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Towards a typology of solar energy landscapes: Mixed-production, nature based and landscape inclusive solar power transitions

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ABSTRACT

Development of ground-mounted solar power plants (SPP) is no longer limited to remote and low population density areas, but arrives in urban and rural landscapes where people live, work and recreate. Societal considerations are starting to change the physical appearance of SPPs, leading to so-called multifunctional SPPs. In addition to electricity production, multifunctional SPP produce food, deliver benefits for flora and fauna, mitigate visual impact or preserve cultural heritage. In this paper, we systematically examine the different spatial configurations of multifunctional SPPs that reflect a range of contemporary societal considerations. The purpose of this research is to create and test an SPP typology that can support evidence-based and transparent decision-making processes, from location finding to implementation. Comparative case analysis, expert interviews and questionnaires are used to distinguish different types of SPP. We propose a typology that consists of four dimensions: energy, economic, nature and landscape. These dimensions lead to three main types of multifunctional SPP: mixed-production, nature-inclusive, landscape-inclusive, and their combinations. This typology supports decision-making processes on solar power plants and adds to the existing (solar) energy landscape vocabulary. In doing so, the research supports the transformation of energy systems in a way that meets both the quantitative goals and qualitative considerations by society.

1. Introduction

Solar power plants (SPP) contribute to achieving renewable energy targets and mitigating climate change. SPPs are no longer limited to remote and low population density areas, but appear in urban and rural landscapes where people live, work and recreate [1,2]. The physical appearance and experience of these landscapes by people is changed by photovoltaic (PV) panels, inverters, transformers and other supporting electrical infrastructure [3–6]. Consequently, new landscapes are created. These are conceptualized as (solar) 'energy landscapes' [3,7] and increasingly understood as co-constructions of social and material relations, notably in the ERSS special issue *Spatial Adventures in Energy Studies* (for example [1,8,9]).

Recent publications highlight the need to include a broad set of societal considerations in the creation of solar energy landscapes, beyond techno-economic considerations such as energy efficiency and cost-effectiveness [10,11]. In the context of energy landscapes, societal considerations can be economic, for example loss of existing land use [12,13], related to nature, for example interference with flora and fauna [14,15] and related to landscape, for example visual impact [5,16]. These considerations become more urgent in the light of (local) resistance against planned SPPs [2,17,18], which is expected to increase while SPP become a major player to meet renewable energy targets. In this paper, we consider an SPP as an *overlay* on rooftop, water or land surface, while in building integrated PV (BIPV) construction elements are *merged* with PV [19]. We focus on land based or ground-mounted SPP because they have received most criticism, compared to for example PV on water or rooftops [20].

Societal considerations regarding SPPs, as with any other energy infrastructure, are commonly discussed among stakeholders during the planning and design process [21]. Currently, societal considerations are often used to distinguish between suitable and unsuitable sites for SPP development. Bridge [9] refers to this siting as a strategy of *territorial differentiation*: stakeholders, often governments, differentiate between

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Abbreviations: SPP, solar power plant; PV, photovoltaic; BIPV, building integrated PV; LAOR, land area occupation ratio; MpSPP, mixed-production solar power plant; NiSPP, nature-inclusive solar power plant; LiSPP, landscape-inclusive solar power plant.

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spaces based upon local characteristics and geographical conditions according to considerations of suitability. Suitable locations are often those with favorable technical conditions (e.g. high solar irradiance, available grid capacity) and minor negative impacts. Minimizing negative impact is articulated by identifying low-cost land (e.g. [22]), minimizing ecological effects (e.g. [23]) or addressing visual aspects (e.g. [24,25]). For SPPs, low impact locations often come down to degraded or contaminated land, peripheral areas, infrastructure, surface water and rooftops [26,27]. However, this strategy of finding locations with the least negative impact becomes less effective as the transition progresses and 'easy' locations become scarce [11,18,27]. This strategy also raises ethical questions about social and environmental displacement as the landscape of some communities is targeted more than those of others [28,29].

In this paper we therefore turn our attention to build cases where societal considerations change the physical appearance of the SPP itself [3]. The great majority of SPPs are monofunctional, yet stakeholder values and preferences have started to give rise to multifunctional SPPs [30]. These multifunctional SPPs produce renewable electricity, but at the same time include agricultural functions [31], deliver benefits for flora and fauna [32,33], mitigate visual impact or preserve cultural heritage [34,35].

As a result of including multiple functions, these SPPs have a different spatial configuration when compared to monofunctional SPPs. Spatial configuration in this paper refers to the material and perceivable energy landscape [36], specifically PV infrastructure and accompanying interventions that provide other functions. For example, arrays are elevated to enable agricultural functions beneath PV panels. Developing parts of the SPP project area as nature, uncovered by PV panels, is another example of an alternative spatial configuration. As multiple spatial configurations of SPPs exist, they can be differentiated and specified based on their spatial properties. This aligns with what Bridge [9] refers to as *material differentiation,* where the spatial properties of an SPP serve as markers to 'specify certain qualities'. An overview of different spatial configurations of SPPs is needed to foster the inclusion of societal considerations in evidence-based and transparent decision making processes [37–39].

Several studies have described SPPs with alternative spatial configurations that attend to societal considerations. Together, these studies offer a range of possible differentiations. For example, SPPs that provide for suitable habitats [32,40], or that address the relationship between SPP, landscape patterns and landscape perception [5,41]. Recently, several studies have focused on co-locating PV with agriculture, also known as agrivoltaics or agrophotovoltaics [31,42,43]. This type of SPP is characterized by a synergetic relationship between crop or livestock and PV, as the latter improves microclimatic conditions for the former [31,42,44,45]. A few studies have identified differences between SPPs. Recently, Nilson and Stedman [20] argued for different 'spatial arrangements' of solar energy, although their study focuses on elements such as scale, ownership and distribution of electricity and financial benefits. Hernandez et al. [26] have presented an overview of techno-ecological synergies of solar energy with 'recipient systems' (land, food, water and the built environment). Frantal et al. [27] have identified a group of smart practices of renewable energy, among which SPP, that provides synergy with for example infrastructure, other land uses and cultural heritage. Similarly, Burke [46] has presented an overview of beneficial practices of solar energy, including floatovoltaics (floating PV panels), agrivoltaics and conversion of degraded areas.

However, most of the existing literature has either discussed individual *types* of SPP in detail without considering other types or has presented a *typology* of land use combinations, with little attention to spatial configuration. Existing litsoerature lacks insights in the interaction between societal considerations and the spatial configuration of SPPs. Such insights, however, can support local participatory planning and design processes as well as evaluation of and decision-making on SPPs. The purpose of this research is therefore to create and test a typology of multifunctional SPP that can support evidence-based and transparent decision-making processes, from location finding to implementation. To this end, we systematically examine the spatial configurations of 20 multifunctional SPPs in Europe that reflect a range of contemporary societal considerations. Whether or not considerations have been included sufficiently and the responses of the local communities are outside the scope of this research. The comparative case analysis, supplemented by expert interviews and a questionnaire to case informants provides a starting point for distinguishing between different types of ground-mounted SPP. Our research question is: *which societal considerations materialize in Solar Power Plants and what types of multifunctional SPP can be defined to support evidence-based and transparent decision-making processes?*

In Section 2, Methods and materials, is explained how the case study and literature analysis provided the building blocks for the typology. Furthermore, this section explains how the typology was developed and tested using expert interviews and a case informant questionnaire. The typology of multifunctional solar power plants is presented in Section 3, with dimensions, types and spatial variations as key elements. In Section 4, application of the typology by decision- and policy makers, solar industry and local inhabitants is discussed, as well as avenues for future research and reflections on methods and data. In Section 5, conclusions are drawn on how the typology of multifunctional solar power plants informs the larger debate on renewable energy landscapes.

2. Methods & materials

2.1. Case study and literature analysis

We used a comparative case study [47] and literature analysis to examine how societal considerations start to shape the spatial configuration of SPPs. To capture a large variety of spatial configurations, we identified, selected and analyzed very diverse cases [48]. We first selected Germany, the Netherlands, United Kingdom and Italy as the installed solar power capacity in these countries is among the top of Europe [49]. Language proficiency enabled us to study project documentation of the cases.

Across these countries, over 30 cases were initially identified by reaching out to both spatial and solar energy experts and national associations. We contacted known experts for solar power plants and asked them for cases of exemplary SPP that accommodate multiple functions in addition to electricity production. Furthermore, we identified cases by approaching associations of solar industry and spatial experts and searching their websites.[1] These associations shared our call for exemplary multifunctional SPPs via their regular digital newsletters. From the resulting longlist of cases, we excluded those (1) where other functions in addition to electricity production were limited or absent, (2) where other functions were envisioned but not realized, and (3) where project documentation was insufficient. This led to the selection of 20 cases (Table 1) that were subsequently analyzed.

The spatial analysis was performed on the basis of an existing analytical framework that focuses on the interaction between solar infrastructure and the host landscape, visibility, multifunctionality and temporality of SPP [30]. To the best knowledge of the authors, no other analytical framework exists that supports the analysis of spatial properties of multifunctional SPPs. We examined project documentation, including design drawings, and satellite imagery to identify the spatial properties. Once the properties were identified, they were further

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[1] Associations in Germany: German Solar Association (BSW) and German Association of Landscape Architects (BDLA). The Netherlands: Holland Solar, Netherlands association for garden- and landscape architecture (NVTL) and Dutch association of urban designers and planners (BNSP). Italy: Italian Association of Landscape Architecture (AIAPP). United Kingdom: Solar Trade Association and Landscape Institute.

Table 1
The selected cases. The project area includes all functions associated with the spatial development. For case no. 20, agrivoltaics has currently been implemented on only half of the fruit farm.

#	Case	Country	Year constructed	Power of PV system (MWp)	Project size (ha)
1	Solarfeld Gänsdorf	Germany	2009	54,0	180,9
2	Solarpark De Kwekerij	Netherlands	2016	2,0	7,1
3	Valentano	Italy	2011	6,0	17,6
4	Southill Solar	United Kingdom	2016	4,5	18,1
5	Solarpark Hemau	Germany	2002	4,0	18,0
6	Zonnepark Laarberg	Netherlands	2018	2,2	6,4
7	Sinnegreide	Netherlands	2018	11,8	12,0
8	Solarpark Mühlenfeld	Germany	2013	3,5	24,4
9	Zonnepark Midden-Groningen	Netherlands	2019	103,0	121,2
10	Monreale	Italy	2010	5,0	28,0
11	Southwick Estate Solar Farm	United Kingdom	2015	48,0	83,4
12	Energielandschaft Morbach	Germany	2002	4,5	36,3
13	San Gabriele	Italy	2009	4,0	14,5
14	Energie- und Technologiepark Eggebek	Germany	2011	83,5	449,0
15	Merston Community Solar Farm	United Kingdom	2016	10,0	25,0
16	Zonnepark ‘t Oor	Netherlands	2019	2,1	4,2
17	Eco-zonnepark Ubbena	Netherlands	2017	0,6	2,0
18	Sawmills Solar Farm	United Kingdom	2015	6,5	31,0
19	Verwood Solar Farm	United Kingdom	2015	20,4	44,0
20	Babberich Agri-PV	Netherlands	2020	2,7	3,4

specified and confirmed with field observations. Output of the spatial analysis was a list of spatial properties for each case.

A literature analysis was used to identify societal considerations with potential consequences for the spatial configuration of SPPs. Societal considerations were collected from peer-reviewed literature, for example studies examining the development of SPP in specific communities ([2,17,50,51]) or reviews that identified social, environmental and economic implications of SPP ([5,14,15]). Literature was identified by combining alternative terms for SPP, with terms related to societal considerations and the type of research. Reference list checking was used to identify additional studies.

2.2. Development and testing of typology

The typology of multifunctional SPP was developed by grouping the considerations and spatial properties into *dimensions*, identifying *types* by applying the dimensions on the individual cases and using a cross-case comparison to specify sub-types or *spatial variations* [47,52].

To start, we applied the ‘people-planet-profit’ elements of the triple bottom line [53] as *dimensions* to categorize the societal considerations, because it represents a general focus on sustainable development of energy systems [54,55]. Application of the triple bottom line on multifunctional SPPs led to landscape considerations (‘people’), nature considerations (‘planet’) and economic considerations (‘profit’). ‘Landscape’ was used to represent the non-economic ‘people’ element of the triple bottom line, as the respective considerations shape the physical landscape that is experienced by people [35,56]. We then related each of the considerations to the spatial properties found in the cases. Relating the considerations to the properties enabled us to also categorize the properties according to the economic, nature and landscape dimensions.

Once the dimensions of the spatial properties were established, we determined for each case the number of properties related to either economic, nature or landscape dimensions. For example, *Solarpark Hemau* (Section 3.4) consisted of six properties related to nature, three to landscape and one to the economic dimension. The output of the spatial analysis (Section 2.1) – a list of spatial properties – served as input for this step. The number of properties per dimension were used to identify a focus for each case, e.g. ‘nature’ for Solarpark Hemau. We grouped cases with a focus on similar dimensions, using different means to capture and display data such as tables, dot graphs and spider diagrams [47]. This grouping revealed *main types* and *combination types* as some cases expressed a strong focus in one dimension, while other cases combined multiple dimensions. Spatial properties were identified as key spatial properties if they were consistent across multiple cases of the same type. Sub-types or *spatial variations* within these types were identified by examining the similarities and differences across the cases of a single type (for example, scale and location within the project area).

The typology has been further supplemented and elaborated in an iterative process of critically reviewing the case evidence informed by feedback from case informants and experts. Feedback from case informants was gathered using a single question e-mail questionnaire to understand how people involved in the development of the SPP interpreted the dimensions. As this paper specifically focuses on multifunctional SPPs, informants were asked to distribute a total of 100 points between the economic, nature and landscape dimension to represent the focus of their project and support their distribution of points with key arguments. All case informants have been involved in the development of one of the cases, for example as initiator, designer or developer. We were able to identify and approach informants from 16 of the 20 cases of which 14 (response rate 87 %) responded to our questionnaire.

In addition to the case informants, experts (other experts than those contacted for case identification) were interviewed to test the typology. We selected 17 experts from an active community of professionals and academics in the Netherlands that is engaged with the spatial development of SPPs. The selected experts have an overview of the development of multifunctional SPPs. We were able to interview 14 of these experts (response rate 83 %), with backgrounds in solar industry (4), design & consultancy (4), academia (3), government (2) and NGO (1). The interviews were conducted and recorded using Microsoft Teams. The semi-structured interview protocol was designed to question the expert on the delineation of the types and the completeness, comprehensibility and applicability of the spatial properties and types. The protocol was tested in advance and allowed experts to use an SPP well known to them to discuss the typology. We used cognitive interviewing to understand how the experts interpreted and related the spatial properties of their case to the typology [57]. By discussing the expert case, we received feedback on the dimensions, the types and the spatial properties. Of the 14 experts, 10 discussed a case that was not part of the initial case study, introducing new case evidence to the development of the typology. The transcribed interviews were analyzed to identify patterns among the experts. The feedback on the spatial properties was used to further specify the case analysis framework. Feedback on the dimensions and types was used to shape the emerging typology of SPPs.

3. Typology of solar power plants

This section starts with the societal considerations that we observed shaping the spatial configuration of the cases, forming the foundation of the typology (Section 3.1). In the following, the typology and its dimensions are explained (Section 3.2), and the three main types of SPP are described in detail (Sections 3.3–3.6).

3.1. *Building the foundations for the typology*

The spatial configuration of SPPs are shaped by economic, nature and landscape considerations (Fig. 1). An overview of the literature that discusses these considerations can be found in Appendix A. *Nature* considerations mainly represented consequences for flora and fauna and their living environment. Cases attended to these considerations by retaining existing ecological qualities or introducing new ecological features. Altering the layout of solar infrastructure by, for example, decreasing the patch density (i.e. increased row-to-row distance), is another way to retain or improve the living environment of flora and fauna. *Economic* considerations included the loss of existing land use, effect on tourism and the local economy and grid capacity. Several cases included one or multiple commercial land use functions in the spatial configuration of the SPP, in addition to solar electricity production. *Landscape* considerations mainly represented consequences for

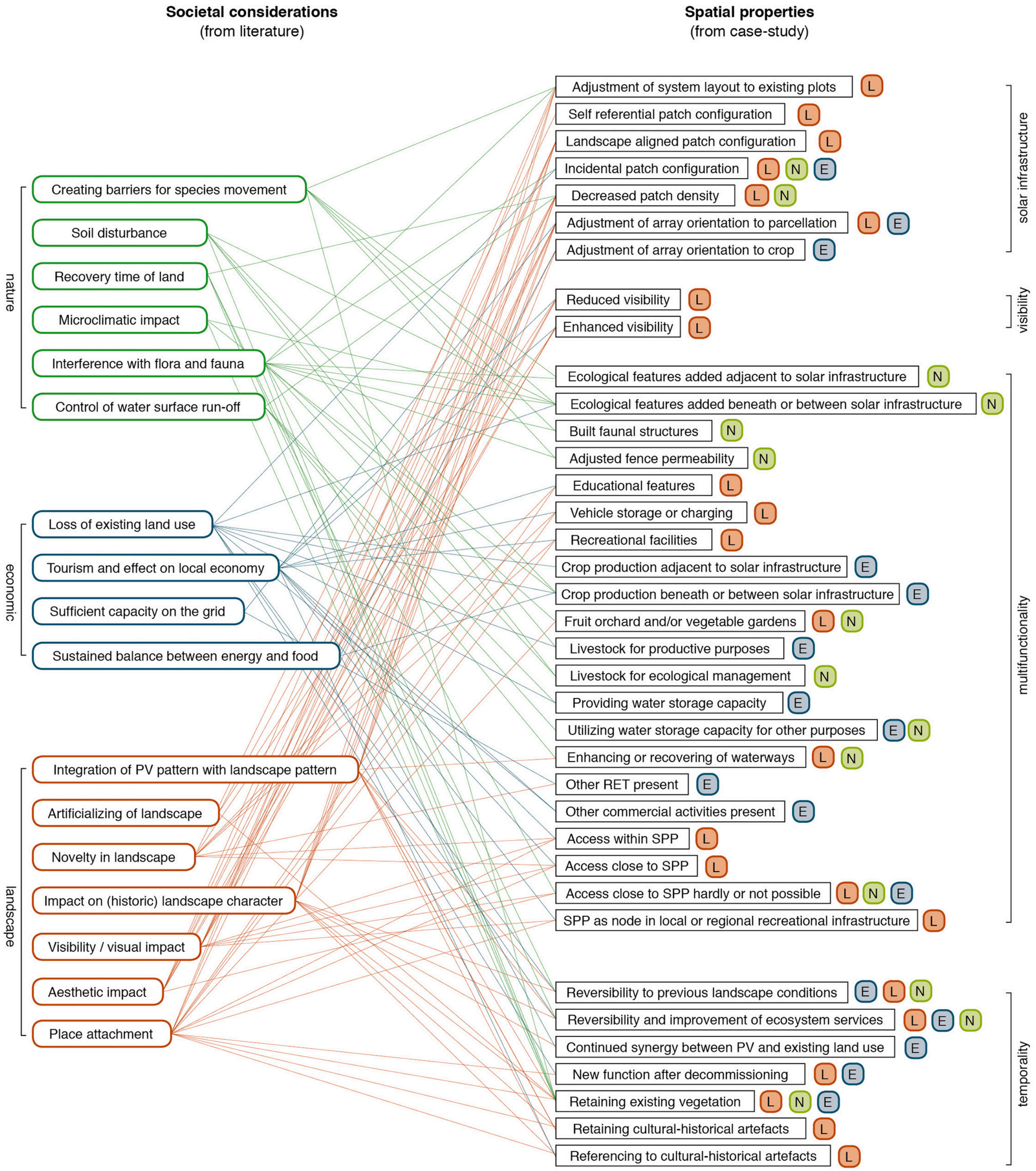

Fig. 1. Societal considerations (left) and spatial properties of cases (right). The societal considerations are categorized into three groups: nature, economic and landscape. The spatial properties have been identified in the cases and are thematically grouped: properties are predominantly related to solar infrastructure, visibility, multifunctionality or temporality in line with the analytical framework of [30].

landscape patterns and perception by landscape users. These considerations materialized in the cases through, for example, careful interaction between solar infrastructure and landscape, addressing visibility and providing recreational and education functions for local landscape users.

The spatial properties were based upon earlier research [30] and categorized as properties that are predominantly related to *solar infrastructure*, *visibility*, *multifunctionality* and *temporality* (Fig. 1). The expert interviews, which included additional case evidence, resulted in the textual adjustment of nine properties, addition of one property and splitting of a property into two separate properties.

Relating the spatial properties from the cases to the considerations from literature, revealed that most properties specifically address either economic, or nature or landscape considerations. Some properties can serve multiple groups of considerations, depending on how the property materialized in a specific location. A decreased patch density, for example, was used in *solarpark de Kwekerij* to allow visitors to walk between the PV arrays, while in *eco-zonnepark Ubbena* this was used to increase biodiversity. For each of the studied cases, the properties that determine the spatial configuration can be found in Appendix B. Presented with this categorization of spatial properties, the experts confirmed economic, nature and landscape as 'dimensions' for multifunctional SPPs. Despite the new case evidence introduced by the experts, no additional dimensions were identified during the interviews. Yet, experts stressed to acknowledge a separate 'energy' dimension to account for the differences in energy density across multifunctional SPPs. The following section describes the dimensions in more detail.

3.2. Four dimensions: energy, economic, nature and landscape

Together with the energy dimension of electricity production, the economic, nature and landscape dimensions shape the spatial configuration of a multifunctional SPP (Fig. 2). Using these four dimensions of the typology, the spatial configuration of an SPP can be examined and discussed.

Similar to monofunctional SPPs, the energy dimension forms the basis of a multifunctional SPP and – in relationship to spatial configuration – is expressed by energy density. Often, energy density of multifunctional SPPs is lower compared to regular SPPs that focus only on maximizing electricity production. Attention for the other three dimensions decreases energy density because either available space for PV panels or panel efficiency is reduced. Energy density is therefore useful to describe differences between multifunctional SPPs with regard to the energy dimension. Energy density is indicated by, for example, yearly production per hectare (in MWh/ha/y), power capacity per hectare (in MWp/ha) or spatial footprint of the system (land area occupation ratio, LAOR) [5,30]. The latter indicator is illustratively used in this section because it allows a comparison of SPPs across time as panel efficiency has increased significantly. This indicator does not, however, account for projects where stakeholders may consider to use more efficient

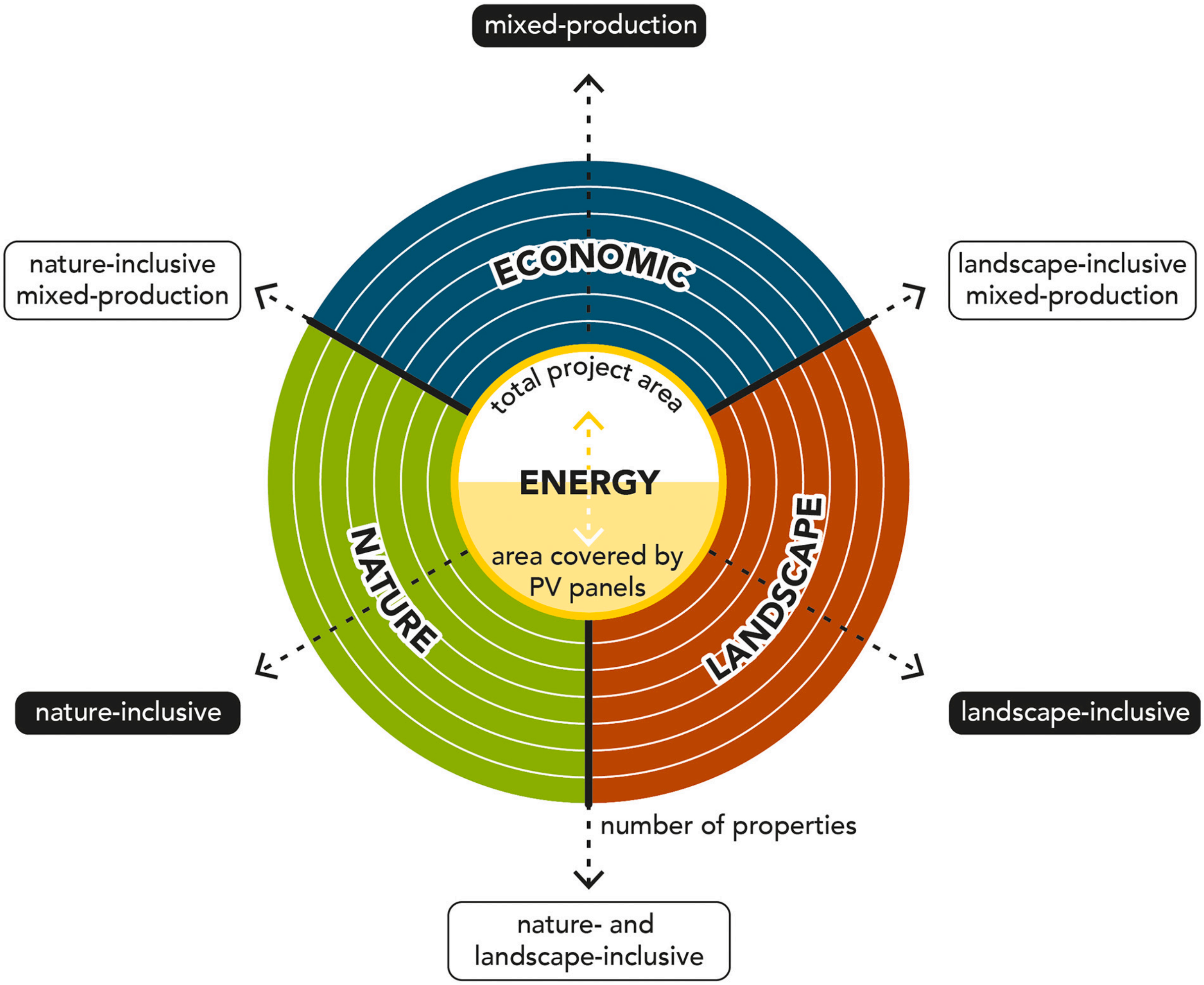

Fig. 2. Four dimensions of multifunctional solar power plants: energy, economic, nature and landscape. The energy dimension forms the basis of the SPP and is expressed by energy density, in this figure by the land area occupation ratio (LAOR) [5,30]. The economic dimension comprises economic activities in addition to electricity production. The nature dimension consists of spatial properties related to nature. For the landscape dimension the same logics apply.

panels to reduce the spatial footprint at a higher financial cost.

With the energy dimension as basis, societal considerations are addressed in an SPP with a predominant focus on either the economic, nature or landscape dimension. Such a focus leads to three main types: *mixed-production, nature-inclusive* and *landscape-inclusive* SPPs (Fig. 2, Table 2).

In general, the presence of one or multiple key spatial properties (Table 2) in a specific dimension and the absence of properties in the other dimensions indicates the main type for an SPP and its spatial variation.

Based upon the case study, the expert interviews and the responses from the case informants, attention to the economic, nature and landscape dimension is expressed by a combination of the number and the weight or scale of the properties. An SPP with many spatial properties related to one of the dimensions, reflects the many considerations, preferences or opportunities that stakeholders have included in the spatial configuration. At the same time, a consideration can also materialize in a single property that receives more attention compared to other properties. For example, in *Southill Solar*, the local sustainability cooperative decided to dedicate more than half of the project area to biodiversity improvements. Furthermore, case informants used terms such as 'marginal' and 'small-scale' to indicate certain features were present but were of limited significance for the project as a whole. In addition, seven experts mentioned the aspect of scale, an ecologist for example argued "more space [for nature] is always better from a nature perspective". This feedback makes clear that attention to a certain dimension is not only the presence of a certain feature, but also the weight or level of attention that is given to this feature in comparison to the other dimensions. However, the level of detail of the spatial data was insufficient to include the differences in the weight of the properties in the typology. To convey the typology in a systematic and transparent way, the examples in the remainder of the results section show the number of properties related to the dimensions.

In addition to the main types, the case analyses often detected a mix of dimensions. These combination types are *nature- and landscape-inclusive, nature-inclusive mixed-production* and *landscape-inclusive mixed-production.* Nature- and landscape-inclusive SPP and landscape-inclusive mixed-production SPP were found during the case study, while the nature-inclusive mixed-production combination was stressed by several experts during the interviews. In the following, we will describe the three main types, mixed-production (Section 3.3), nature-inclusive (Section 3.4), landscape-inclusive (Section 3.5) and the types that combine multiple dimensions (Section 3.6).

3.3. Mixed-production SPP

Mixed-production SPPs (MpSPPs) are optimized for economic profit by combining electricity production with other profitable land use functions. Based upon the case study, we found three major land use functions in addition to solar energy generation: agriculture, other renewable energy technologies and other commercial activities related to the SPP or the site. In agricultural MpSPPs, often termed 'agrivoltaics', PV panels are located between or above some form of agriculture, either crop production or livestock.

In a fruit farm in Babberich (the Netherlands), the solar developer placed semi-transparent PV panels above the fruit trees to improve micro-climate for plants and reduce weather-related risks for the farmer (Fig. 3). The case informant stressed the continued synergy between the two productive functions as key arguments for this specific sub-type of MpSPP.

In other MpSPPs, multiple (renewable) energy technologies are co-located, for instance wind turbines and biomass facilities. Co-location of multiple renewable energy technologies may include a shared use of grid capacity, but it is also used for place branding: *Eggebek*, a former military airport in Germany, presents itself as an 'energy and technology park' and includes other commercial activities related to renewable

Table 2

Monofunctional SPPs are optimized for maximum electricity production. Multifunctional SPP provide benefits additional to electricity production and three main types have been identified: mixed-production, nature-inclusive and landscape-inclusive SPP.

Main type	Description	Key spatial properties	Spatial variations
Monofunctional SPP	SPP is optimized for maximum electricity production	– High energy density – Adjustment of plots to optimal system layout – Removing existing vegetation to avoid shading	– n.a.
Mixed-production (MpSPP)	SPP is optimized for maximum economic profit by mixing electricity production with other profitable land use functions.	– Crop production – Other renewable technology present – Other commercial activities present	– Agrivoltaics (agriphotovoltaics); – Hybrid energy systems – Energy – technology parks
Nature-inclusive (NiSPP)	SPP is developed to improve living conditions of flora and fauna. This may lead to a suboptimal system layout for electricity production.	– Ecological features beneath, between or adjacent to solar infrastructure – Built faunal structures – Adjusted fence permeability	– Ecological features next to a dense PV patch (adjacent multifunctionality) – Ecological features beneath or between PV panels in a porous PV patch (array or patch multifunctionality)
Landscape-inclusive (LiSPP)	SPP is developed to improve physical landscape elements or patterns and/or the use and experience of the SPP by landscape users. This may lead to a suboptimal system layout for electricity production.	– Adjustment of system layout to existing plots – Landscape aligned patch configuration – Reduced visibility – Educational features – Recreational facilities	– Recreational or educational features or a zone that considers visibility next to a dense PV patch (adjacent multifunctionality) – Recreational or educational features beneath or between PV panels in a porous PV patch or multiple smaller patches (array or patch multifunctionality) – Engagement of landscape users through recreation and education – No engagement of landscape users; – Preservation of existing landscape elements – Restoration of existing landscape elements – Transformation of the existing landscape and introduction of new landscape elements

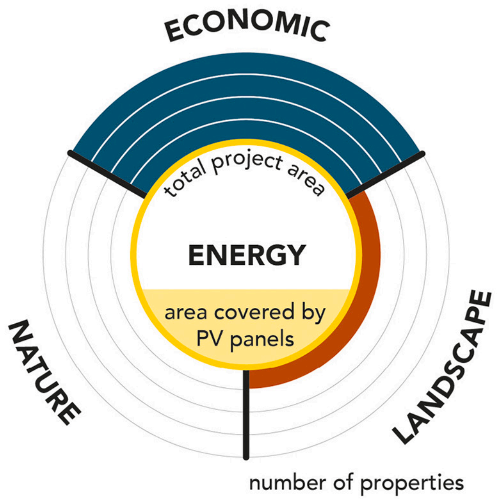

Fig. 3. Mixed-production Solar Power Plant 'Babberich Agri-PV' in the east of the Netherlands. Left: the high number of economic properties in this case illustrates the focus on economic considerations. Right: Raspberries grow in an improved micro-climate and the panels protect the fruit from extreme weather conditions. The semi-transparent panels generate electricity and leave enough solar irradiation for the growth of the raspberries.

energy technologies. In this case, the SPP is combined with wind energy testing and research, a biogas facility and other companies related to renewable energy [100].

3.4. Nature-inclusive SPP

In nature-inclusive Solar Power Plants (NiSPP), the living conditions for flora and fauna are improved, in addition to renewable electricity production. Key characteristics are space for ecological features (e.g. habitats), creating the proper conditions for these ecological features (e.g. permeability of the fence), and the proper management regime to sustain flora and fauna through time.

Reserving space includes both creation of new habitats (e.g. wildflower meadows, fruit orchards) and retaining existing vegetation. In

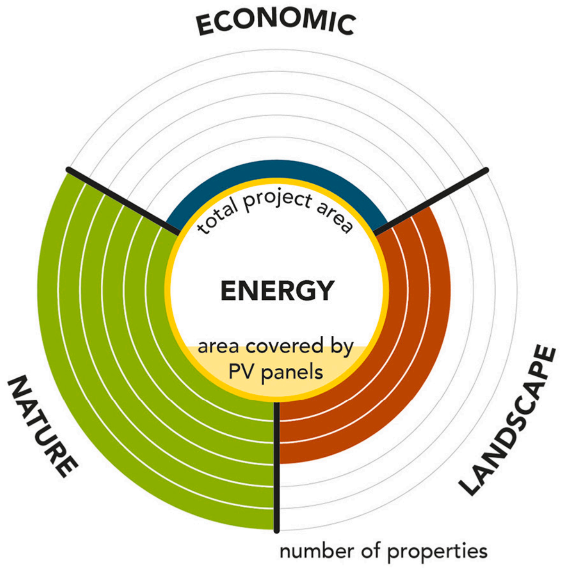

Fig. 4. Nature-inclusive Solar Power Plant Hemau in Germany, near Regensburg. Left: Hemau illustrates some attention to landscape and economic considerations, but most measures are taken for nature. The area covered by PV panels is relatively low because of the high row-to-row distance and areas kept free of PV panels to preserve and improve ecological conditions. Right: wet habitats have been created within the SPP.

both situations, stakeholders may decide to adjust the scale and layout of PV infrastructure to this end. The patch density may be decreased, existing trees are retained or ecologically valuable areas are kept free from PV panels. These two models of creating space for habitats result in two different spatial variations of NiSPPs: either a relatively dense PV patch with an adjacent area for ecological features, or a relatively porous PV patch with ecological features mainly between or beneath PV panels. The former exhibits *adjacent multifunctionality* while the latter exhibits *array or patch multifunctionality*. Providing the right conditions for the (created or retained) ecological features is related to accessibility: adjusting the permeability of the perimeter (usually a fence) to deny or allow access to certain species, depending on the ecological targets and potentially limiting access for humans when sensitive species are targeted. Experts stressed that proper management of SPPs is needed to achieve the set ecological targets and sustain these through time.

An example of a nature-inclusive SPP is *Solarpark Hemau* in Germany (Fig. 4). This NiSPP is located on a former ammunition depot that lies within a forest area. Existing areas with high ecological qualities have been kept free from PV panels and new wet and dry ecological areas have been created. The case informant argued, similar to the interviewed experts, that in addition to *creation* of ecological areas, *maintenance* of these areas is essential for improving ecological conditions.

3.5. Landscape-inclusive SPP

In landscape-inclusive Solar Power Plants (LiSPPs), physical landscape elements, landscape patterns, and/or the use and experience of the SPP by landscape users are improved. The interviewed experts stressed the significance of the host landscape character when taking decisions on spatial features. To illustrate, a regional government official stated: "in open polder landscapes […] I would find it strange to use dense vegetation around a large solar park to hide it from sight".

Indicatively, three sets of variations in spatial configuration emerge. First, similar to nature-inclusive SPPs, landscape-inclusive SPPs reserve space for functions other than electricity production *beneath or between* PV panels (array or patch multifunctionality, e.g. walking paths between PV panels) or *next to* PV panels (adjacent multifunctionality, e.g. a lookout next to PV panels).

Second, variations in *engagement* and *no engagement* with landscape users exist. LiSPP that *engage* landscape users include recreational or educational functions. Functions may vary from providing a visual overview of the SPP from constructed vantage points, to providing public access to the SPP for leisure and community gatherings. Some of these functions may affect energy density as community event spaces and similar features require space.

Contrastingly, for LiSPP that do *not engage* landscape users, stakeholders decided to keep the SPP (partly) away from the perception of landscape users. Such SPPs use, for example, local landscape elements or low PV arrays to reduce visibility of the PV panels.

The third set of variations involves which kind of interventions are realized in the existing landscape. Some cases focus on *preserving* existing landscape features, other cases on *restoring* landscape features that were present in the past and again others on *transforming* the site using new landscape features.

An example of a landscape-inclusive SPP is *Southwick Estate Solar Farm* (United Kingdom) (Fig. 5). Landscape considerations have mainly materialized *next to* the PV patches, focusing on *preserving* the existing hedgerow structure and plot shapes. The existing hedgerow structure has been improved to reduce the visibility on the PV panels. This is therefore an example of an LiSPP where users are *not engaged* in the physical energy landscape.

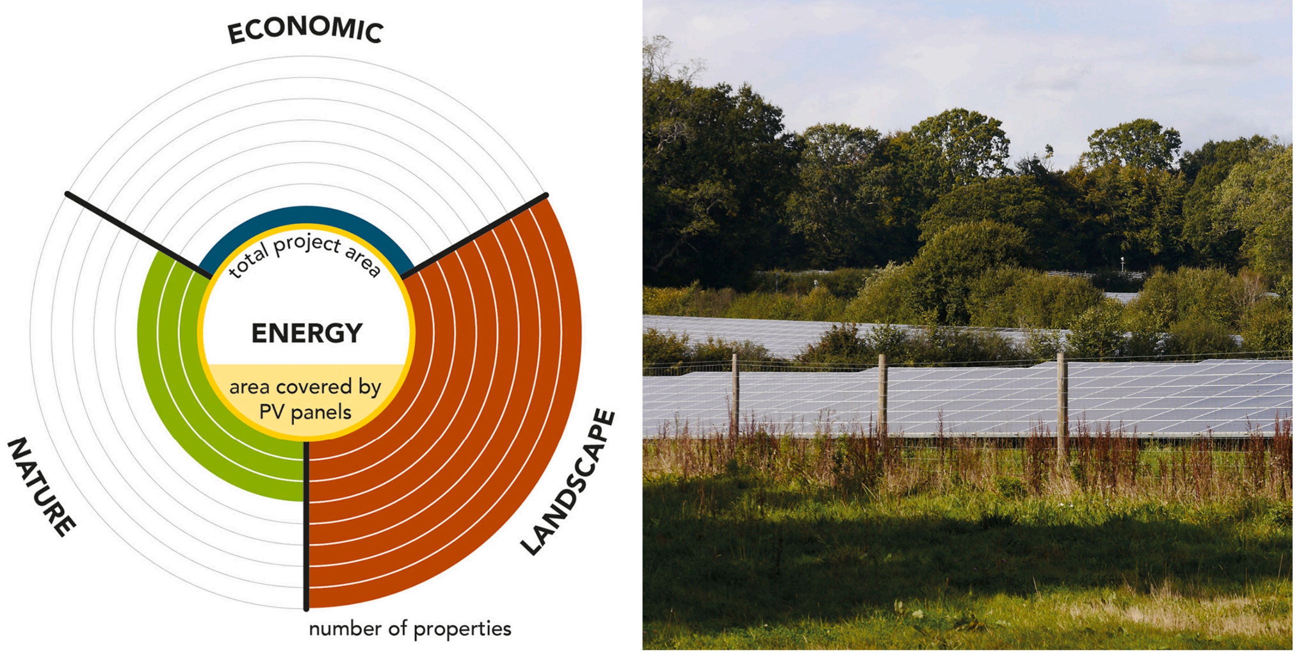

Fig. 5. Landscape-inclusive Southwick Estate Solar Farm, north of Portsmouth, United Kingdom. Left: In this case, some attention was paid to nature and economic considerations, but exceeded by the amount of landscape properties. Right: PV panels are aligned in the landscape to keep existing vegetation intact and reduce their visibility.

3.6. *Combinations of economic, nature and landscape dimension*

In addition to SPPs with a single focus on the economic, nature or landscape dimension, attention to diverse societal considerations leads to a combination of multiple dimensions. Departing from the typology (Fig. 2), combinations of economic-nature, economic-landscape, nature-landscape and economic-nature-landscape can be distinguished. The case study revealed multiple examples of SPPs that focus on both the nature and landscape dimension. In line with the other types, this combination type is referred to as a *nature- and landscape-inclusive SPP* (e.g. cases *Solarpark de Kwekerij* and *Solarpark Mühlenfeld*). Nature- and landscape-inclusive SPPs attend to both nature and landscape with spatial features that are either synergetic or co-located without synergy. Synergetic nature and landscape features work together to provide benefits for both nature and landscape. For example, using native vegetation to reduce visibility, or using landscape (micro-)relief to improve ecological quality. Similar to NiSPPs and LiSPPs, spatial variations such as (no) engagement of landscape users and adjacent or array/patch multifunctionality can be distinguished.

A few cases showed attention to all dimensions. *Monreale* (Italy) was developed as a demonstration project and includes an olive grove for local olive oil production (economic dimension), an ecological corridor (nature dimension) and aligns with existing landscape patterns (landscape dimension). In addition, one of the experts discussed a case, under construction at the time of the interview, that combined electricity production with nuts and berry production (economic dimension), ecological improvements of the waterways (nature dimension) and recovery of historical landscape elements (landscape dimension). Moreover, the agricultural activities are performed by a social farm that employs people whom have difficulties in finding employment [58].

Former ammunition depot *Energielandschaft Morbach* (Germany) combines the economic and the landscape dimension. This case presents itself as an ‘interesting mix of renewable energies […] and material flow cycles’ offering ‘a sustainable basis for innovative companies’ [59]. The site is publicly accessible, includes a visitor center and educational activities in the former ammunition storage bunkers.

The combination of economic and nature dimension was not identified during the case study nor was any such case discussed during the expert interviews. Yet, multiple experts emphasized the potential of this combination as, for example, organic pest-control by birds living in planted hedgerows may benefit food production in agrivoltaic solutions.

4. Discussion

This paper presented an emergent typology of multifunctional SPPs. Compared to monofunctional SPPs, the spatial configuration of these solar power plants is adapted to include a variety of functions. The typology consists of four dimensions: energy, economic, nature and landscape. These dimensions lead to three main types: mixed-production, nature-inclusive, landscape-inclusive, and their combinations. We will first discuss the application of this typology in decision-making processes on SPPs (Section 4.1), followed by current and future research (Section 4.2), and a reflection on methods and data (Section 4.3).

4.1. *Application of typology in decision-making processes of SPPs*

Existing literature has called for improved decision-making and communication related to siting and design of renewable energy technologies [60]. Participatory processes need to be transparent, evidence-based and inclusive in terms of values, interests and concerns [60–62]. The presented typology, with the dimensions, types and spatial variations, supports these processes and provides advantages for decision- and policy makers, solar industry and local inhabitants.

Decision- and policy makers can use this base of dimensions, types and spatial variations to set qualitative criteria for an SPP to improve clarity and transparency in permit regulation and procedures [37,63]. Criteria can be set on different levels of governance, for example from legislation set by national or regional governments to normative criteria agreed upon by local stakeholders [62]. Criteria can even be used to develop evidence-based certification for specific types, currently pursued for nature-inclusive solar power plants [64]. An example of a criterion is that in the design of nature-inclusive SPPs the fence permeability should align with the desired species movement in the host landscape.

For solar industry, specifically developers of solar power plants, the typology provides the means to customize the solar power plant in an early stage according to the characteristics of the host landscape and expectations and opportunities voiced by the local community and other stakeholders. Developers encounter various stakeholders during the planning procedure: representatives of local administrations, nature or heritage protection organizations and local inhabitants [65]. The overview of dimensions, types and spatial variations can be used in the conversation with local decision- and policy makers, as well as local inhabitants. Early consideration of different types may prevent local opposition late in the planning and design process and therefore reduce risks for solar developers. Solar industry could even further specialize their practices using the directions of the dimensions. Specializing could range from customizing PV panels for agrivoltaics or aesthetic considerations, to the design and management of nature-inclusive SPP. Such innovations in multifunctional SPPs require specialized knowledge and collaboration of solar industry with social and natural sciences.

Local inhabitants can use the typology to engage in conversation within their community on which considerations need to be prioritized and taken into account in the spatial configuration of an SPP [37]. Shaping and customizing energy landscapes is considered an essential condition to empower local inhabitants in participatory processes [66]. The typology expands the range of potential solutions to local inhabitants and allows a discussion not only about renewable energy, but inclusive of other local issues (e.g. nature or landscape related) as well [2]. Considering other (local) issues together with renewable energy provision invites local stakeholders to think integrative, potentially supporting high-quality participatory processes [66,67]. Earlier research showed that local inhabitants mostly perceive benefits of solar power plants to be non-spatial, e.g. job creation and additional revenues for local administrations [68]. The types presented in this study illustrate that benefits can also materialize in local landscapes, for example recreational facilities.

Currently, societal considerations of SPPs are mainly included in the planning and design of SPPs by *territorial differentiation*: identifying suitable and beneficial land use combinations [9]. Solar electricity production is combined with urban areas (rooftops) or degraded land to address land use pressure [26,27]. SPPs located on water bodies have an increased annual electrical output compared to on land-based SPPs and are generally located further away from urban areas [69]. *Material differentiation* [9], in this paper specifying a variety of spatial configurations of SPPs, is a complementary approach in addressing societal considerations in the planning and design process of renewable energy landscapes. Although the cases studied in this research were mainly located on former agricultural land or brownfields, the typology of spatial configuration may also apply to SPPs on rooftops and water bodies. Alternative spatial configurations on other land uses are already recognized in literature, for example green solar rooftops [70] or aquavoltaics, the combination of aquaculture and SPP [71]. This study places these innovations in a larger thinking framework and opens up the opportunity for other potential combinations, for example nature-inclusive solar carparks. The main types and most combinations of dimensions followed from case evidence, either from the case study or the cases discussed during the expert interviews. Only the combination of the economic and nature dimension remains hypothetical for now. Nordberg et al. [72] too identified this gap and suggest future research on the synergies between electricity production, agriculture and biodiversity improvements.

The types presented in this paper include functions that provide economic, nature or landscape benefits in addition to renewable electricity production. Despite these obvious benefits, trade-offs may emerge. For example, the elevated PV panels in agrivoltaics (mixed-production SPP) may be perceived negatively from a landscape aesthetics perspective. Or including recreational facilities (landscape-inclusive SPP) may require additional land. It is therefore essential that for each landscape, local stakeholders discuss and decide whether the proposed solution is of added value compared to the existing landscape. This significance of the existing landscape in the planning and design of renewable energy has been conceptualized by Devine-Wright [73,74] and others [75,76] as 'place-technology-fit' or 'landscape-technology fit'. This concept refers both to the spatial characteristics of a landscape (e.g. industrialized or natural landscape types) and the symbolic meanings associated to that landscape by people [75,77]. 'Landscape-technology-fit' suggests the types need to be carefully matched with the existing landscape. One way of establishing this match or fit, is to include the types as variable in suitability analysis and energy potential mapping (e.g. [62,78]). To illustrate potential outcomes, a mixed-production SPP such as agrivoltaics may fit fruit production landscapes, where temporary protective foils are replaced by permanent PV panels. Nature-inclusive SPPs may present a fit with low-productive agricultural land, using native vegetation species to improve local biodiversity. Brownfield sites in urban fringes, on the contrary, may fit landscape-inclusive SPPs offering recreational opportunities for inhabitants and other landscape users. Matching location with spatial configuration supports a long term improvement of existing qualities, avoiding the mere mitigation of negative impacts [79], increasing the likeliness of public support [77].

4.2. Current and future research

Whether the typology is applied in national or regional suitability studies or in local participatory processes, sufficient knowledge on all dimensions is needed to identify and assess cross-dimensional synergies and trade-offs [17]. This study partly brings together and articulates knowledge on individual dimensions discussed and examined elsewhere. With regard to the *economic dimension* of SPPs, primarily agrivoltaic systems have been studied for their cost-efficiency [80], land use efficiency [81] and shade effects on pollinators [82]. Ecological measures of multiple cases of *nature-inclusive* SPPs have been monitored and evaluated (e.g. [32,40]). The *landscape dimension*, however, is scarcely studied, while others have already advocated that the energy transition requires 'learning to love the landscapes of carbon-neutrality' [35]. As this and other research has shown, multifunctional SPPs also provide positive impacts on the current and future landscape [5,30,83]. Future research could focus, for example, on the long-term landscape changes that take place during the operational stage of the SPP and how these changes are perceived by local landscape users [84]. Or, on the capability of landscape users to see, understand and differentiate between main types of SPPs. SPPs with tangible spatial features such as lookouts, community event sites and other recreational or educational facilities may be more easily recognized as 'different', compared to SPPs that enable the preservation of rare grasslands with carefully selected and executed ecological measures and maintenance.

This study used the *number* of properties in the different dimensions as basis for distinguishing an SPP case as one type over another. Future research in our group will be dedicated to how the *weight* or *level of attention* to certain properties, relative to other properties, informs the distinction between different types of multifunctional SPPs. The weight of properties could be expressed by for example scale, volume or amount of resources used for the properties and further increases the transparency and evidence base of the typology.

4.3. Reflection on methods and data

The typology of SPPs was built upon cases from four European countries (Germany, The Netherlands, United Kingdom and Italy). Although this selection provided national and regional variety in for example landscape type, policy and legal regulations, other contexts may bring forth additional insights on the spatial configuration of multifuncitonal SPPs. The typology may be further expanded and enriched by spatial analysis of solar power plants in other parts of the world. Furthermore, the experts that were interviewed were all Dutch and part of a professional and academic community that also includes the authors of this paper. This brings two limitations. The first is that the experts discussed the typology primarily from their daily 'reality' in the Dutch context. However, we believe that the Netherlands, with its high population density and scarcity of space, is representative of other urban delta's in the Global North. The second limitation is that some of the experts were aware of previous work of the authors, which may have led to social desirability bias. To counter this response bias, not uncommon in such studies, experts were continuously asked to articulate themselves as specific as possible and support their arguments with evidence from the expert case.

The case informants scored the attention for landscape lower compared to the outcomes of the case study. This lower attention for landscape of case informants can be explained by the fact that case informants primarily mentioned tangible landscape features added to the case, for example picnic benches, lookouts and charging points for electric bicycles. Less tangible properties, such as alignment of PV patch to landscape patterns, were only mentioned by one case informant.

5. Conclusion

This study set out to create and test a typology of multifunctional solar power plants (SPP) that can support evidence-based and transparent decision-making processes. Informed by case evidence and confirmed by expert interviews, a typology with four main dimensions has been identified: energy, economic, nature and landscape. Each of these dimensions illustrates how co-construction of social and material relations give rise to different types of multifunctional SPPs as alternatives to monofunctional SPPs. More specifically, the main types *mixed-production*, *nature-inclusive*, and *landscape-inclusive* SPP have been distinguished through our analysis of 20 different SPPs.

Not all identified types of multifunctional SPP have received equal attention from academia, solar industry or design practice. One type, nature-inclusive SPP, is substantiated by multiple cases and already receives substantive attention by scholars. Another type, landscape-inclusive SPP, is clearly present in the case evidence, but has yet received little attention in the scientific literature. SPPs that combine economic (other than energy exclusively) and nature functions present an opportunity for future innovations in both academia and practice.

The typology presented in this paper gives direction to and provides ingredients for (local) decision-making on solar energy landscapes. Yet, the typology also answered to the call of Pasqualetti and Stremke [1] to advance 'the larger conversation' on energy landscapes. In their first typology of energy landscapes, they distinguished between the substantive qualification (type of energy source), the spatial qualification and the temporal qualification. The paper at hand informs the discourse on solar power plants (*substantive qualification*) by studying their spatial configuration (*spatial qualification*) and starting to consider temporal aspects. The spatial qualification is influenced by energy density, spatial dominance and the compatibility with other land uses [1]. This research illustrates that adjusting PV infrastructure (e.g. energy density, height of PV panels) makes energy generation compatible with other functions. This study shows that solar energy landscapes cover the spatial dominance spectrum from entity (sharp borders, monofunctional) to component energy landscape (diffuse borders, multifunctional).

As the energy transition requires a 're-appraisal of the form, function and value' of contemporary landscapes [3], the opportunities of SPPs to adapt to societal considerations may become a trailblazer for other types of energy landscapes. Research on and discourse about energy landscape differentiation can therefore support the transformation of energy systems in a way that meets both the quantitative goals and qualitative considerations by society. This paper has, among others, contributed to the vocabulary of solar energy landscapes that may support such a process.

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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.

Data availability

Data will be made available on request.

Appendix A

Table A.1
Societal considerations of solar power plants identified in literature.

Societal consideration	Dimension	Literature
Loss of existing land use / land availability	Economic	[2,5,13,50,83,85–88]
Tourism and effect on local economy	Economic	[2]
Sustained balance between energy and food	Economic	[42]
Sufficient capacity on the grid	Economic	[17,50,89]
Landscape fragmentation (creating barriers for movement of species and their genes)	Nature	[5,14,83]
Soil disturbance (clearing of soil)	Nature	[14,90]
Recovery time	Nature	[2,5,15]
Microclimatic impact (heat effect PV modules)	Nature	[12]
Interference with flora and fauna / wildlife impact	Nature	[2,12,14,15,17,32,85,91]
Control of water surface runoff	Nature	[5]
Integration of PV pattern with landscape pattern	Landscape	[4,5,83]
Artificializing of landscape (through panels, supporting structures and electrical infrastructure)	Landscape	[4,14,24,83,87,92]
Loss of greenspace for exercise and relaxation (recreation)	Landscape	[2,17]
Novelty (peculiarity, landmark) in landscape	Landscape	[16]
Impact on (historic) landscape character	Landscape	[2,5,24,83]
Visibility / visual impact of SPP (including glare)	Landscape	[2,5,16,17,24,25,41,83,87,93–95]
Place attachment (expression of love, emotional bond, strong affection to site or wider area)	Landscape	[2,51,96]
Aesthetic impact (color, fractality, geometry)	Landscape	[5,97–99]

Appendix B

Table B.1
Overview of the spatial properties across the cases. The spatial properties are described in detail elsewhere [30] and can be categorized as properties that are predominantly related to solar infrastructure, visibility, multifunctionality and temporality. Some properties mainly reflect either economic, nature or landscape considerations, while other properties can be linked to multiple groups of considerations.

Category	Spatial property	Economic (E)	Nature (N)	Landscape (L)	Exemplary case	1. Solarfeld Gänsdorf	2. Solarpark De Kwekerij	3. Valentano	4. Southill Solar	5. Solar park Hemau	6. Zonnepark Laarberg	7. Sinnegreide	8. Solarpark Mühlenfeld	9. Zonnepark Midden-Groningen	10. Monreale	11. Southwick Estate Solar Farm	12. Energielandschaft Morbach	13. San Gabriele	14. Energie- und Technologiepark	15. Merston Community Solar Farm	16. Zonnepark 't Oor	17. Eco-zonnepark Ubbena	18. Sawmills Solar Farm	19. Verwood Solar Farm	20. Babberich Agri-PV
Solar infrastructure	Adjustment of system layout to existing plots			x	11	L			L			L		L	L	L				L	L		L	L	L
	Self-referential patch configuration			x	6		L				L														
	Landscape aligned patch configuration			x	19				L			L		L	L	L				L	L	L		L	
	Incidental patch configuration	x	x	x	5					N			N				E		E		N		N	L	
	Decreased patch density		x	x	17		L					L				L						N	N		
	Adjustment of array orientation to parcellation	x		x	12												E		E			L			
	Adjustment of array orientation to crop	x			20																				E
Visibility	Reduced visibility			x	1	L	L	L	L	L	L	L	L	L	L	L		L	L				L	L	
	Enhanced visibility			x	2	L	L				L		L							L					
Multifunctionality	Ecological features added adjacent to solar infrastructure		x		10	N	N	N	N	N	N	N	N	N	N	N					N	N	N	N	
	Ecological features added beneath or between solar infrastructure		x		8		N		N	N			N		N			N		N		N	N	N	
	Built faunal structures		x		19	N	N		N		N					N				N	N	N	N	N	
	Adjusted fence permeability		x		4		N	N	N	N	N	N	N	N	N	N		N		N	N		N	N	
	Educational features			x	12		L		L	L	L		L				L	L			L				
	Vehicle storage or charging			x	6		L				L	L	L					L							
	Recreational facilities			x	2		L	L			L	L	L												
	Crop production adjacent to solar infrastructure	x			10										E			E	E						
	Crop production beneath or between solar infrastructure	x			20																				E
	Fruit orchard and/or vegetable gardens		x	x	7	L	L		L		L	L									L				
	Livestock for productive purposes	x			3			E											E						
	Livestock for ecological management		x		5					N	N									N	N			N	
	Nutritional production by animals (e.g. bee hives)			x	12	E			E	E							E				E		E		
	Providing water storage capacity	x			6						E														
	Utilizing water storage capacity for other purposes	x	x		2		N								E										
	Enhancing or recovering of waterways			x	7			L				L													
	Other RET present	x			14												E		E						
	Other commercial activities present	x			12												E		E						
	Access within SPP			x	2		L										L				L				
	Access close to SPP			x	16	L		L			L	L	L	L		L		L		L	L			L	
	Access close to SPP hardly or not possible	x	x	x					N	N					L				E			N	L		E
	SPP as node in local or regional recreational infrastructure			x	8		L						L			L								L	
Temporality	Reversibility to previous landscape conditions	x			9				E					E		E			E						
	Reversibility and improvement of ecosystem services	x	x	x	15										E	L				E					
	Continued synergy between PV and existing land use	x			20																				E
	New function after decommissioning	x		x	2	E	L																		
	Retaining existing vegetation	x	x	x	18			L							L			L							
	Retaining cultural-historical artefacts			x	5		N		N		L		N			L	E						L		
	Referencing to cultural-historical artefacts			x	13					L							L		L						

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