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Ecosystem Approach in Agrivoltaic Parks Design

An Innovative Integral Methodology for the Implementation and Design of Agrivoltaic Fields

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Abstract. The approach to strategic landscape design faces today two challenges: a) the reduction of biodiversity loss b) the mitigation of the negative impact that anthropic activities have on ecosystems. As these are subject to a continuous transformation process, it is essential that the design methodology considers its underlying properties. Hence, arises the need of a profound paradigm shift: integrate better the human landscape into the natural one. To achieve this goal, it is necessary to understand first landscape dynamics as well as the mechanisms that facilitate its resilience and functionality in ecological terms. This is possible thanks to the strategic framework of the Ecological Infrastructure. The landscape proposal must evaluate then the sequence of actions to be carried out, the measures necessary for the improvement of the recognised systems, and its possible evolution over time. Then, according to the Sustainable Development Goals (SDGs), agreed by the EU 2030 biodiversity strategies, the proposal must demonstrate: How biodiversity will improve and how it will be preserved - How ecological processes linked to biodiversity will be upgraded - How cultural and social processes linked to the site will be enhanced - How agricultural and energy production will increase land efficiency - How disturbances will be modulated and controlled. This methodology carried out in Spain aims to demonstrate that the implementation of agrivoltaic fields create an optimal synergy to ensure food security and mitigate the effects of climate change, but also provide the chance to make the landscape more sustainable, efficient, and beautiful.

Keywords: Agrivoltaic, Ecologic Infrastructure, Ecosystem Services, Landscape Design, Sustainable Landscape

First section

Method carried out

The design of agrivoltaic parks raises several issues: its difficult implementation into the territory, its dimensioning in relation to the surrounding landscape, the balance between the natural and artificial landscape, the intensive exploitation of natural resources, the coexistence with the agricultural activity, the change of sociocultural paradigm, the adequacy of existing energy infrastructures, the coexistence with heritage elements, among others. All these issues can be addressed through a transdisciplinary methodology that approaches landscape design as a proactive and effective tool. The main challenge of this methodology is then ensured sufficient consistency and strength of the proposal, as well as data, throughout the entire work process thanks to its articulation in 3 steps:

- First step: Analysis and Diagnosis. Describes the different interactions between the components of the agrivoltaic park and the landscape systems; this provides a better understanding of which systems are most relevant to the balance of landscape's structure and state.

- Second step: Evaluation and Modelling. Helps to assess potential negative impacts and their progressive mitigation through modelling of alternative scenarios.

- Third step: Strategic Design. Defines the technical and design criteria for integrating agrivoltaic parks ensuring a better ecological and landscape functionality and efficiency.

These steps relate to all stages of agrivoltaic landscape design and are a prerequisite for the validity and appropriateness of the proposal.

Second section

Case study

For a better understanding of the methodology, being applied in other projects endorsed by large energy companies as well as by the technical departments of the catalan government, is taken as a reference the work carried out in Castellfollit del Boix (41°39'28.2 "N 1°39'54.1 "E), in Catalonia (Spain).

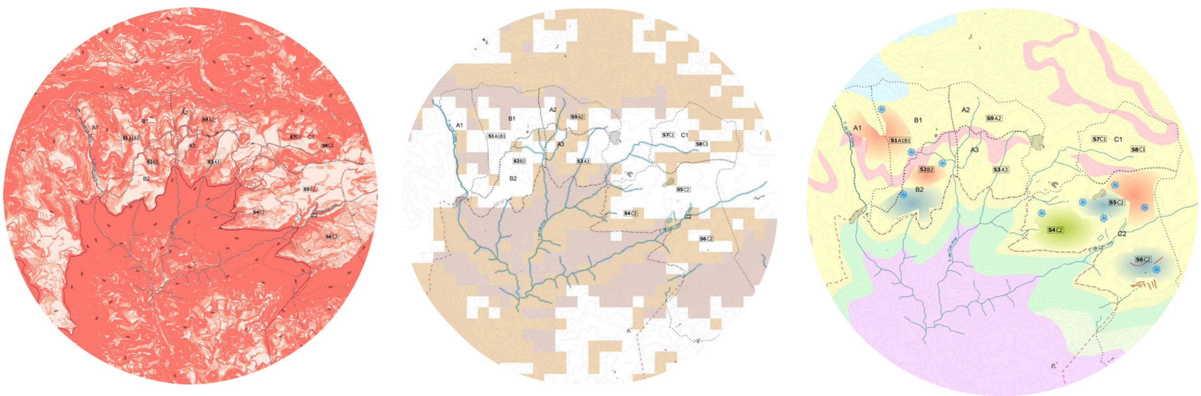
The project foresees the implementation of an agrivoltaic field with an energy production of 44 MWp. To achieve the most suitable integration of the photovoltaic sectors on site, the analysis covers an area of more than 300 ha, much wider than that required for its implementation. This helped to adapt and progressively reduce the surface of the photovoltaic sectors and its impact on landscape.

Ecosystem services - supporting, provisioning, regulating and cultural - served as a guide, on a large scale, for the configuration of the ecological infrastructure, and on a smaller scale, for the definition of environmental and landscape integration criteria as well as technical design, balancing the actions on site.

First step: Analysis and diagnosis.

This analysis allows the recognition of the most significant landscape components based on their ecological properties: composition, structure, boundaries, complexity, and stability.

Topography and Soil



FUNCTIONAL SLOPES | EROSION RISK | GEOLOGY AND ITS AESTHETIC VALUE

Figure 1. Functional slopes – Erosion risk – Geology and its aesthetic value

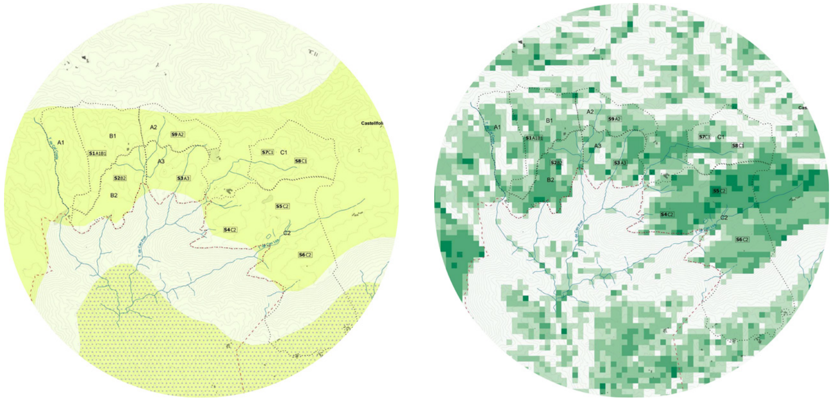


Figure 2. Type of soil –Agrological classification

- "Functional Slopes" Map. In white colour are represented the areas with a maximum slope of 14%; the photovoltaic structure can be installed on these surfaces, reducing earthworks and the impact on the ground to a minimum. In the red zones, with a slope greater than 15%, by contrast, a negative impact on soil composition and structure would be generated. Therefore, in the second step of evaluation and modelling of alternative scenarios, the occupation of these zones is minimized.

- "Erosion Risk" Map. The risk of soil erosion is low in most of the study area, although in the watercourses it is high due to the acceleration of the water flooding. This information is useful to define the necessary measures to restore and enhance soil complexity and stability.

- "Geology and its aesthetic value" . This map describes different landscape qualities of the geological system [1] (geotopes and geozones): In the southern fringe where marked linear shapes generate a visual horizon characteristic of this landscape - Occasionally on paths and stream banks, where surface outcrops stand out as elements of interest - On the borders of some fields, where rock mounds reveal the local practice of land levelling in agricultural areas.

To maintain these physical and aesthetic qualities and optimize the management of this natural resource in situ, already in this preliminary step, the project foresees: The preservation of singular rock formations and the creation of equipped paths to enhance its cultural value - The use of the stones that may appear during the excavation works in the execution phase, for the new drainage system

- "Type of soil" Map. This analysis is useful to know soil's permeability directly related to the other significant landscape components.

- "Agrological Classification" Map. In most of the area, the agrologic quality levels are medium except for specific areas where they are medium-high. This map is useful to know soils limitations and its general vocation.

The analysis of topography and soil is directly related with the ecosystem services of regulation and maintenance of physical conditions. CICES V5.1 [2]: [2.1.2.3 - 2.2.1.1 – 2.2.1.2 - 2.2.4.1 – 2.2.4.2 - 3.1.2.4]

Water System

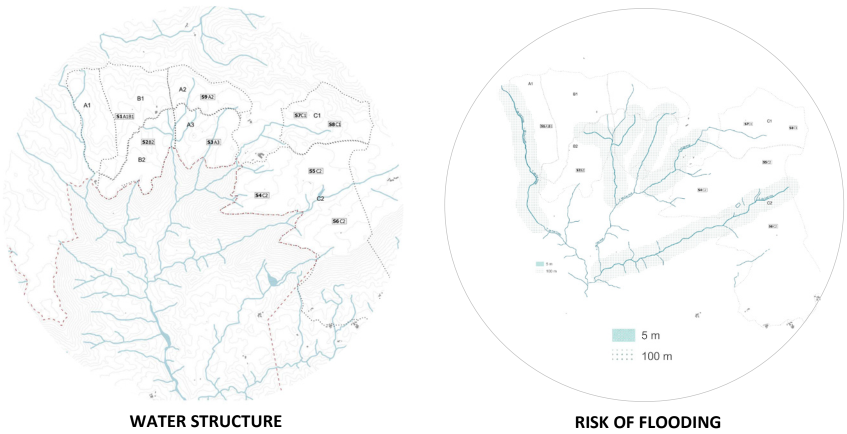


Figure 3. Water structure - Risk of flooding

Habitats

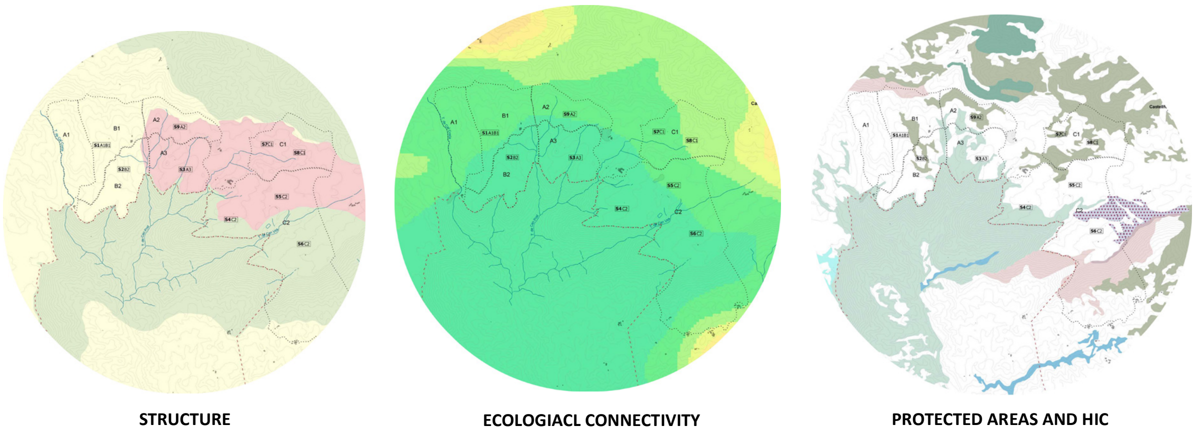


Figure 4. Habitats structure - Ecological connectivity - Protected areas and Habitat of Community Interest (HICs)

- "Water Structure" Map. The hydrological system has been particularly disrupted by agricultural activity. In the case of the streams that cross the zones identified in the Territorial Plan of the Central Regions [3] (PTCC) as areas of special protection, in the later steps are proposed a series of actions aimed at recovering their ecological functionality, also associated with Habitats of Community Interest.

- "Risk of Flooding" Map. To favour the evacuation of water flows and avoid the possible risk of flooding, the photovoltaic sectors do not occupy the 100-meter-wide buffer strips; in these areas, the proposal defines actions focused on soil stabilization, water infiltration and runoff erosion reduction.

- "Habitats Structure and Ecological Connectivity" Maps. The photovoltaic sectors are mostly located on agricultural land, but in the north and south, the presence of ecological connectors, especially habitats of natural interest, requires special care. Thus, is reduced the occupation of these habitats, and, at the same time, nearby areas have been identified to counteract its disruption, reinforcing ecological connectivity on a large scale.

- "Protected Areas and Habitats of Community Interest" Map. The Annex I of Directive 97/62/EC [4] distinguishes two types of HIC: priority and non-priority. They are not protected natural habitats, but catalogued habitats whose conservation must be guaranteed. These are habitats that are either threatened with extinction in their natural range in the European Union or have a reduced area of distribution due to their regression.

All the HICs listed on the map are of non-priority interest, except for the Mediterranean meadows rich in annuals and the Iberian gypsiferous vegetation, which are of priority conservation interest. This map helps to assess the impact that the different photovoltaic sectors may generate with respect to these. As a general criterion in the development of the PV proposal, the distribution of panels, access roads and service areas are designed to affect as little as possible the HIC areas; in addition, wherever possible, a buffer zone of variable width has been provided around the PV sectors, in order to control the disturbances caused by several activities (energy and agricultural production, cultural/educational activities along the routes of interest, etc.) planned in the surrounding landscape. The analysis of water and habitats is directly related with the ecosystem services of regulation and maintenance of physical conditions. CICES V5.1 [2]: [2.2.2.1 – 2.2.2.2 – 2.2.2.3]

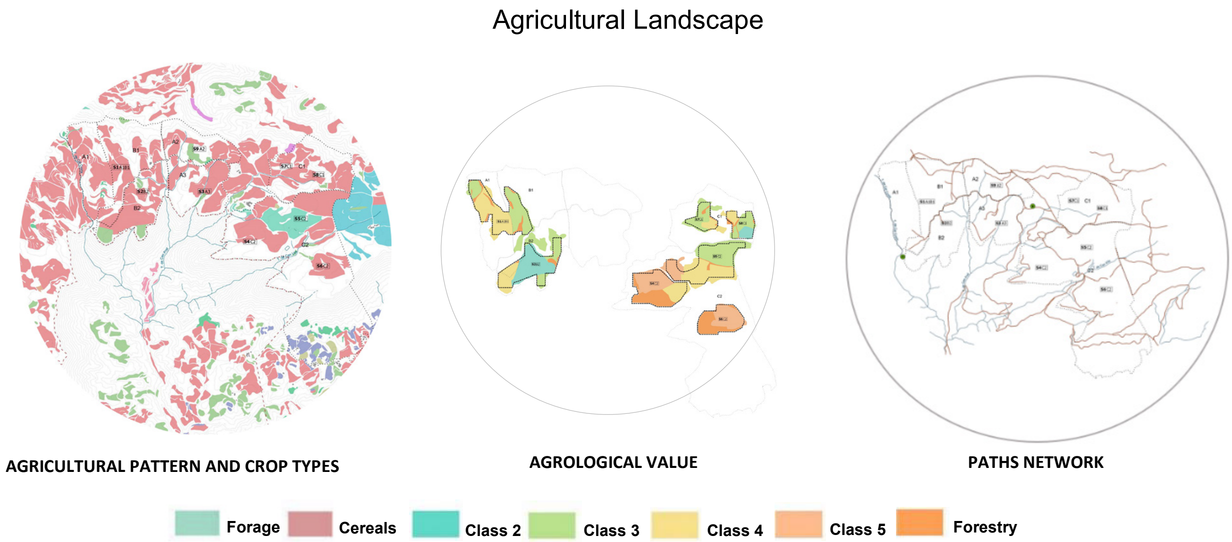


Figure 5. Agricultural pattern and crop types – Agrological value – Paths network

- “Agricultural Pattern and Crop Types” Map. Characterized by the presence of cereal crops, integrated with small, wooded areas and natural stone outcrops, agricultural activity has shaped over time this landscape in which topographic changes are evident in some areas. This map describes agricultural landscape productivity and pattern, as well as its relationship with the local economy.

According to the Department of Agriculture Report 2020 and subsequent decree laws [5]: the maximum PV occupation allowed on agricultural land with rainfed crops is the 10% of the municipal agricultural area. The proposal has therefore been adapted to this specific requirement as shown in the table below:

Table 1. Agricultural land occupation allowed

OCCUPATION OF AGRICULTURAL LAND		
	Surface ha	Percentage
Agricultural land in municipal areas	**947**	100%
Agricultural land in analysed area	136	14%
Agricultural land in PV sectors	68	7%

According to the agrologic initially defined by the Soil Conservation Service of the United States Department of Agriculture, and then adapted to Catalan conditions by the Ministry of Agriculture, Fisheries and Food, and by DARP:

- PV plants cannot be implemented on soils of agrological class I and II.

- Photovoltaic plants will be allowed on soils of agrological class III and IV, when there are no other alternatives and provided that an in-depth study has been carried out to prove it and limiting the surface area.

- In soils of agrological class V, VI, VII and VIII, photovoltaic plants are admissible without limitations.

- "Agrological Value" Map. In accordance with these requirements, the map describes soil fertility according to agrological classes [6].

Hence, the project proposes:

- On soils of agrological class II: agrivoltaic production. It is planned to implement the local species, the Mongeta del Ganxet (Phaseolus vulgaris, a variety of bean catalogued by the Red de Productos de la Tierra program and included in the Catalogue of local varieties of agrarian interest of Catalonia [8]), to curb the loss of genetic diversity.

- On soils of agrological class III - IV – VI, the production of two complementary crops for the restoration and agricultural improvement of the soil: 1. The sowing of native seed mixture that provides flowering for a large part of the year for pollinators, linked to an existing local beekeeping activity in the environment. 2.The implementation of low height forage sowing for sheep feeding, linked to the local grazing activity.

Table 2. PVSP Occupancy in agrological class soils

OCCUPANCY OF AGROLOGICAL CLASSES (ha)	
	Surface ha
Surface Agrological class II	7,82
Surface Agrological class III	19
Surface Agrological class IV	37,01
Surface Agrological class VI	11,33
TOTAL SURFACE	**75,16**

The specific design of productive areas is still in process. It is worth mentioning among the two proposal, agrivoltaic design is relatively complex: first, it is necessary to combine the PV infrastructure with the type of crop to optimize land use. Their composition must be designed to meet desired yield and quality objectives. Parameters such as LER (Land Equivalent Ratio), help to test how polyculture can increase land yield compared to single use. Shade area, angle of inclination and orientation of panels, technology used, size of PV structure, etc. should be considered to achieve maximum energy and agricultural efficiency in terms of production and maintenance. Anyway, the benefits associated with the proposal: 1. Increased social acceptance. 2. Improved ecological functionality. 3.Regeneration of agricultural land. 4.Increased biodiversity. 5.Creation of habitat and food for pollinators. 6. Promoting the conservation of agricultural activities, which are at risk due to the adverse effects of climate change. 7.Increased efficiency and innovation of the local and circular economy.

- "Paths Network" Map. The agricultural landscape forms a mosaic of relatively small pieces associated with farmhouses of heritage value. As it is bordered to the north by forested areas that accompany the undulating relief, and to the south by several streams that together with the topographic depression represent its natural boundary, the paths network is analysed to preserve their continuity and functionality.

The analysis of agricultural landscape is directly related with the ecosystem services of provisioning and preservation of cultural landscape: CICES V5.1 [2]: [1.1.1.1 – 3.1.2.3]

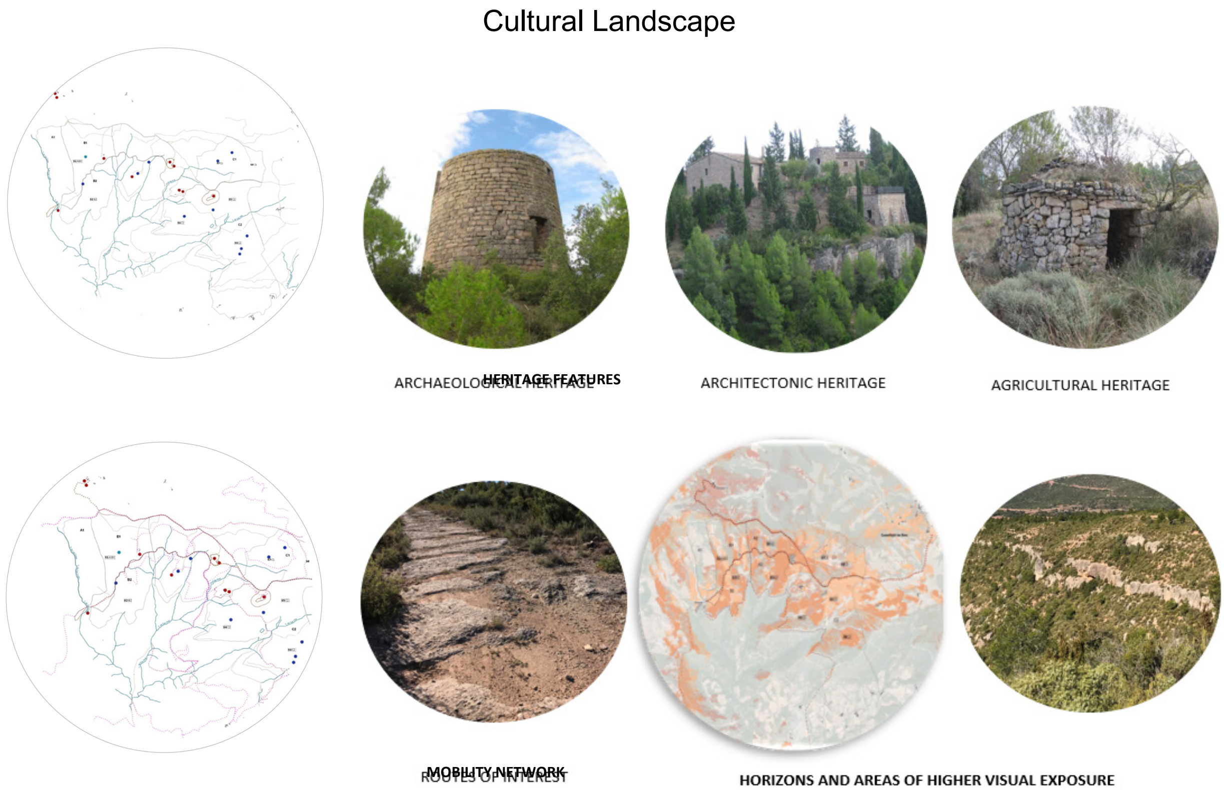


Figure 6. Heritage features - Mobility network- Horizons and areas of higher visual exposure

- "Cultural Landscape" Maps. The archaeological, architectonic, and agricultural features, as well as the mobility network and visual horizons, are considered integral part of landscape proposal.

For the heritage elements - both natural (tree patches or monumental specimens) - and patrimonial (architectural and archaeological) - which are currently quite degraded and abandoned, a series of actions are planned for their improvement and enhancement, giving way to future municipal actions aimed at the revitalisation of the local landscape. The analysis of the paths of interest, is useful to ensure its continuity making possible a better accessibility to the areas of interest (farmhouses, archaeological sites, etc.) that will participate in the process of dynamization that the proposal intends to activate. Along these paths, is mapped landscape perception, to identify the most beautiful horizons, geological formations of interest to preserve, as well as the most exposed photovoltaic sectors where it will be necessary to reduce the visual impact.

The analysis of agricultural landscape is directly related with the ecosystem services of preservation of cultural landscape: CICES V5. 1 [2]: [3.1.1.1 – 3.1.1.2 – 3.1.2.1 – 3.1.2.2 - 3.1.2.3 -3.1.2.4 – 3.2.1.1 – 3.2.1.3]

Second step. Evaluation and Modelling

The diagnosis output is relevant for the modelling of alternative scenarios to reduce impacts of agrivoltaic parks and finally conceive the most suitable proposal.

For each scenario, thanks to the GIS (Geographic Information System) - a software that allows to create interactive queries, analyze, and represent in an efficient way any kind of referenced geographic information associated to a territory, connecting maps with databases – have been designed specific maps showing the areas of soil, HIC, etc., affected by the implementation of the photovoltaic sectors. The potential negative impact, called "friction area", is represented and measured on a spatial map, and helps to progressively reduce the areas or points of impact and ensure a better ecological functionality (connectivity and biodiversity) and landscape integration and efficiency.

For each scenario the “friction areas map” shows the impacts on: Soil: a. Ground (excavations and movements) b. Areas of geological interest (direct impact) - Water: a. Water bodies (discontinuity) – Habitats: a. Habitats of Community Interest (HICs) (fragmentation) - Agricultural land: a. Crops types (diversity) - b. Agricultural pattern (structure) c. Path network (discontinuity) - Heritage elements: a. Archaeological areas (direct impact) - Horizons and areas of higher visual exposure: a. From urbanizations and routes of interest (visual impact).

The maps show that among the different systems analyzed, habitats and soil are the most affected. Therefore, once the friction areas map for each scenario has been modeled, the scenario with the least impact on habitats is chosen as the best, although its impact surface on soil is slightly higher than that of Alternative 2.

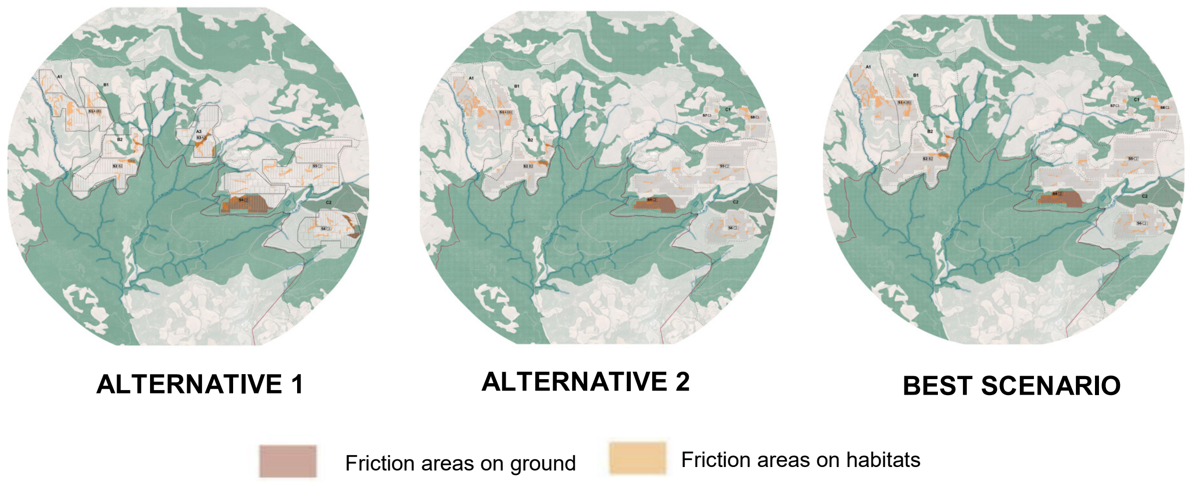


Figure 7. Impacts comparative study

Table 3. Comparative study of the impact areas of three scenarios

COMPARATIVE STUDY	Scenario A1	Scenario A2	Best Scenario
AGRIVOLTAIC SECTORS	92,65 ha	90,19 ha	75,16 ha
PANELS COVERAGE	53,10 ha	52,71 ha	51,76 ha
GROUND FRICTION AREAS	7,32 ha	5,09 ha	5,40 ha
HIC FRICTION AREAS	5,85 ha	4,70 ha	3,62 ha

Hence, the exhaustive analysis of all the significant components allows to configure a final proposal, considered to be the most suitable.

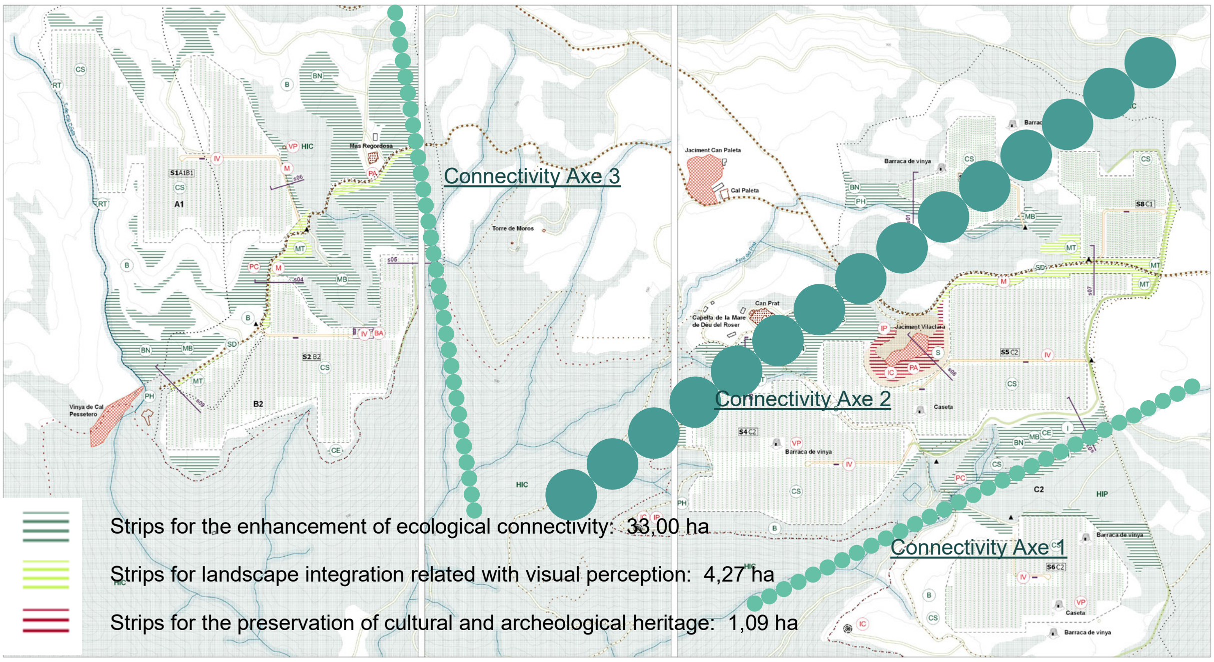


Figure 8. Strips for the ecological enhancement and landscape integration

For the best scenario, are designed the strips for the ecological enhancement and landscape integration; these aim to create a buffer, of variable width, to regulate and mitigate disturbance and impacts on Habitats of Community Interest, on hydrological system, on areas of cultural interest - both natural (wooded areas or monumental trees) as well as architectural or archaeological; the fringes are designed also to preserve the horizons of aesthetic interest.

Strips for the enhancement of ecological connectivity. Over a surface of 33,00 ha, the green color represents the areas where it will be necessary to improve the ecological processes and environmental functionality. Based on the forecasts of the Territorial Plan [3], these strategic zones have been mapped to enhance ecological connectivity along three axes where the habitats are currently very fragmented.

Strips for landscape integration related with visual perception. Over a surface of 4,27 ha, the light green color represents the zones where managing earthworks and/or planting vegetation, it will be possible to ensure maximum visual integration of the PV sectors and its elements.

Strips for the preservation of cultural landscape. Over a surface of 1,09 ha, the red color represents the areas that will be transformed to promote the cultural landscape & innovation according to the following activities: a) eco-didactic – b) science-didactic – c) cultural-didactic – d) social gathering. The design of equipped pedestrian paths will also make possible a better accessibility to the different areas (farmhouses, archaeological sites, etc.) that will participate in this process of revitalization that the proposal intends to activate, making the local community aware of their value and benefit.

Some of the design criteria adopted to accomplish these goals are: Soil: a) use and management of ground and rocks on site- b) preservation of areas of geological interest - Water: a) Preservation of water system – b) regulation of water infiltration and storage – Habitats: a) Buffer zones to preserve HICs – b) structural composition of vegetation – Agricultural Production: a) production of a specie of local interest within photovoltaic sectors – b) agrivoltaic sectors integration on site – c) continuity and accessibility of agricultural paths - Perception: a) strips for visual integration – Culture & Innovation. Areas for the implementation of a) eco-didactic areas – b) science-didactic areas – c) culture-didactic areas – d) social gathering areas. Coherently, within the strips for the ecological enhancement and landscape integration, the design criteria are then developed to improve the ecosystem services previously identified according to the CICES V5.1 [2]: regulation and maintenance of physical conditions: [2.1.2.3 - 2.2.1.1 - 2.2.1.2 – 2.2.1.3 – 2.2.2.1 – 2.2.2.2 – 2.2.2.3 - 2.2.4.1 – 2.2.4.2.] Provisioning and preservation of cultural landscape: [1.1.1.1.] preservation of cultural landscape: [3.1.1.1 – 3.1.1.2 – 3.1.2.1 – 3.1.2.2 - 3.1.2.3 -3.1.2.4 – 3.2.1.1 – 3.2.1.3.]

Third section

Conclusion

The main advantage of this methodology is the recognition and comprehension of landscape components and its ecological properties. With this approach the agrivoltaic parks become an ecological infrastructure strategically designed as a tool for didactic and scientific promotion and for the improvement of local culture. The production of clean energy that have a relevant role in the ecological transition is therefore the chance to promote a more sustainable and efficient landscape and economic development model, as recommended by the EU 2030 biodiversity strategies.

As the urgent challenges to be addressed today are to reduce biodiversity loss and mitigate the negative impact of human activities on the landscape, the methodology focuses on an integral transformation strategy that goes beyond the specific design of agrivoltaic fields. In line with the current Sustainable Development Goals (SDGs), the recognition of environmental and landscape dynamics and values is of paramount importance in defining the transformation actions of the proposal, which is based on the simultaneous consideration of three relevant aspects (green infrastructure, Ecosystem Services, and les Nature based solution (NBS)).

The green infrastructure concept introduces objectives aimed at: Improve biodiversity and strengthen connectivity between natural areas, thereby increasing large-scale wildlife mobility - Promote a better quality of life and well-being in the landscape where people live and work - Recognize and enhance elements of cultural interest - Counteract the effects of climate change (flooding, soil erosion, etc.) by improving water management, soil management, reducing CO_2 emissions etc.

Ecosystem services provide solid guidance for defining and planning actions and design criteria, allowing quantitative and qualitative evidence of the contribution of each to landscape improvement. A wide range of ecosystem services are analysed in the proposal, a potential trend toward increased environmental quality and greater opportunities for social, cultural, and economic development.

At a more detailed scale, design according to Nature Based Solutions, is key to restoring, regulating, and maintaining ecosystem functionality and efficiency. In conclusion, the main advantage of this methodology is that it demonstrates how, by managing the complexity of landscape and the interactions and needs of the different components analysed, ecosystem services can be sustained.

Introducing ecosystem services into the development model is not an additional cost but a benefit, as it increases the income related to the ecological and social benefits that can be developed. This is an important aspect of stimulating the interest of private companies to implement sustainable solutions, creating shared value in the landscape. This ecological development model, which can enhance both private and public benefits, requires a multidisciplinary approach to share knowledge among different stakeholders and fill information gaps typical of a sectoral perspective, creating a holistic view of the professional skills and experiences involved.

Data availability statement

Institut Cartogràfic i Geològic de Catalunya.
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CICES. https://cices.eu/

DARP. Departament d'Acció Climàtica, Alimentació i Agenda Rural.
https://agricultura.gencat.cat/ca/inici

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Competing interests

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The case study carried out has been realized with: Jordi Bellmunt and Xavier Mayor: conceptualization and methodology

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