is detected, but there is a consensus against on-ground solar plants. Landscape with high scenic and agrological values should be carefully considered for SPPs implementation. The use of PV on roofs, especially in residential commercial and industrial areas is the most appreciated,

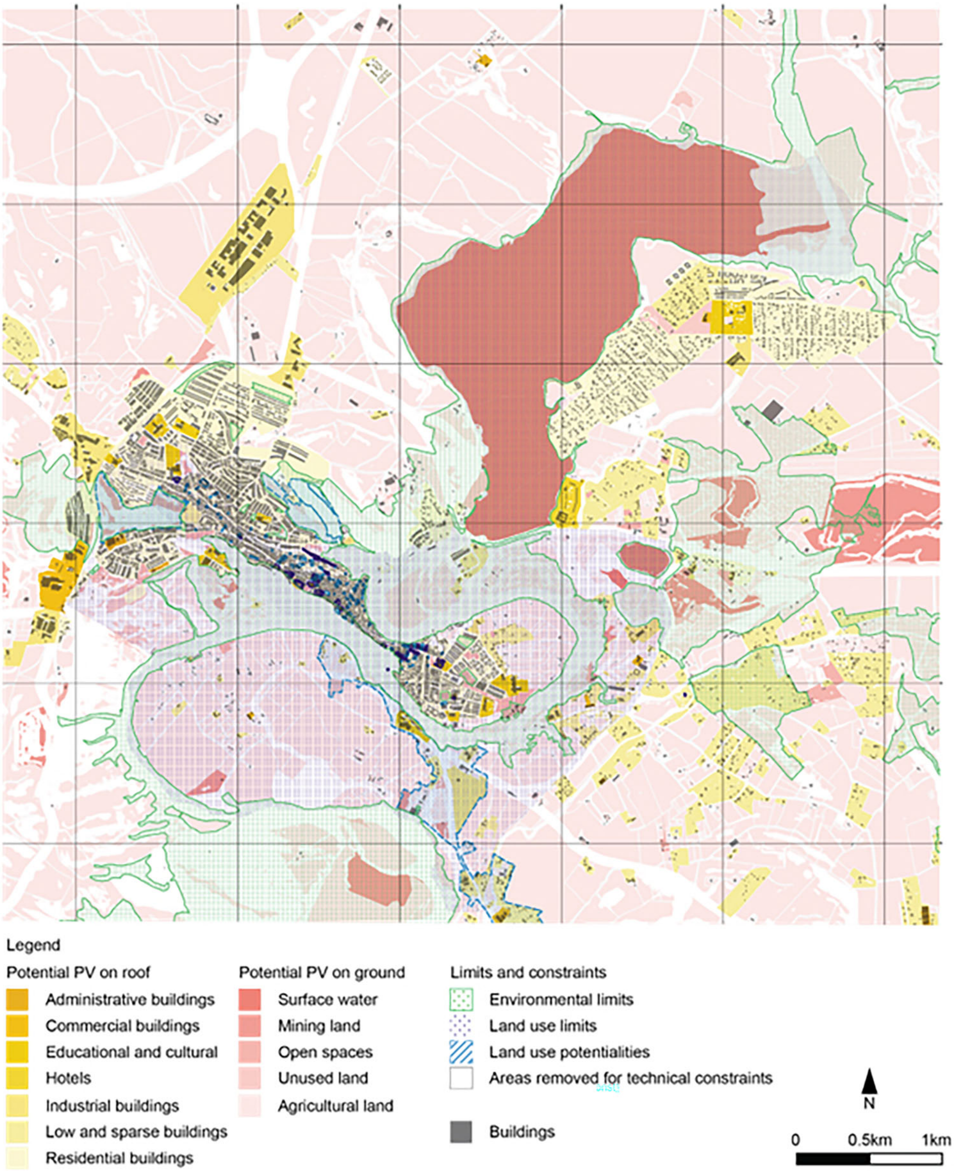

Figure 5. Map of solar energy potential: on-roof and on-ground PV panels by land use considering environmental and technical constraints.

despite the level of integration. Factor 1 expressed its preference towards hidden solutions in the roofs in the urban context; Factor 2 positively evaluated solutions in roofs despite the land use, giving its preference towards efficient solutions; Factor 3 preferred innovative design solutions in which the PV components are integrated into the envelope; Factor 4 positively evaluated PV in roofs both in rural and urban contexts. The use of roof surfaces in residential, commercial, and industrial areas should be prioritized compared to on-ground installations.

Figure 6. General overview of the results of the interviews with the inhabitants, carried out with the Q methodology: most liked and disliked situations for each factor.

4.4. *Interviews with experts*

The interviewees offered a view on the deployment of solar photovoltaic systems in Andalusia. They all reported the absence of local planning tools guiding the energy transition, resulting in the expression of different opinions on the types of RESs to use and the dimensions of future solar farms. There was a common agreement on the need for local planning tools to regulate the model of RES deployment to preserve the landscape and guarantee engagement and acceptance of the inhabitants. The interviewees

Table 3. Overview of the results from the evaluation of assessment criteria: type of criteria, criteria and scores (bandwidth and average).

Type of criteria	Criteria	Lowest score	Highest score	Average score
Environmental and biodiversity	Urban green	1,40%	13,37%	6,26%
	Local natural reserves	2,57%	13,37%	8,28%
	Landscape and landmarks	6,50%	21,62%	14,04%
	Conservation areas	1,42%	15,99%	8,79%
Land use and cultural	Historical heritage zone	2,71%	29,88%	12,25%
	Historical buildings	5,44%	20,12%	12,61%
	Soil agrological value	2,39%	11,32%	8,59%
Visual impact	Visibility from public space	2,39%	5,68%	4,30%
	Visibility from touristic areas, paths	3,10%	21,76%	8,31%
	Visibility from streets	2,13%	5,24%	3,12%
Technical	Slope of the roof and of the land	1,08%	21,26%	9,39%
	Orientation and irradiation	1,28%	10,66%	4,04%

revealed many insights related to tools for energy planning and design. For example, with regard to planning tools, defining land use boundaries and suitable areas for RES deployment by municipalities seems to be important. Moreover, they highlighted the importance of using the roofs of buildings for the implementation of SPPs, especially on top of parking lots, in industrial and commercial areas. Finally, the participants were asked to complete a correlation matrix for the importance of assessment criteria in the case study of Arcos de la Frontera. The correlation matrix is composed of 12 criteria. They represent a simplification of the list of criteria of Step One to be manageable during the interview. The results were analysed through Analytical Hierarchy Process (AHP) (Uyan, 2013; Sánchez-Lozano *et al.* 2013; Watson and Hudson, 2015) and each participant was considered with the same importance. They are synthetized in Table 3.

4.5. Operationalization of public preferences

For solar energy, the physical potentials and constraints derived from the inhabitants' and experts' interviews were made spatially explicit. The information acquired by the interviews are both quantitative, through the AHP method, and qualitative. The results contribute to the definition of sensitivity levels within the municipal area, as it will be explained in the following subsection. For example, the aesthetic value of the landscape is highly important for the inhabitants. Thus, agricultural fields surrounding the peri-urban areas are considered sensitive. Recreation and tourism are also stressed by local experts and inhabitants. Hence, the reservoir and its surroundings, as well as the visible areas from walking paths, are excluded from potential sites for PV farms. The prioritization of the AC according to the outcome of the local experts' surveys has been used to define levels of sensitivity of the areas.

4.6. Criticity

Three levels of criticity have been identified for on-ground and on-roof PV panels: highly critical, critical and non-critical, by crossing three levels of visibility (low-medium-high) and three levels of sensitivity (low-medium-high). Considering the definition of criticity given by Munari Probst and Roecker (2015, 2019) which refers to roofs and facades; further reflections have been made to also include open spaces.

Sensitivity

A first understanding of sensitivity levels is determined by the level of protection of zones: protected areas in land use plans represent a sound exemplification of highly sensitive zones, while commercial and industrial areas represent low sensitive ones. By contrast, areas without clear identity or qualities are not sensitive. Despite land use, to evaluate sensitivity, the urban fabric and morphology of the landscape have been considered. However, this classification might not always be exhaustive without a deep understanding of local specificity and without the discussion with stakeholders (Florio *et al.* 2018). For this reason, the reflections gathered from the interviews with citizens and experts have also been considered. For example, special clusters of buildings and areas which are visible from touristic viewpoints are considered highly sensitive, views from walking paths and from the reservoir are considered sensitive, as they seem to be important for the inhabitants.

Visibility

The visibility analysis requires Digital Surface Model (DSM) and Digital Terrain models (DTM), the road network, the location of viewpoints, the walking paths as well as the buildings' footprint. The DSM model used includes only the building shapes and not the trees, representing therefore the most visible scenario. The quality of the results highly depends on the resolution of the DSM and DTM. In this study, a resolution of 2.5 m was available and was sufficient to obtain indicative results, which was enough for the purpose of proposing a solar planning framework. However, higher levels of precision of the DSM could be useful for other stages of planning focusing on specific areas (Florio *et al.* 2018) or for more in-depth visibility analysis.

To be reproducible in a wide range of cases and for simplicity, the target points of the analyses are the DSM raster cells, which represent the surfaces of roofs and open spaces. The viewpoints have been extracted from the road network with 10 m distance between each point, in line with Florio *et al.* (2018). The visibility analysis of urban areas is carried out from the viewpoints with a height of 1.5 m, as the standard view-height of the observer, and with a maximum distance of 500 m (Figure 7) representing the visibility of pedestrians rather than occupants (Zheng *et al.* 2023). The visibility analysis from panoramic points and walking paths have been assessed at a height of 1.5 m with a distance of 500, 1,200 and 2,500 m, according to Chiabrando, Fabrizio, and Garnero (2011) (Table 4). The visibility analysis was carried out between each target point and viewpoints showing the number of times each cell was visible, known as cumulative viewshed. A more detailed list of source data and methodologies to assess visibility is available in Appendix C (online supplementary material). The results of the visibility analysis show that the majority of the roofs as well as the surrounding flat areas are visible, due to the topographic configuration of the town. For this reason, the threshold of the visibility analysis has not been set as "the visible areas", but as the "most seen areas from most locations". To evaluate this, a visibility map has been created and classified into three classes (from most visible to less visible) with the Jenks' Natural Breaks algorithm (De Smith, Goodchild, and Longley 2018) to flag as "0" low visible cells, as "1" visible cells, and as "2" highly visible cells (Figure 8).

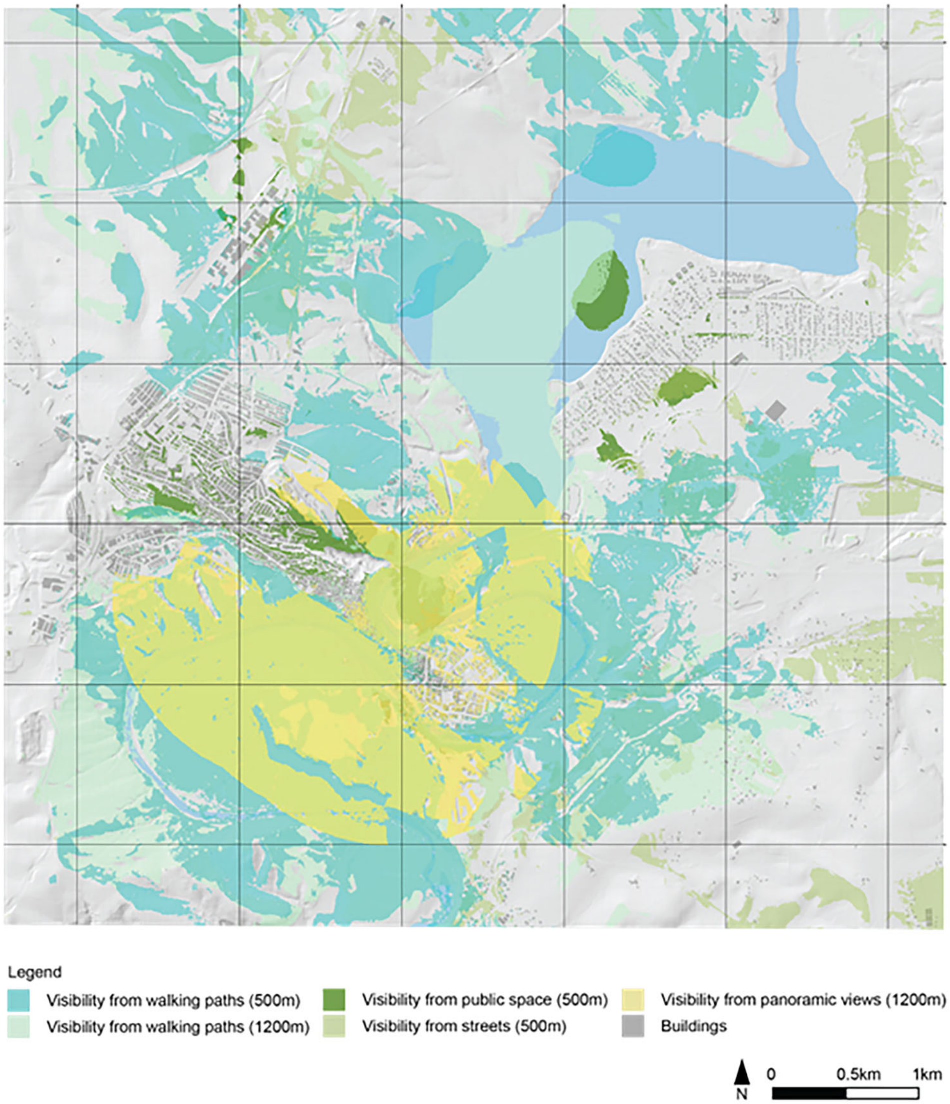

Figure 7. Sampling viewpoints of the street axis every 10 m. Cumulative viewshed resulting from the visibility analysis (times that the pixel is seen).

Table 4. Visibility thresholds.

Criteria	Parameter	Distance
Visibility	Visible from public space (streets and squares)	500m
	Visible from viewpoints, tourists routes, touristic areas	500m–1,200m–2,500m

4.7. Solar energy spatial plan

The map combines the levels of suitable areas for solar energy with potential applications within the Municipality of Arcos de la Frontera, considering on-roof and on-ground plants. To each category of criticity, a certain level of integration is required:

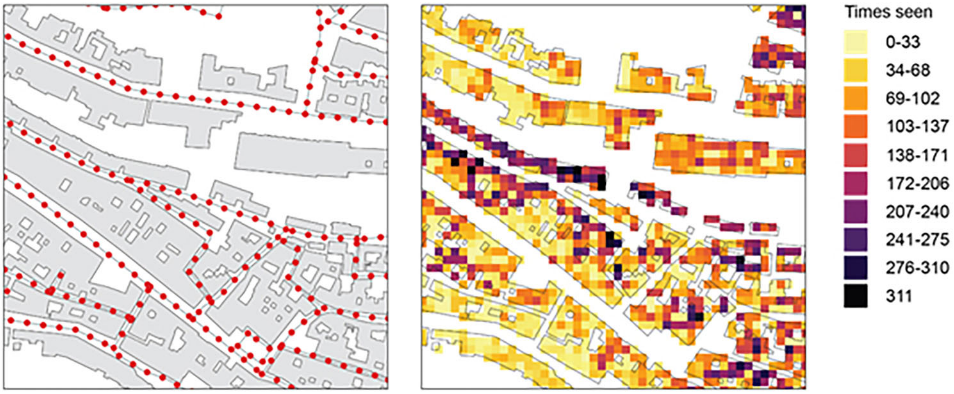

Figure 8. Map of the most visible areas.

very fragile areas will need high integration, fragile areas will need a good level of integration and preferred areas will need basic requirements (Figure 9). The landscape integration strategies include key factors, such as land use, visibility, in relation to landscape character, visual properties, addressed by specific parameters at the spatial planning level, such as the frequency of views, land cover, and at the design level, such as size, composition, density and colour of the solar power plant. Multifunctional solar farms are also considered as integrated solutions. These strategies are meant as a guideline for developers to address the required levels of integration.

5. Discussion

In this section, the authors address several key aspects of the case study methodology, including data considerations, spatial extent, stakeholder involvement, and its comparability to similar approaches in sustainable energy transition at the local level. Furthermore, we explore the potential integration of this approach into existing local urban planning tools.

5.1. *Data and spatial extent*

Creating spatially explicit content for energy transition requires a large amount of data. Data should be both accurate and up-to-date. While higher-resolution data (e.g. DSM with 0.50 m resolution) in the visibility analysis and solar irradiation mapping could have yielded more precise results, this would demand substantial computational resources. Moreover, more up-to-date data would facilitate the integration of the energy spatial plan with other planning strategies: for example, regeneration plans and future development plans. The proposed study requires land use and morphological information since it aims to work with the existing geometries as well as zones. In general, such data are available in local cadastres and georeferenced repositories. In case it is not possible to find such data through municipal datasets, the Corine Land Use offers a good solution for land use, and Open Street Map can be used for morphological information (e.g. streets, buildings). The urban scale is beneficial for the management of energy transition of local administrations and can be aligned with regional or provincial studies, if available. Because of the limited dimensions of the city, the work

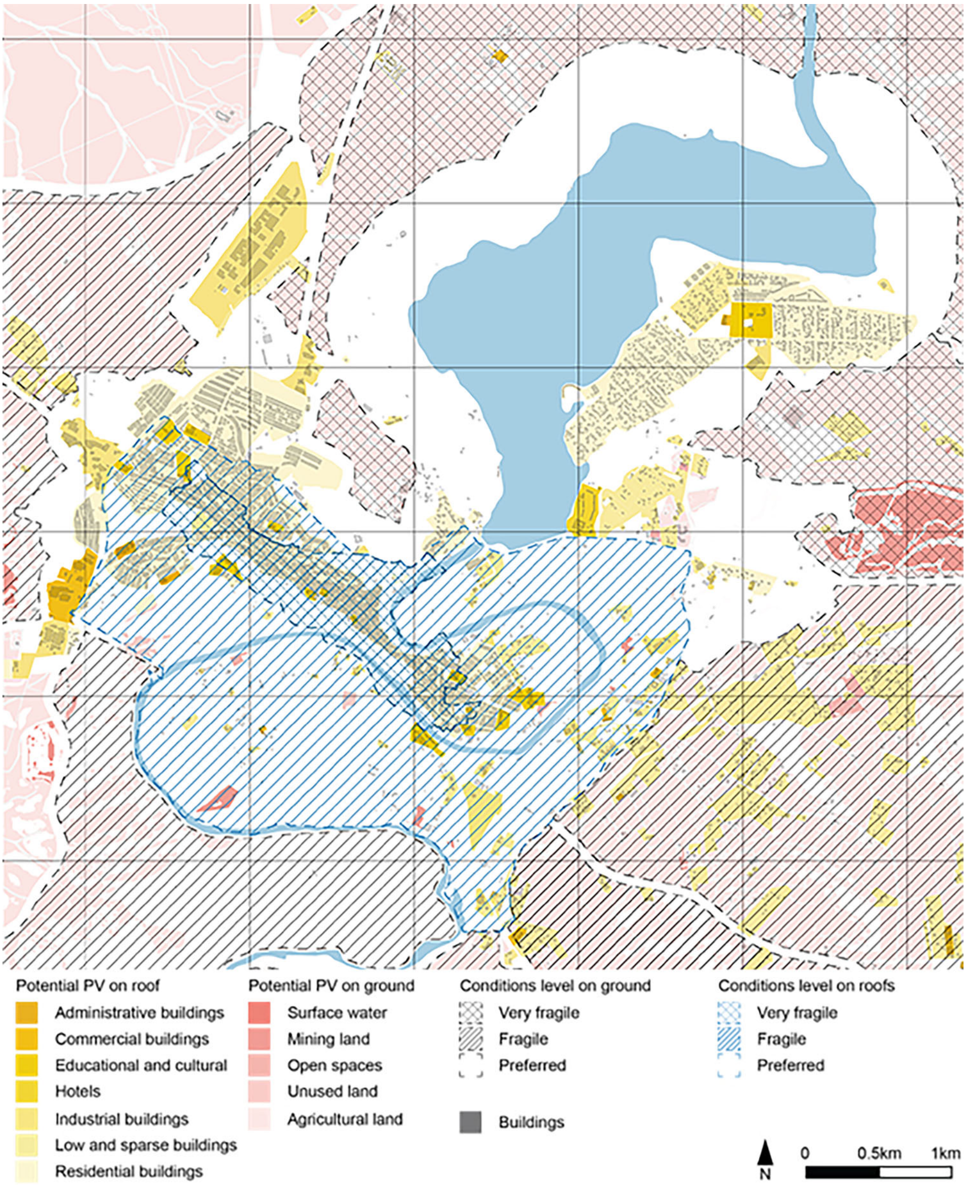

Figure 9. Solar energy spatial plan.

does not require scale-dependent methodologies, as in the case of Florio *et al.* (2018). This aspect should be evaluated at the beginning of the study according to the type and dimension of the city and to the scope of the study.

5.2. Comparison with similar methodologies

The proposed workflow combines quantitative data for renewable energy potentials with qualitative considerations of the inhabitants and local experts. Moreover, it introduces varying levels of suitability with corresponding integration requirements. Similar studies have combined qualitative and quantitative aspects using GIS, for example in Oudes and Stremke (2018) and Spyridonidou *et al.* (2021). The latter combines spatial planning tools and multi-criteria decision-making methods (AHP) in the process of site selection. The former gathers spatially explicit data on potentials, constraints, existing supply and assessment criteria for solar planning. However, the mentioned studies define suitable and unsuitable areas for PV farms without considering possible levels of landscape integration. The methodology proposed by Clarke, McGhee, and Svehla (2020) combines aspects related to sustainable energy landscapes (technical constraints, environmental, social and economic issues) as well as the visual impact of neighbouring housing to improve acceptance levels. However, similar to the previous studies, the result is a support map defining suitable and unsuitable locations. The method proposed by Florio *et al.* (2018) defines levels of architectural integration required in relation to the criticity of the area. However, they only consider solar applications in roofs, excluding on-ground applications and they do not consider in relation to other ecological issues and qualitative considerations. Our work expands the idea of suitability levels to encompass on-ground applications, offering a comprehensive workflow that blends assessment criteria, qualitative data, and integration quality levels. This work relies on the mentioned studies to combine the main concepts: sustainable energy landscapes (through assessment criteria), social acceptance (through qualitative data and visibility analysis), and landscape-architecture integration (through the levels of integration required). However, specific procedures could be upgraded in terms of precision and detail. For example, with regard to the visibility analysis, including the mass effect and the possible hours per year in which a PV plant is observed (Zorzano-Alba *et al.* 2022; Fernandez-Jimenez *et al.* 2015) or the visibility degree (Zorzano-Alba *et al.* 2022; Wrózyński, Sojka, and Pyszny 2016) could increase the precision of the results. Furthermore, the output could change according to the preferred type of representation by the Municipality to match other plans, such as presented by cadastral parcel instead of by cell (Zheng *et al.* 2023). With regard to the concept of social acceptance, despite limiting the impacts affecting public perception, strategies could be introduced to promote social benefits, such as financial involvement (van den Berg and Tempels 2022; Terwel, Koudenburg, and Mors 2014), within the procedures.

5.3. Interaction with stakeholders

Interactions with stakeholders have been increasingly considered in energy planning studies. The present study is built on the feedback received by local experts. However, the formation of the proposed methodological procedure does not rely on a direct involvement of municipality members. This aspect is a limitation of the research, as designing the procedural workflow in collaboration with decision-makers could enhance its potential application and to better frame it to the context. Yet, an interaction with local experts and with the inhabitants has been established to integrate their opinion and perception for the generation of the plan, specifically on the assessment of siting criteria and criticity levels of municipal areas. Besides the inclusion of local knowledge and public perception, stakeholders' interactions can be useful to define energy potentials (Feizizadeh and Blaschke 2013; Oudes and Stremke 2018; Spyridonidou *et al.* 2021), and capacity building (Oudes and Stremke 2018). Moreover, the design strategies for landscape and architectural integration should be discussed in accordance with local stakeholders. For this purpose, we suggest the revision of each step with local stakeholders in the overall methodological framework to better frame the results to the area (González and Connell 2022) and improve the quality of participatory processes (Roddis *et al.* 2020). Finally, translating the qualitative considerations into quantitative scenarios required degrees of interpretations, which could be facilitated by a more frequent and organized stakeholder interaction working table.

5.4. Integration in the local planning tools

According to the interviews with local experts, a local planning tool to manage energy transition is not present, limiting the capacity to control landscape transformations derived by renewable energy production. According to their comments and to the literature studies, the proposed framework should be integrated within the local planning tools (e.g. General Urban Plan). The methodological procedure that we propose aims to be used as a spatial energy plan, defining zones within the Municipality and assigning quality requirements. Thus, it could be used for the landscape impact assessment of proposed projects or for the development of scenarios. In the first case, it defines suitable areas and areas with special integration requirements to evaluate projects. In the second case, it assists the delineation of a future scenario according to an established energy target, ensuring the preservation of landscape values. As a local planning tool, it divides the Municipality into zones according to the level of criticity, defining if and how SPPs can be implemented. Moreover, the proposed framework links spatial planning considerations to architecture and landscape quality aspects, by setting levels of integration to pursue by design practices.

Currently, landscape quality legislation is a responsibility of the regional level. Moreover, some landscape-related issues are competencies of environmental and territorial law, and cultural heritage protection. However, they do not include landscape quality requirements related to the exploitation of RET (Roth *et al.* 2018). The approach we propose allows more controlled and organized landscape transformations, preserving urban quality. Moreover, being defined as a spatial planning tool, it can be aligned with other urban and territorial issues, such as climate adaptation, facilitating decisions with trade-offs and integration between challenges. By contrast, this requires efforts and skills in which Municipalities should be willing to invest. Dividing the Municipal area into performative zones may create economic disadvantages, since some areas would require better quality of solar materials, geometries or patterns resulting in higher costs or lower efficiency. For this purpose, incentives could be introduced by the Municipality. In this view, the definition of clear energy targets and the prioritization of preferred areas are important aspects. Moreover, temporary solutions which do not affect soil permeability might be considered in certain areas.

6. Conclusion

Achieving a successful energy transition necessitates a link between its spatial dimension and sustainable development scenarios and calls for dedicated planning and policy-making efforts. The primary aim of this research was to advance a spatially explicit and evidence-based approach for sustainable energy planning on a local scale. The framework we propose includes stakeholders' reflections and landscape integration considerations. The former is included through qualitative insights garnered from interviews with the inhabitants and local experts, which are subsequently translated into spatially explicit data. The latter is realized by establishing specific quality requirements within the municipal area. Compared to the current practices, the proposed method involves early-stage incorporation of qualitative stakeholders' considerations and outlines quality requirements for landscape- and architecture-integration in future projects.

Although the study draws on international cases, the scope of the research was influenced by the context of the case study. Thus, the findings apply to the involved country and in others with comparable physical, social, and economic conditions. Additional studies in different contexts or focusing on different technologies may lead to additional knowledge. The proposed procedure is expected to support Municipalities to plan energy transition, by facilitating public acceptance. Moreover, the proposed approach shows how to integrate stakeholder and inhabitants' considerations in the selection of suitable areas for RES deployment in the early stages of the process. Economic considerations have not been included in the proposed process, but they require attention in a planning process. The trade-offs between qualitative considerations and economic aspects can be considered during the creation of a scenario or in its evaluation. Considering the inevitable exploitation of RET in urban areas, a close collaboration between scientists, stakeholders and inhabitants would favour sustainable energy transition and enable more accepted landscape transformations. Defining energy transition scenarios at the local level, as exemplified in Arcos de la Frontera, necessitates recognition and alignment with existing local initiatives, strategies, and planning tools. This ensures a comprehensive evaluation of trade-offs between various urban challenges.

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