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Next generation solar power plants? A comparative analysis of frontrunner solar landscapes in Europe

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ABSTRACT

Solar power plants transform the existing landscape. This landscape change raises concerns about *visual impact*, *land use competition* and the *end-of-life stage* of solar power plants. Existing research stresses the need to address these concerns, arguing for a combined spatial arrangement of solar power plant and landscape: solar landscape. Solar landscapes share the aim to achieve other benefits (e.g. reducing visibility, habitat creation) in addition to electricity generation, yet empirical evidence on solar landscapes is scarce. This comparative analysis of 11 frontrunner cases aims to contribute to the understanding of solar landscapes, by studying the spatial properties *visibility*, *multifunctionality* and *temporality*. Visibility is reduced in all cases. In five cases, however, visibility is partly enhanced in combination with recreational amenities. Between 6 and 14 provisioning, regulating and cultural functions were found in the cases. Functions were located beneath arrays, between arrays and adjacent to photovoltaic patches. Temporal considerations were identified in most cases, yet only two cases introduced new landscape features to enhance future use of the sites after decomissioning. Across cases, this case study shows how contemporary concerns about solar power plants, such as visual impact, land use competition and the end-of-life stage are addressed. Although the cases altogether present a portfolio of measures responding to societal concerns, the full potential of the three key properties is yet to be explored. Furthermore, this comparative analysis highlights the need to address emerging trade-offs between spatial properties and to discern between different types of solar landscapes. The used analytical framework may supplement the assessment of solar power plants to examine not only *negative*, but also *positive* impacts.

1. Introduction

Solar power plants (SPP) have been constructed at an increasing rate over the past decades [1]. These power plants, consisting of ground-mounted photovoltaic (PV) arrays and electrical infrastructure, transform the landscape [2–7]. Landscape is here defined as 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors' [8]. SPP not only transform existing landscape patterns, that is the size, shape, arrangement and distribution of individual landscape elements [9], but also how the landscape is perceived by inhabitants and other landscape users [10,11].

These landscape transformations raise societal concerns about visual impact, land use competition and the end-of-life stage. Visual impact is a key concern with respect to SPPs [2,12,13]. SPPs can have visual impact due to their scale, color, pattern and artificiality [2,14–16] and, as a consequence, influence perception adversely [11]. Furthermore, SPPs require land previously occupied by other uses and therefore increase land use pressure. SPPs can, for example, result in the loss of agricultural land [17,18] and also affect habitats, as vegetation is degraded or removed [17,19,20] and soil is moved or covered [18]. These land use changes can be substantial in a short period of time [21] and require recovery time for vegetation and soil [19]. The common life-span of SPP is 20–30 years, due to the life expectancy of the modules [22]. Concerns about the end-of-life stage of SPPs are whether decommissioning will take place [23] and if so, what the state of the resulting landscape will be [24]. All these three groups of concerns have a clear spatial dimension

Abbreviations: SPP, solar power plant; PV, photovoltaic; LAOR, land area occupation ratio; GCR, ground coverage ratio; CICES, Common International Classification of Ecosystem Services.

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and can result in negative responses of local inhabitants and other landscape users towards SPP [2,11,12,25]. Consequently, these responses may threaten the progress of the energy transition [26,27].

Existing research points to the need of SPP to address societal concerns, by attending to three key properties: visibility, multifunctionality and temporality. *Visibility* refers to whether an SPP is observable by landscape users from a certain location [13,28]. Visibility can be changed, for example, by using vegetation for screening or adjusting the size of the SPP to the characteristics of the host landscape [2,11,29]. *Multifunctionality* refers to the capacity of a certain area of land to serve multiple purposes and fulfill several needs at the same time [30–32]. Electricity generation in SPP can be combined, for example, with ecological restoration [24,33–35] and outdoor education [2,24]. *Temporality* is a relatively new, emerging topic in energy landscape research and refers to the dynamic character of SPP [4,23]. Elements introduced during the SPP construction have the potential to enhance the future landscape or inhibit certain developments after decommissioning of the solar infrastructure [4,24]. Temporality is also relevant in the context of recycling energy landscapes: renewable energy technologies are introduced at sites formerly used for conventional energies. In Nijmegen in the Netherlands, for example, an SPP is built on a site previously occupied by a coal-fired power plant.

Others have recently introduced the concept of 'photovoltaic landscape' or 'solar landscape' that encompasses a joint approach between SPP and landscape [2,36]. This approach involves a combined spatial arrangement of SPP and landscape where solar infrastructure is adapted (e.g. height of arrays, distance between arrays) and 'landscape features' are included (e.g. hedgerows, wildflower meadows). While contemporary spatial arrangements of SPPs are optimized for energy and/or economic benefits, spatial arrangements of solar landscapes aim to achieve other benefits (e.g. reducing visibility, habitat creation) in addition to electricity generation [13,16,24,29]. For this paper, we make use of and build upon the novel concept of solar landscapes to examine SPPs that pay attention to visibility, multifunctionality and temporality.

However, few studies have investigated the visual, functional and temporal properties of constructed cases of solar landscapes. Lobaccaro et al. [36] is the only study that examines spatial properties of built solar landscapes. They partly address visibility and multifunctionality and do not discuss temporality. Anyhow, most studies overlook the spatial arrangement of SPP and landscape [14,37,38], focus on a single property [16,35,39], or present theoretical discussions on what solar landscapes *can* be or *should* be [2,29,33], but not on what solar landscapes *are*. The following research question is central to this paper: *what are the visual, functional and temporal properties of frontrunner solar landscapes in Europe?*

This research aims to contribute to the growing body of knowledge on solar landscapes by analyzing and comparing the spatial properties of constructed solar landscapes in Europe. This study used expert consultation and desk-study to identify so-called 'frontrunner' SPPs. Insights in the innovative properties of these frontrunner cases constitute a vital contribution to the debate on how societal concerns about SPP can be resolved. Due to the novelty of the topic, an analytical framework was developed for the case study, based on a literature review. This framework focusing on visibility, multifunctionality and temporality of SPP may also enrich environmental impact assessments and multi-criteria decision analyses of SPP in response to prominent societal concerns. Furthermore, a better understanding of frontrunner cases, in combination with the cultivation of solar landscape vocabulary, is believed to support policy and decision makers, SPP developers, designers and other stakeholders to conceive solar landscapes supported by landscape users [2,11,40].

The second section of this paper presents the methods and materials. The framework for the case analysis is presented in section three. The results and discussion section first presents the solar infrastructure and landscape feature properties, followed by visibility, multifunctionality and temporality. The paper is concluded in section five.

2. Methods and materials

2.1. Case-study approach

This study examines the spatial properties of built solar landscapes. We adopted a case-study approach in our research, as this allows for the description of a contemporary phenomenon in its spatial context [41]. We used a multiple embedded case design to document and compare a high variety of spatial properties across all cases [41].

2.2. Case selection

Our research focuses on the Netherlands, the United Kingdom, Germany and Italy, as these countries have shown increasing attention for solar landscapes. In addition, the travel distance and language of these countries allowed us to study the cases within the time and resource provided. We aimed to study cases of SPP that were recognized for being at the front of addressing societal concerns and providing functions additional to electricity generation. We identified so-called 'frontrunner cases' through recognition in the form of awards granted, for example by solar industry, and expert judgement. We reached out to photovoltaic and environmental design experts using personal contacts and approaching photovoltaic developer and environmental design associations.[1] We asked the experts to provide us with the names of SPPs that provided benefits besides to electricity generation, such as ecological restoration, recreation or aesthetics.

The expert contact and the desk study on SPP awards resulted in a longlist of over 30 cases. A quick-scan was used to identify their main spatial properties. Based on the quick-scan, we selected cases that complied to two criteria that are key to solar landscapes. First, the case needed to demonstrate a combined spatial arrangement of SPP and landscape. Second, the case needed to include new landscape features in addition to solar infrastructure, for example water retention areas, opportunities for recreation or habitat patches. For each case, these criteria were evaluated using design maps or project documentation and confirmed by satellite imagery or field visits. We diversified according to spatial properties, as well as landscape type and project scale; variety in the latter two are expected to increase the variety of spatial properties [13,29]. Ultimately, 11 cases were selected (Fig. 1 and Table 1).

2.3. Research process

For each case, we performed a spatial analysis [42,43] and studied accompanying project documentation. The spatial and document analysis was subsequently verified by field observations. To start, the spatial analysis was conducted using a case-study protocol, to strengthen consistency of the analysis by the multiple researchers involved [41]. This protocol was tested and further refined by analyzing two contrasting cases. The properties that were used to guide the spatial analysis are presented in section 3. Results of the analysis were presented in maps, text and tables. Data used for the mapping were design maps as well as recent and historical satellite imagery.

Next, project documentation was used to confirm and specify the spatial arrangement of SPP and landscape. The document analysis was mainly based on project reports and websites that were collected until June 2020. This data was occasionally complemented by insights from

[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.

Fig. 1. The 11 selected cases. Scale of the images varies, see Table 1 for actual size of the cases (source satellite imagery: Google Earth and Kadaster).

case informants. Finally, intermediate results of spatial and document analysis were enhanced and verified by field observations that took place from May until October 2019.

The results of the individual cases were synthesized to identify similarities and differences across cases [41]. Maps, textual descriptions and numerical date were aggregated using tables and examined along the categories of the framework for case analysis (section 3). Aggregating the data of all cases helped to profile the individual cases, specify the framework for case analysis and subsequently enhance the cross-case synthesis in an iterative manner.

3. Framework for case analysis

The framework for case analysis was developed deductively (drawing from literature) and inductively (drawing from the cases) through multiple iterations of application and reflection. The framework was used to analyze the spatial properties of the embedded cases. The larger host landscape was analyzed as well, as this forms the backdrop for the spatial properties. Solar infrastructure and landscape features refer to physical changes in the landscape that can, to some extent, be examined independently [e.g. 38,44]. Contrastingly, *visibility*, *multifunctionality* and *temporality* are *emergent* properties: properties of the whole revealed by interactions between individual characteristics [45,46]. These properties of solar landscapes were analyzed by jointly examining *solar infrastructure* and *landscape features* [2,36] (Fig. 2). This section first introduces the solar infrastructure and landscape feature properties (3.1), followed by the procedure for the study of emergent properties visibility, multifunctionality and temporality (3.2).

3.1. Solar infrastructure and landscape features

The spatial analysis started by identifying landscape type and previous land use function. These properties of the host landscape informed the subsequent analysis of solar infrastructure and landscape features.

Solar infrastructure of SPP is discussed extensively in the literature [e.g. 2,16,29]. We created an overview of properties found in literature and specified these with the findings of the case analysis. For solar infrastructure, the spatial properties are grouped in three nested levels: the *system* as a whole, the *patch* as distinct group of arrays, and the *array* as specific object (Table 2).

Literature reports on both potential and realized landscape features of SPP [2,20,34,36]. We used the main categories identified in the literature to group the individual features found in the cases (Table 2), namely ecological, recreational and educational, agricultural and water retention features.

3.2. Emergent properties of solar landscape

3.2.1. Visibility

The combined spatial arrangement of SPP and landscape affects the visibility of the solar infrastructure [16,29,39,50]. To investigate this relationship, first the existing and new landscape features at the edge of the solar landscapes were analyzed. The edge is defined as the space between solar infrastructure and the project boundary (Fig. 3a). Second, the part of the solar infrastructure visible to on-road observers was analyzed [28] and subsequently expressed in the degree of visibility. The degree of visibility is the part of the outer edge of the solar infrastructure visible to observers, as seen from the first line of observation (Fig. 3a). The first line of observation is the set of roads or paths closest to the edge

Table 1
General information on the 11 cases.

	GENERAL			SOLAR INFRASTRUCTURE					HOST LANDSCAPE	
Cases	Latitude	Year of construction	Country	Power (MWp)	Size (ha)	Energy density (MWp/ha)	Land Area Occupation Ratio (LAOR)	Technology	Landscape type	Previous land use
1. Gänsdorf	48°48'12	2009	Germany	54,0	180,9	0,30	22%	Fixed tilt	Open agricultural	Agriculture: highly productive arable land
2. Kwekerij	52°03'24	2016	Netherlands	2,0	7,1	0,28	16%	Fixed tilt	Semi-open bocage landscape	Agriculture: low grade, tree nursery
3. Valentano	42°35'19	2011	Italy	6,0	17,6	0,34	23%	Fixed tilt	Open agricultural	Agriculture: highly productive arable land
4. Southill	51°51'31	2016	United Kingdom	4,5	18,1	0,25	16%	Fixed tilt	Semi-enclosed valley side farmland	Agriculture: extensive, low grade
5. Hemau	49°02'10	2002	Germany	4,0	18,0	0,22	20%	Fixed tilt	Enclosed, agricultural landscape with large evergreen forests	Brownfield: military ammunition depot within production forest
6. Laarberg	52°06'43	2018	Netherlands	2,2	6,4	0,35	21%	Fixed tilt	Semi-open bocage landscape	Agriculture: intensive grassland and corn production
7. Sinnegreide	53°26'04	2018	Netherlands	11,8	12,0	0,98	53%	Fixed tilt	Open agricultural	Agriculture: grassland
8. Mühlenfeld	51°27'51	2013	Germany	3,5	24,4	0,14	10%	Fixed tilt	Semi-open bocage landscape	Brownfield: gravel mining and nature development
9. Midden-Groningen	53°10'48	2019	Netherlands	103,0	121,2	0,85	61%	Fixed tilt	Open peat landscape	Agriculture: arable and grassland
10. Monreale	37°52'07	2010	Italy	5,0	28,0	0,18	13%	Single-axis tracker	Undulated open agricultural landscape	Agriculture: extensive, wheat and olive groves
11. Southwick	50°52'50	2015	United Kingdom	48,0	83,4	0,58	35%	Fixed tilt	Enclosed, mixed farmland/woodland	Agriculture: arable and grassland

of the case. We distinguish between visible, partly visible and invisible, based on visibility levels as presented in Ref. [13]. Visibility from a larger distance and for on-site observers [28,29] was examined during the field observations but not included here to allow a comprehensive comparison of the 11 embedded cases.

3.2.2. *Multifunctionality*

Solar landscapes provide multiple services and functions [2,3,51]. We use the term function as it indicates a capacity to deliver a certain service. In this research, we aimed to *identify* deliberately added functions with a certain expected service. The quantification and assessment of services is beyond the scope of this comparative analysis of 11 frontrunner cases. The Common International Classification of Ecosystem Services (CICES) was used to systematically identify and describe functions [52]. For each case, a list of deliberately added functions was identified in project documentation and subsequently verified during field observations. These lists were discussed and adjusted during multiple workshops among involved researchers to ensure cross-case consistency. Using CICES, we analyzed the presence and number of functions identified in the cases. Three types of multifunctionality were identified: *array multifunctionality* (beneath arrays), *patch multifunctionality* (on patch area and not underneath arrays) and *adjacent multifunctionality* (next to patches) (Fig. 3b).

3.2.3. *Temporality*

Landscapes change through time, largely driven by societal demands and expressing changing societal values [53]. The demand for renewable energy results in the introduction of energy technologies that transform landscapes within a relatively short period of time; this is why the development of SPP is considered dynamic. The life-span of SPPs is relatively short (20–30 years) compared to other, more permanent energy technologies, such as nuclear power plants [4]. Others have studied the *construction* and *operation/maintenance* stages of SPP [54,55]. This study adopted a wider temporal perspective and focused on the former state of the host landscape (i.e. *before* construction), the case during operation and maintenance stage and the decommissioning stage (Fig. 4). Project documentation was used to identify if and how temporality was considered in these three stages: (1) inclusion of existing features of the host landscape in the case, (2) active management of landscape features during operation and maintenance stage and (3) plans for the decommissioning stage.

4. Results & discussion

The results are presented and discussed in three parts. The first two parts present the solar infrastructure (4.1) and landscape feature (4.2) properties. The third part (4.3) takes the perspective of the solar landscape as a whole and discusses the visibility, multifunctionality and temporality of the examined cases.

4.1. *Solar infrastructure*

4.1.1. *System layout and host landscape pattern*

We found that the way the system layout responded to the host landscape differed between cases with a former agricultural use and those with a brownfield use. In the nine cases with a former agricultural use, the system size and plot size were key factors in the way the system layout responded to the pattern of the host landscape. In only one case the system was entirely located within a single plot (Monreale). In the other eight cases, solar infrastructure was distributed over multiple plots, whether the cases were small (e.g. Sinnegreide, 12 ha) or large (e.g. Gänsdorf, 181 ha). In these multiple-plot cases, the plots of the host landscape either remained (almost) completely intact (five cases) or were aggregated into a single larger plot (three cases). For some cases, although parcellation remained intact, the individual plots are potentially not always recognized as such by observers. Recognition of

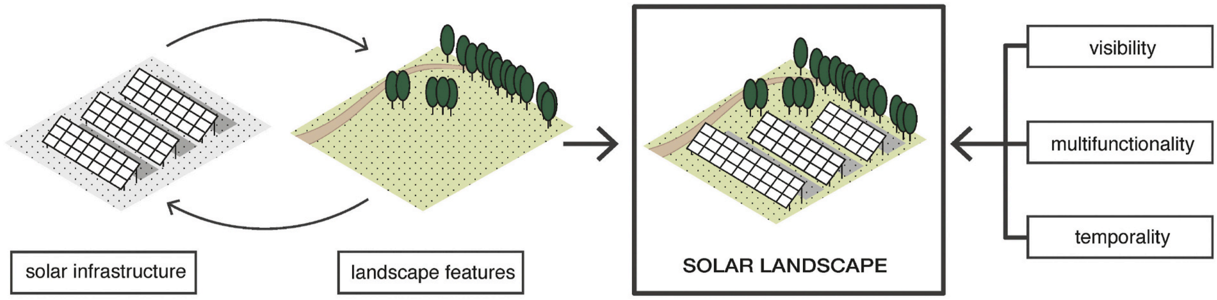


Fig. 2. Solar infrastructure and landscape feature properties refer to physical changes that can be examined independently. Visibility, multifunctionality and temporality are emergent properties of the solar landscape as a whole.

Table 2
Framework for the analysis of the host landscape, solar infrastructure and landscape features.

Category	Sub-category	Property	Description	Literature
Host landscape		Landscape type	Open/enclosed, parcellation/plot sizes, existing landscape infrastructure/features, urban settlements.	[2,36]
		Previous land use	Previous land use(s) at the site	[19,47]
Solar infrastructure	**System**	Layout	The number, size and position of the patches as part of the solar system.	[11,29]
		Response to parcellation	The response of the system layout to the original parcellation.	[29]
	Patch	Configuration	Size, position and alignment of the of patch within parcellation.	[2,11,16,29,36]
		Density	Density of the array within a patch. Indicator is the ground-coverage-ratio (GCR), which is the array length (L) divided by the row-to-row pitch (R)	[2,11,48]
	Array	Orientation	Orientation or azimuth of the arrays. Traditional orientation (east-west or north-south) results in a stripes pattern, but other types of patterns are possible if the azimuth is varied.	[2,29]
		Dimensions	Dimension of array, determined by: tilt of modules, total height of the array from the ground; length (l) of array; width of array; layout of array (orientation of modules and number of rows);	[36]
		Concurrence	Presence of multiple PV technologies or types of modules in a single case	[14]
		Materials	Color of modules, materials used in supporting structure.	[16,29,49]
Landscape features	**Ecological**	Feature	Features that support ecological functions, for example patches of wildflowers or hedgerows.	[24,30,33,34]
	Recreational and educational	Feature	Features that support recreational and education functions, such as community gathering spaces and outdoor classrooms.	[2,24,36]
	Agricultural	Feature	Features that support agricultural functions, such as grazing or orchards.	[2,24,33]
	Water management	Feature	Features that support hydrological functions, such as water retention areas.	[30,33,34]

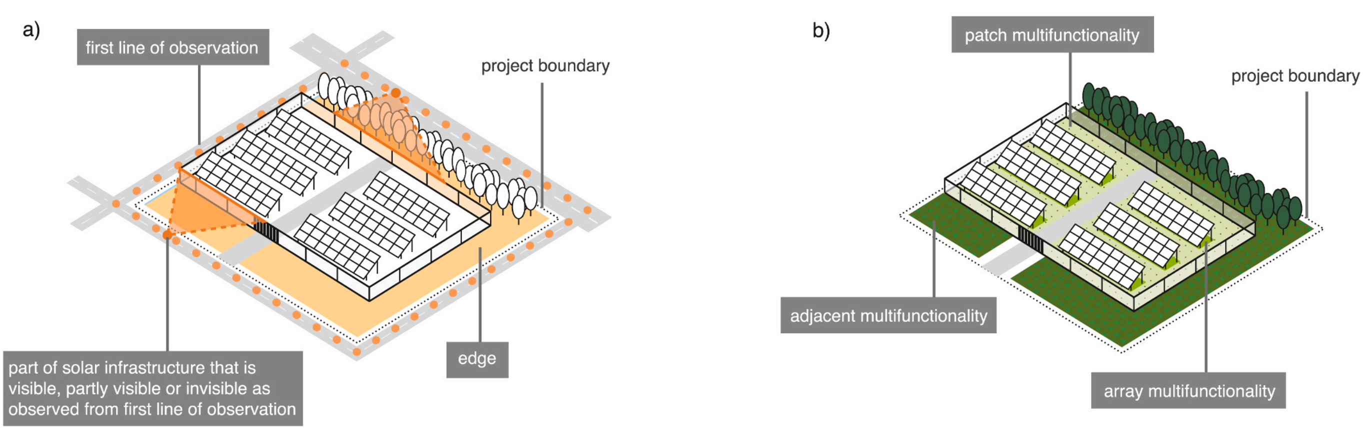


Fig. 3. a) Visibility of the solar infrastructure is expressed by the ratio of the outer edge of the solar infrastructure that is visible, partly visible or invisible (based on visibility levels as presented in Ref. [13]). b) Multifunctionality beneath the arrays (array multifunctionality), on the patch area (patch multifunctionality) and next to patches (adjacent multifunctionality).

individual plots can occur if there is high vegetation along the plot border and/or a field margin; a zone between plot border and PV patch.

In the two cases with a former brownfield use, the system layout was adjusted to site specific elements of the previous land use function, for example a gravel mining pit in Mühlenfeld.

4.1.2. Patch configuration and density

The system layout consists of multiple PV patches that are each configured within a specific plot. Five different types of patch configurations were found (Fig. 5). Most cases consisted of a single configuration. In the *responsive configuration*, the size of the PV patch

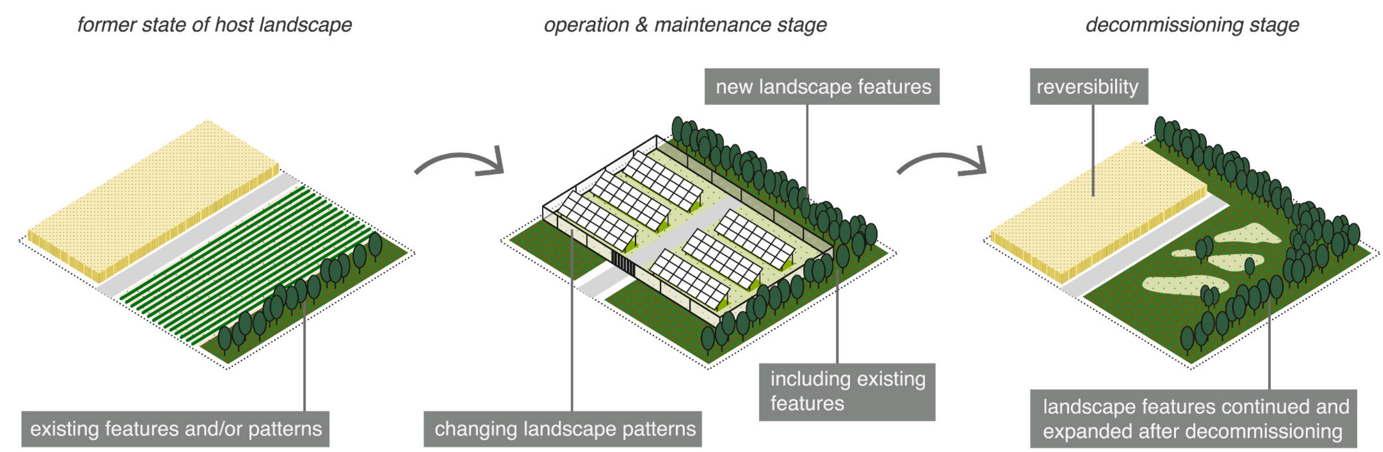
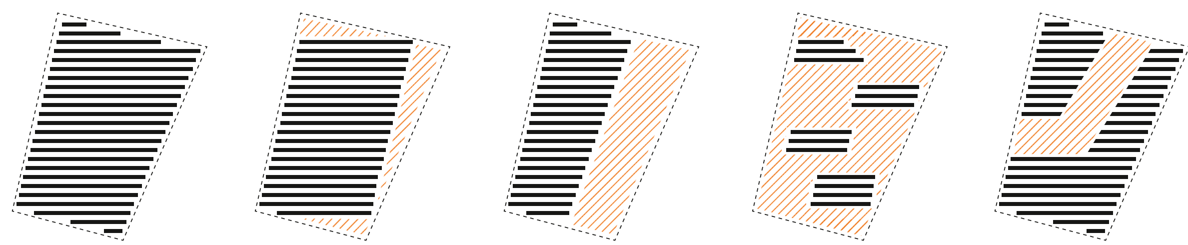


Fig. 4. Temporal properties: former state of the host landscape, case during operation/maintenance stage and decommissioning stage.



Type of patch configuration	RESPONSIVE	IRRESPONSIVE	SPLIT	ISLANDS	INCIDENTAL
	Shape of patch mimics shape of plot and PV patch largely covers size of plot. Original parcellation structure, both shape and size remain recognizable. Potentially high variation in array length.	Patch shape is self-referential, variation in array length is kept to a minimum. Large part of plot is covered by PV patch. Potentially results in left-over spaces within the plot.	Shape of PV patch matches shape of plot, but a substantial part of plot is not covered by the PV patch. Result is a split of the plot and an area next to the patch that has a different function.	Small part of plot is covered by PV arrays. The shape is independent from existing parcellation.	Local circumstances (such as underground infrastructure or build elements) prevent presence of arrays.
Alignment (of patch to plot)	Plot border	(partially) self-referential	Plot border (sometimes partially self-referential)	Self-referential	To site specific elements
Coverage (of plot by patch)	Very high (65-90%)	High (50-75%)	Low (25-50%)	Low (35-40%)	Dependent on local circumstances.
Cases	Sinnegreide Midden-Groningen Southwick	Gänsdorf Valentano	Southill Monreale [Sinnegreide]	Kwekerij Laarberg	Hemau Mühlenfeld [Southill] [Midden-Groningen] [Southwick]

Fig. 5. Five types of patch configurations. Main determinants for the patch configurations are alignment to plot and coverage of the plot by the PV patch. Case names between brackets indicate a certain configuration was identified, but it was secondary to another, primary configuration.

predominantly matched the plot size. For example, in Sinnegreide, PV arrays with various widths were used to cover the entire plot; the original parcellation remained intact. Contrastingly, in the *irresponsive configuration*, the patch shape was mainly self-referential, which, dependent on the plot shape, can result in left-over spaces. In Gänsdorf, constructed in 2009, the limited flexibility in array width of that time can have contributed to this configuration.

In the *split configuration*, the patch responded to the shape of the plot, yet only partially covered the plot area (25–50%). This partial coverage resulted in a perceived split of the original plot. In Southill for example, only the south-western part of the plot was used for arrays, the remainder of the plot consisted of landscape features. The fixed size of the single-axis tracker system employed in Monreale seems to have resulted in roughly equal patch sizes.

In the *islands configuration*, a single patch was divided into sub-patches and the patch shape was almost entirely self-referential. The plot was only for a small part (30–45%) covered by arrays. In the Kwekerij and Laarberg for example, this configuration resulted in multiple small PV patches dispersed across the plot. These configurations corroborate the proposals for patch variations by Scognamiglio [2]. The irresponsive, split and island configuration increase the spatial heterogeneity of the landscape, dependent on the previous land-use. In a host landscape with monofunctional agricultural plots, these configurations increase the variety of functions within a single plot, countering agricultural upscaling often seen in the countryside [56]. However, some of these configurations are less aligned with landscape parcellation and recent research has shown this can negatively influence perception [11].

For brownfield cases, the patch configuration coincided with the strategy for the system layout: site specific elements determined the configuration. In the case of Hemau for example, the patch was shaped around the existing (elevated) bunkers and identified hotspots for biodiversity were also excluded for electricity generation. This fifth, *incidental configuration*, was also found in other cases in addition to another, primary configuration. In these cases, elements were highlighted that otherwise remained invisible, for example underground infrastructure became visible as a blank space between arrays.

The *patch density* is determined by the width of the array and the row-to-row-pitch, expressed by the ground-coverage-ratio [48] and ranged for the cases between 0,35 and 0,84 (Table 3). Existing research points to two consequences of patch density: visual impact and impact on land use [2,11].

Potential visibility affected patch density in three cases: the Kwekerij, Sinnegreide and Southwick. In these cases a lower, secondary ground-coverage-ratio (GCR) was found where a high visibility of the solar system was expected. For Southwick though, we could not confirm a causal relationship. Although Scognamiglio [2] stresses that a low patch density is pivotal to increase multifunctionality, no relationship between multifunctionality and patch density was found (see also 4.3.2). Cases with multifunctionality beneath arrays or on the patch area had a GCR ranging from 0,35 to 0,73, covering almost the entire spectrum of GCR found in the cases.

4.1.3. Array orientation, dimensions and materials

On the level of arrays, we found that in all cases the *orientation* of the PV arrays was optimized for maximum solar energy generation. This optimization was for 10 cases east-west oriented arrays facing south, and for one case with a single-axis tracker north-south oriented arrays (Table 4, see also Table 1). In other words, the type of pattern was the same for all the cases: parallel stripes [2]. To relinquish energy optimization and vary the azimuth is considered a key feature of solar landscapes. A variable azimuth can improve ecological performance or allow the solar infrastructure to align with the landscape pattern [2,11,16] that, in turn, can result in new patch configurations. In addition, non-optimal azimuth angles reduce peak loads on the electricity grid and allow for a more flexible integration into the landscape [1,57]. If business models can incorporate these benefits, non-optimal azimuth angles can also result in an improved alignment of array and landscape pattern.[2]

The *dimension* of the arrays is specific to each case, although the height was variable in three cases (Table 4). In two cases (the Kwekerij and Sinnegreide), arrays were found with two different heights. Arrays with a lower height were closest to where most observers were expected (see also table GCR). In Monreale the difference in height of the arrays was caused by partial ground levelling.

The *color* of the arrays in the cases was the blue commonly seen in SPP. However, the rapid development of colored modules in the built environment may also permeate to solar landscapes [58]. Only in Hemau, modules were three different shades of blue, as at the time of construction (2002) suppliers were not able to deliver the requested amount of modules from a single type of module. Consequently, Hemau is also the only case where *concurrence* was identified. The same applies for the type of supporting *structure* used: all cases except Hemau used metal structures, while Hemau used a wooden structure.

Table 3
Patch density of the cases expressed by the ground-coverage-ratio (GCR). In three cases, two different array types were found, resulting in two values for the GCR. The GCR is calculated by dividing the array length (L) by the row-to-row pitch (R) [48].

Cases	GCR of primary array type (*L/R*)	GCR or secondary array type (*L/R*)	Location of secondary array type
1. Gänsdorf	0,45	n/a	
2. Kwekerij	0,44	0,41	Most visible patches for nearby inhabitants.
3. Valentano	0,49	n/a	
4. Southill	0,63	n/a	
5. Hemau	0,35	n/a	
6. Laarberg	0,52	n/a	
7. Sinnegreide	0,84	0,69	Most visible patch near road.
8. Mühlenfeld	0,44	n/a	
9. Midden-Groningen	0,73	n/a	
10. Monreale	0,40	n/a	
11. Southwick	0,63	0,57	Most visible patch in west compartment.

4.1.4. Reflections on solar infrastructure across frontrunner SPPs

Southwick illustrates that combining solar infrastructure with landscape occurs at multiple scales: on the system level, the size of the existing plots determined the system layout; on the patch level, individual patches matched the shape of the plots. Even more, the existing parcellation remained visually recognizable as existing hedgerows were combined with a sufficient field margin around the PV patch. This spatial arrangement required additional space, resulting in the trade-off of a decreased maximum amount of arrays (lower LAOR value).

4.2. Landscape features

4.2.1. Ecological features

Several ecological features were found in the cases: patches of dry or wet vegetation, vegetative buffers, built structures for roosting, nesting and hibernating, wildlife permeable fencing and some cases incorporated existing vegetation into the system layout (Table 5).

Vegetative patches were identified in all cases, for example wildflower fields or shrubs. Vegetative buffers were found in seven cases, often combined with screening function at the edge of the case (see also 4.3.1). Buffers were for example hedgerows, tree rows or reed zones. In one case, Hemau, an existing monoculture forest patch was removed to avoid shadow on the arrays. The presence of vegetative patches and buffers in the cases reflects the growing evidence that SPP contribute to local biodiversity of [24,34,35,59]. Several similarities in ecological features were found, independent of landscape type: hedgerows, orchards and flower fields were found in many cases. Landscape features dependent on landscape type and other contextual characteristics become especially important when SPP become a more familiar phenomenon in the landscape [60]. In five cases, built structures for roosting, nesting and hibernating, such as beehives or insect hotels, were identified. In nine cases wildlife permeable fencing was realized by either lifting the fence or by the addition of small mammal gates. These findings show that in most cases landscape fragmentation is addressed [20,36]. In five cases existing vegetation was retained, such as hedgerows or solitary trees, while it is not uncommon that existing vegetation is removed [17,20]. In retaining vegetation, these cases address the loss of identity elements, or fragmentation of the countryside [17].

4.2.2. Recreational and educational features

Recreational and/or educational features were identified in 9 of the 11 cases, confirming the potential suggested in earlier research [2,24]. All recreational and educational features were located next to a PV patch, and not beneath or between the arrays as has been identified in the Solar Strand, USA [2]. Recreational and educational features were for example lookouts, benches and information panels. The Kwekerij, Laarberg and Mühlenfeld seemed to actively enable recreation by adding multiple recreational facilities and connecting the case to a local recreational network. The other cases seemed to be addressing occasional or accidental on-site observers. Recreational features were absent in Midden-Groningen, Monreale and Southill.

In the large-scale cases Gänsdorf, Midden-Groningen and Southwick,

[2] A recent example in the Netherlands is the project 'Energy garden' Assen-Zuid: https://www.nmfdrenthe.nl/wij-werken-aan/energieneutraal-drenthe/energietuin-assen-zuid/(in Dutch).

Table 4
Array orientation, height, materials and concurrence.

	Array orientation		Array height	Array materials		Concurrence
Cases	Adjustment to plot	Optimum for solar energy generation	Consistent/ variable	Color modules	Supporting structures	
1. Gänsdorf		x	consistent	Blue	Metal	no
2. Kwekerij		x	variable	Blue	Metal	no
3. Valentano		x	consistent	Blue	Metal	no
4. Southill		x	consistent	Blue	Metal	no
5. Hemau		x	consistent	Blue (three shades)	Wood	Yes, three types of modules and array types
6. Laarberg		x	consistent	Blue	Metal	no
7. Sinnegreide		x	variable	Blue	Metal	no
8. Mühlenfeld		x	consistent	Blue	Metal	no
9. Midden-Groningen		x	consistent	Blue	Metal	no
10. Monreale		x	variable	Blue	Metal	no
11. Southwick		x	consistent	Blue	Metal	no

Table 5
Ecological features found in the cases (x = new; [x] = enhanced, not completely new; (−) = removal).

	Ecological features						
Cases	Total	Patch of dry vegetation	Patch of wet vegetation	Vegetative buffer	Built structures for roosting, nesting and hibernating	Wildlife permeable fencing	Retaining existing vegetation
1. Gänsdorf	3	x		x	x		
2. Kwekerij	5	x	x	x	x	x	yes
3. Valentano	3	x		x		x	
4. Southill	4/[1]	x		[x]	x	x	yes
5. Hemau	3/(1)	x/(−)	x			x	
6. Laarberg	5/[1]	x	x	[x]	x	x	yes
7. Sinnegreide	3	x		x		x	
8. Mühlenfeld	3	x	x			x	yes
9. Midden-Groningen	3	x		x		x	
10. Monreale	3	x		x		x	
11. Southwick	5/[1]		x	x/[x]	x	x	yes
Total		10/(1)	5	7/[3]	5	10	5

the space between the patches was occasionally publicly accessible (Table 6). In Gänsdorf and Midden-Groningen, this access was the consequence of practical considerations (land ownership and maintenance respectively), while in Southwick the patch shape was deliberately adjusted to maintain an existing path. Across cases, no roads or paths formerly accessible were removed or cut-off. Moreover, in the Kwekerij a path network was created between the patches and access within the fence is possible on a daily basis. This study shows that solar landscapes are able to maintain or increase landscape connectivity [61].

4.2.3. *Agricultural features*

Nine cases included agricultural features, ranging from small fruit tree orchards to substantial olive groves. This high presence of agricultural features may point to addressing the loss of agricultural land [17]. In Monreale, a large olive grove was located next to the solar system, and the left-over spaces within the solar system were planted with olive and almond trees. In Gänsdorf, the case comprised a part of the former arable land. In three cases (Laarberg, Hemau and Midden-Groningen) sheep were kept inside for grazing. In five cases (Gänsdorf, the Kwekerij, Southill, Laarberg and Sinnegreide) small-scale agriculture targeting the local community (fruit orchards, vegetable gardens) was identified.

4.2.4. *Water management features*

Local water management was found in five of the cases. This study identified water retention areas, in addition to techniques of water recuperation [36]. Water retention areas were part of two cases (Laarberg and the Kwekerij). In Laarberg, water run-off from a (future) business area can be stored beneath PV arrays, and the solar infrastructure was adjusted to allow for temporary flooding (above-ground cables). In Monreale, rain water recuperated from the PV patches, was stored in a basin to be used for the adjacent olive grove. In two other cases (Sinnegreide and Valentano) waterways were enhanced or recovered.

4.2.5. *Reflections on landscape features across frontrunner SPPs*

Laarberg includes multiple categories of landscape features: ecological, recreational, agricultural and water retention features have been combined with electricity generation on only 6,4 ha. Southill, on the contrary, displays focus on a single category: ecological restauration is central and to this end human access is limited.

Furthermore, in Southill and Hemau spaces suitable for electricity generation have been deliberately kept free to achieve ecological objectives. In other words, spatial arrangement of solar infrastructure is adjusted and even sub-optimal to accommodate other objectives. The Kwekerij and Gänsdorf are examples of synergy between functions: recreational and ecological values are increased by locating strips of wildflowers next to roads and pathways.

4.3. *Solar landscape*

Three emergent properties that arise from the combined spatial arrangement of SPP and landscape - in this paper and elsewhere conceptualized as solar landscape - are presented in this section: *visibility*, *multifunctionality* and *temporality*.

Table 6
Recreational and educational features and accessibility in the cases.

Cases	Recreational and educational features												Accessibility		
	Total	Lookout	Information panel	Benches	Picnic tables	Community gathering site	Playground features	Car parking	Bicycle parking	Charging point electric bicycles	Walking path	Node in local recreational network	No access	Access between patches	Access within fence
1. Gänsdorf	1	x												x	
2. Kwekerij	9	x	x	x	x	x	x	x			x	x			x
3. Valentano	1										x		x		
4. Southill	1		x										x		
5. Hemau	1		x										x		
6. Laarberg	4		x		x					x		x	x		
7. Sinnegreide	2				x				x				x		
8. Mühlenfeld	5	x	x	x					x			x	x		
9. Midden-Groningen	0													x	
10. Monreale	0												x		
11. Southwick	2										x	x		x	
Total		3	5	2	3	1	1	1	2	1	3	4	7	3	1

4.3.1. *Visibility*

This section presents the visibility of the solar infrastructure based on an analysis of the existing and new landscape features at the edge of the solar landscape.

4.3.1.1. The edge. The edge of the cases consisted of existing eye-level vegetation (appendix A) and new edge measures (appendix B), and in each case the solar infrastructure was completely surrounded by a fence. Existing eye-level vegetation, such as forest patches or hedgerows, were found in eight cases, with five cases consisting of over 60% existing eye-level vegetation along the edge. New edge measures consisted of landscape features, for example hedgerows or a reed zone. Three types of measures were applied in the cases: removal of existing landscape features, enhancing existing landscape features and new landscape features (appendix B).

4.3.1.2. Reducing visibility of solar infrastructure. In all cases, the visibility was deliberately reduced, either through siting within existing vegetation or through new edge measures with screening function [16,39]. The highest ratio of a visible edge in a single case was 30% (Mühlenfeld). Contrastingly, in three cases clear views on the solar system were almost absent (Fig. 6).

Southwick, Laarberg, Mühlenfeld, Hemau and Southill combined low visibility with few new landscape features and many existing landscape features. Existing vegetation, sometimes enhanced, was used for screening purposes. This combination supports the notion that careful site selection is an important aspect to achieve low visibility without the need for many new edge measures [29,39]. Patch configuration also influenced visibility. In Southill for example, positioning the patch into the lower lying part of the plot reduced the visibility from higher located roads [16,28,39].

Monreale, Midden-Groningen, Sinnegreide, Valentano and Gänsdorf combined a low amount of existing eye-level vegetation along the edge (<11%) with a high degree of new screening features (85–100%). Introduction of eye-level vegetation that is not typically found in open landscapes may have an adverse effect on the landscape character [11,16,39]. In some cases, screening measures provided other functions as well. For example, in Gänsdorf an orchard was planted to reduce visibility from the road and at the same time produce fruit.

4.3.1.3. Enhancing visibility of the solar infrastructure. The overall reduction of visibility was contrasted by measures that deliberately *enhanced* visibility. In Gänsdorf, the Kwekerij, Mühlenfeld, Sinnegreide and Laarberg, features were added that provided visitors with a clear view of the solar system (Fig. 7). In the first three cases, the solar infrastructure can be seen from a lookout, while the latter two cases feature an area at the edge of the case that provided amenities for visitors to stay for a short period of time. These five cases showed a combination of two strategies with respect to visibility: in general, visibility is reduced, but at a specific point visibility of the solar infrastructure is enhanced. The latter strategy seems to reflect 'embracing visibility of energy facilities', which can be part of a place branding approach [62]. This research shows that the cases addressed visibility [5,11,13,14,17,18], and at the same time aimed to reframe visibility from a mainly *negative impact* into a potential *positive impact*.

4.3.2. *Multifunctionality*

Solar landscapes that provide functions additional to electricity generation can be considered *multifunctional*. In this section, we further detail the multifunctionality of the cases by examining the presence and number of functions, as well as three types of multifunctionality. The section is concluded with reflections on the assessment of multifunctionality.

4.3.2.1. Presence and number of functions. The studied cases provide a

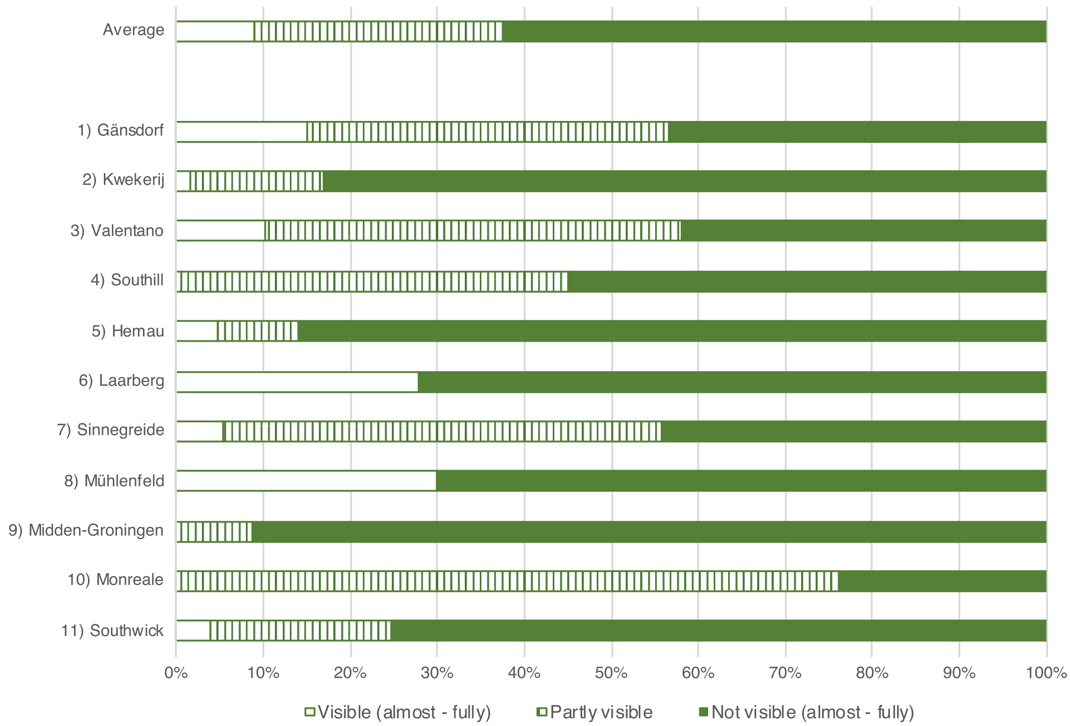


Fig. 6. Visibility of the solar infrastructure as observed from road infrastructure closest to the case, the first line of observation.

Fig. 7. Measures enhancing visibility: lookout in Gänsdorf (a), Mühlenfeld (b, picture by Florian Becker) and the Kwekerij (c), and benches near a clear view to the solar infrastructure in Laarberg (d, picture by Coos van Ginkel) and Sinnegreide (e). All pictures by authors unless otherwise indicated.

multitude of different functions. Of the 65 functions in the CICES model of ecosystem services, 18 were found in the cases (appendix C). The function *Providing habitats for wild plants and animals (2.2.2.3)*, was the only function identified in all cases, besides *Solar power (4.3.2.4)*. Two other functions were identified in nine out of eleven cases: *Pollinating our fruit trees and other plants (2.2.2.1)* and *Screening unsightly things (2.1.2.3)*. Small-scale agricultural functions, such as grazing sheep (1.1.1.3), food production (1.1.1.1) were found in nine cases. These functions confirm that the cases aim to mitigate impacts of SPP identified in earlier research, such as habitat destruction and fragmentation, decrease of wildlife and biodiversity [19,20,63] and land use impact or loss of productive land [18,19,47,64].

From the 18 identified functions, four were provisioning, seven regulating and seven were cultural functions. All three types of functions were found in all cases. The total number of functions ranged from 6 to 14 (Fig. 8).

No clear relationship was found between the number of functions and the land area occupation ratio (LAOR, see Table 1) [2]. Cases with a high LAOR (highest ratio found was 61%) still supported multiple functions, although these cases represented the lower end of the range of functions (Fig. 9).

4.3.2.2. Three types: array, patch and adjacent multifunctionality. Functions were located beneath arrays (array multifunctionality), on the patch area (patch multifunctionality) and adjacent to patches (adjacent multifunctionality) (Fig. 10). Array and patch multifunctionality allow for interactivity between functions (e.g. sheep finding shade under arrays) and were identified in 8 out of 11 cases (Fig. 11). Adjacent multifunctionality was identified in all cases and was often a form of multiple land use or co-location with little interaction with the solar infrastructure [31,32]. These findings are in line with, and further specify earlier research on solar landscapes; earlier research identified multifunctionality applied to solar infrastructure and as multiple land use within the project boundary [36].

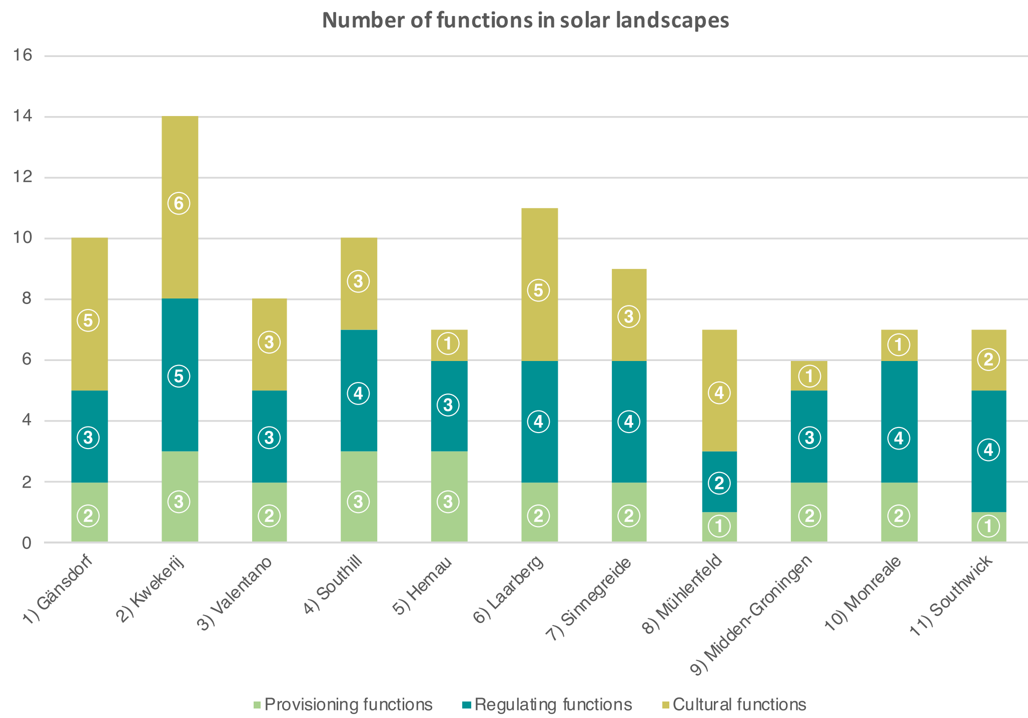


Fig. 8. The number of functions in each case, divided over provisioning, regulating and cultural functions.

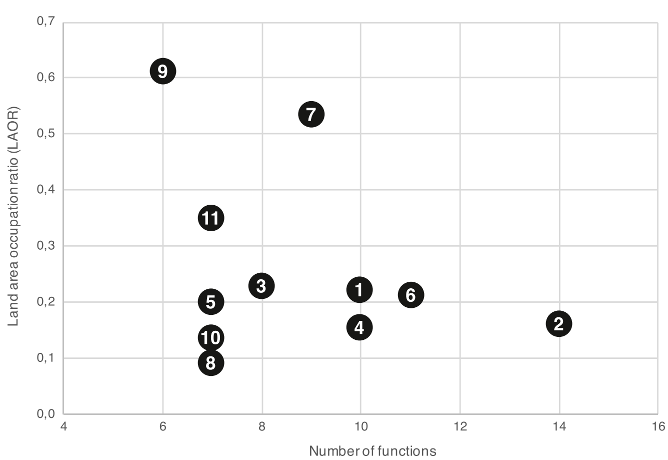


Fig. 9. The number of functions compared to the land use energy intensity, expressed by Land Area Occupation Ratio. 1=Gänsdorf; 2=Kwekerij; 3=Valentano; 4=Southill; 5=Hemau; 6=Laarberg; 7=Sinnegreide; 8=Mühlenfeld; 9=Midden-Groningen; 10=Monreale; 11=Southwick.

On average, the cases contained 28,9% adjacent multifunctionality, 19,8% patch multifunctionality and 11,6% array multifunctionality, totaling to 60,4% (Fig. 11). In seven cases, over 70% of the land surface was allotted to multifunctionality. In three of these cases (Valentano, Hemau and Midden-Groningen), this high share is for a large part caused by harvesting the meadow beneath and between the arrays by or for livestock. Specifically for Midden-Groningen, multifunctionality is arranged as a sharp spatial distinction between the high-density PV patches and livestock (array and patch multifunctionality), and ecological features in the edge (adjacent multifunctionality). The large share of multifunctionality in the other four cases is explained by a diverse set of features: wildflower fields, recreational amenities and water retention (the Kwekerij), livestock grazing and water retention (Laarberg), fields of wildflowers and fine grasses (Southill) and an olive grove and wet ecological corridor (Monreale). The cases with high shares of array and patch multifunctionality indicate the potential to increase multifunctionality without adversely affecting land used for electricity generation. High shares of adjacent multifunctionality were found in Monreale, Southill, the Kwekerij, Valentano, Laarberg and Hemau. With adjacent multifunctionality, however, land otherwise available for electricity generation is used for other functions. This latter type of multifunctionality therefore reduces the overall land use energy intensity of the solar landscape [2].

4.3.2.3. Assessment of multifunctionality. The number of functions and the land surface allocated to multifunctionality are useful indicators to compare SPP on multifunctionality, yet they do not assess functions. Assessment of ecosystem functions and services needs to provide insight in their effectiveness, management [35] and comparison to the baseline situation [47]. Such an assessment requires integrated approaches that make use of a mix of methods and tools on multiple scales of analysis [3]. Without advancing such assessment methods for solar landscapes, cases may emerge that bear the promise of multifunctionality, but only deliver minor provisioning, regulating or cultural benefits. Current assessments of SPP often make use of performance indicators based on installed capacity or electricity generation [64,65]. Using these indicators, most of the cases in this study will be outperformed by SPP that are optimized for electricity generation. These assessments and their associated indicators will need to be supplemented by other indicators that capture multifunctionality.

4.3.3. Temporality

Temporality in the cases was addressed in 8 out of 11 cases by attention for landscape elements and patterns present in the host landscape, active management during operation and maintenance stage and landscape plans for the decommissioning stage.

In five cases, landscape elements and patterns that were part of the *former state of the host landscape* were included in operation and maintenance stage, with the potential to extend into decommissioning stage. These efforts can result in 'remnants of the past' and carry symbolic and historical value [53]. Elements were often vegetation, such as hedgerows or trees, but also former military bunkers were preserved (Hemau).

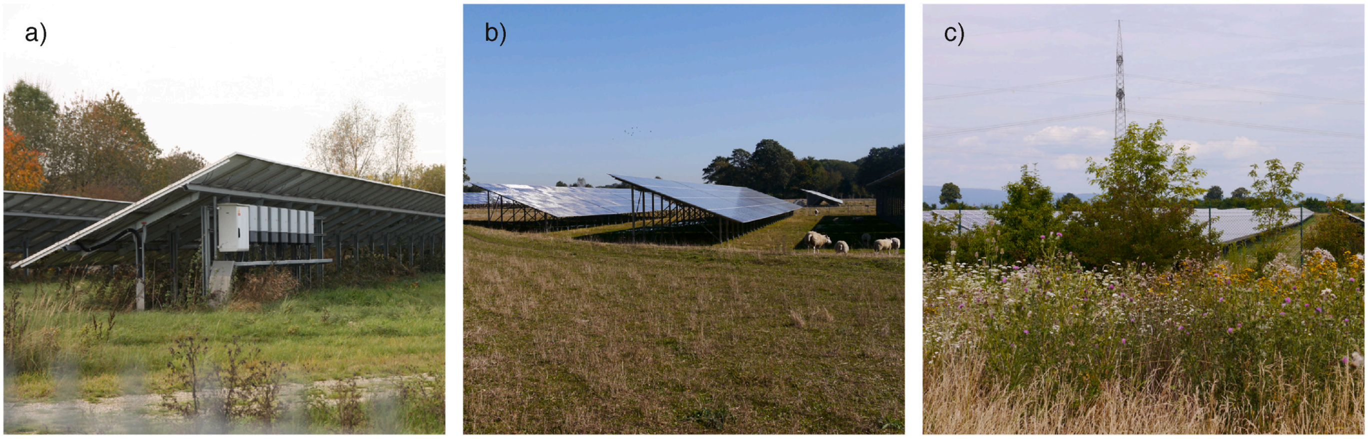


Fig. 10. a) array multifunctionality in Mühlenfeld (picture by Florian Becker): shade tolerating vegetation and inverters beneath arrays; b) patch multifunctionality in Laarberg: sheep grazing on the lowered patch area that also functions as water retention area; c) adjacent multifunctionality in Gänsdorf: hedgerow and wildflower field developed next to the PV patch.

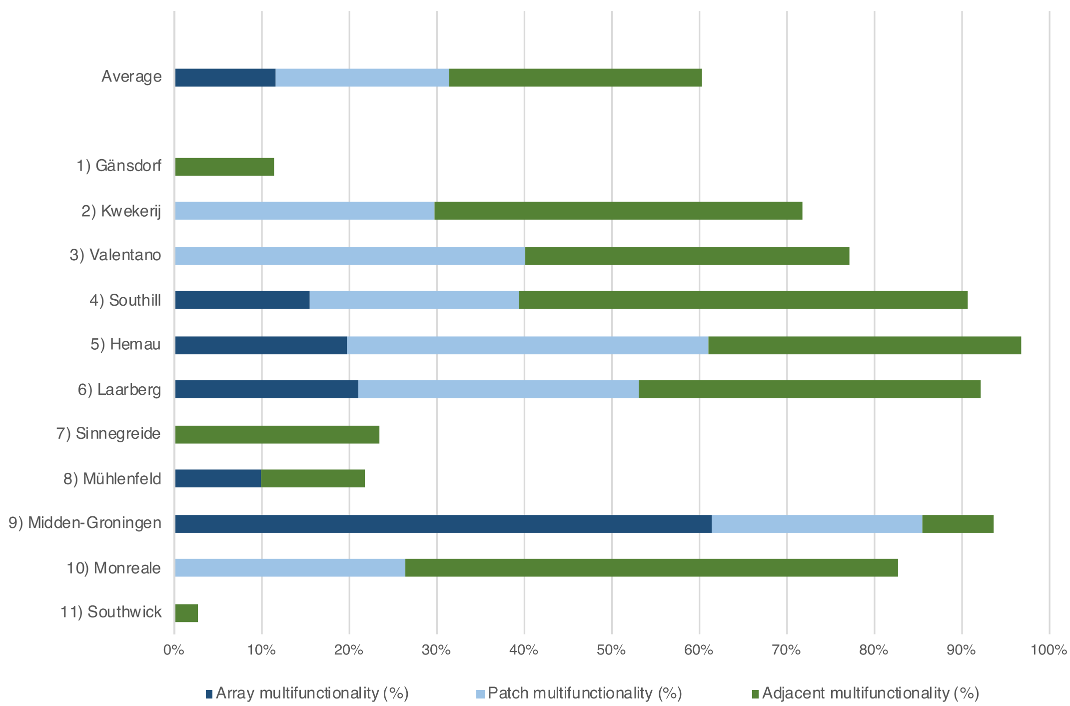


Fig. 11. Shares of land surface allotted to array, patch and adjacent multifunctionality.

In two cases (Gänsdorf and Midden-Groningen) existing parcellation was explicitly considered to maintain landscape character during the operation and maintenance stage.

Active management of landscape features during *operation and maintenance stage* was identified in four cases (Gänsdorf, the Kwekerij, Southill and Hemau). In these cases, monitoring and evaluation was organized, and consequently enabled decision-making based on changing monitoring results and contextual circumstances. A distinctive example is the Kwekerij, where changing demands by local stakeholders resulted in the addition of a vegetable garden in a later stage. On the contrary, other cases indicate a lack of active management and appeared not to be resilient to changing circumstances. In Monreale for example, the olive grove adjacent to the solar system is currently in a poor state. This olive grove was supposed to be used for local olive oil production, but it seems it was not well embedded in the local socio-economic context. In Southwick, original plans involved wildflower fields, grazing sheep and bat boxes. These plans, partially executed, appear to have been abandoned following a change in the ownership of the SPP.

Plans for the *decommissioning stage* were mentioned in six cases, mostly involving reversibility [4]. Three cases (Southill, Midden-Groningen and Southwick) plan to reverse the site into the former state of the landscape, although it is not always clear if this concerns removal of both solar infrastructure and landscape features. In Gänsdorf, rather than decommissioning, the plan is to continue combining electricity generation with habitat creation and agriculture by means of agrivoltaïcs. If executed, this plan will result in the recycling of the existing energy landscape [4]. In the Kwekerij and Monreale, landscape features in operation and maintenance stage supported the plans for the decommissioning stage. In the Kwekerij, local inhabitants benefit from the park function in operation and maintenance stage, and a larger park will be available to them once the solar infrastructure will be dismantled. In Monreale, cultivation of herbs between the arrays is supposed to increase soil quality for agricultural use in the decommissioning stage. Concluding, while in eight cases the temporal character of the cases was considered, only two cases used landscape features to enhance future use of the sites, beyond site restoration [59]. Thus, in most cases use of landscape features in decommissioning stage is not explicitly considered, which in turn might adversely affect their continuation [24]. This unclarity of the decommissioning stage has already been identified for wind energy and can potentially result in repowering or abandonment of renewable energy technologies [23].

4.3.4. Reflections on emergent properties across frontrunner solar landscapes

Although most cases pay attention to visibility, multifunctionality and temporality, the spatial arrangement of each case illustrates varying degrees of integration between solar infrastructure and landscape features. In the Kwekerij, these are entwined to a degree that the case is neither just a solar power plant nor just a public park: it is a combination of both. Patches have been configured to allow visitors to walk between the arrays, height of the arrays has been adjusted to address visibility concerns of neighboring residents. In Gänsdorf however, solar infrastructure and landscape features are strictly separated: additional functions are not found within, but next to the PV patches.

Whether landscape features are sustained beyond the decommissioning of the solar infrastructure depends on the type of the features. Features enhancing landscape character (e.g. Southwick) or features able to provide a function independent of solar infrastructure in the future (e.g. the Kwekerij) are likely to be sustained. In Midden-Groningen, on the contrary, some of the landscape features are unfamiliar to the host landscape and their existence will be less certain when the SPP is decommissioned.

5. Conclusions

This study aimed to contribute to the understanding of solar landscapes by examining 11 frontrunner cases across Europe, guided by the following research question: *what are the visual, functional and temporal properties of frontrunner solar landscapes in Europe?*

The examined frontrunner solar landscapes use a combined spatial arrangement of solar infrastructure and landscape features to address societal concerns. Solar infrastructure operates on system, patch and array level and landscape features are categorized as ecological, recreational and educational, agricultural and water management features. Visibility is reduced in all cases; yet in five cases visibility is simultaneously enhanced in dedicated areas in combination with recreational amenities. Cases contain between 6 and 14 different functions, although the share of land allocated to multifunctionality differs greatly between cases. In addition to electricity generation, habitat creation is identified in all cases, and in 9 out of 11 cases pollinating, screening and small-scale agricultural functions are identified. In eight cases the temporal character is considered in some way, yet only two cases explicitly introduce landscape features to enhance future use of the sites. Across the cases, our analysis of spatial properties shows how contemporary concerns about SPP, such as visual impact, land use competition and the end-of-life stage are addressed. Next to these empirical findings, we draw three main conclusions from this case study.

First, although the cases altogether present a portfolio of measures responding to societal concerns, the full potential of the three key properties is yet to be explored. The orientation of PV arrays, for example, is optimized for maximum electricity generation in all cases. Alternative array orientation may support maintaining existing landscape patterns and, simultaneously, reducing peak load on the electricity grid. Another example is the presence of similar landscape features across cases, despite the differences in character of the host landscapes.

Second, despite the additional benefits found in the cases, some (local) trade-offs may still emerge. To illustrate, some of the identified configurations of PV patches provide space for provisioning, regulating or cultural functions but can, at the same time, destroy existing landscape patterns. Furthermore, a high share of land solely dedicated to ecosystem functions increases the total land area needed to generate a set amount of electricity. These examples show the need to assess both individual properties as well as the SPP as a whole. Where existing research on additional benefits for SPPs is mainly theoretical, the empirical evidence in this research resulted in properties and initial indicators to describe, compare and potentially assess additional benefits. Such properties and indicators can become part of environmental impact assessments, multi-criteria decision analysis and other methods to asses not only *negative*, but also *positive* impacts of SPP. For example, assessment of *enhancing visibility* (e.g. through dedicated recreational areas with clear views on solar infrastructure) may enrich impact assessments that consider visibility as a negative property exclusively. Yet, other properties related to visual impact, such as frequency of views and glare still need to be taken into account. Similar, including properties such as temporality in multi-criteria decision analysis may favor alternative proposals of SPP that allow continuation of existing landscape features.

Third, as individual cases diverge in their attention for certain properties, further distinctions within the concept 'solar landscape' can be made. To illustrate, some cases focus mainly on visibility and only marginally on multifunctionality. In addition, some cases focus on provisioning and regulating functions, while others focus on cultural functions. A clear distinction between the different types of solar landscapes may help to conceive solar power plants appropriate to the site-specific considerations of local stakeholders and society at large.

Credit author contribution statement

Dirk Oudes - Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. Sven Stremke - Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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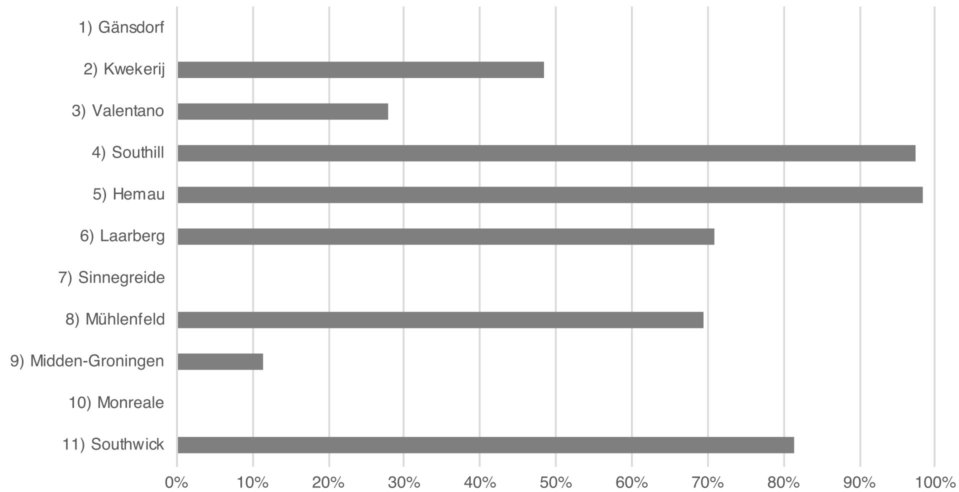
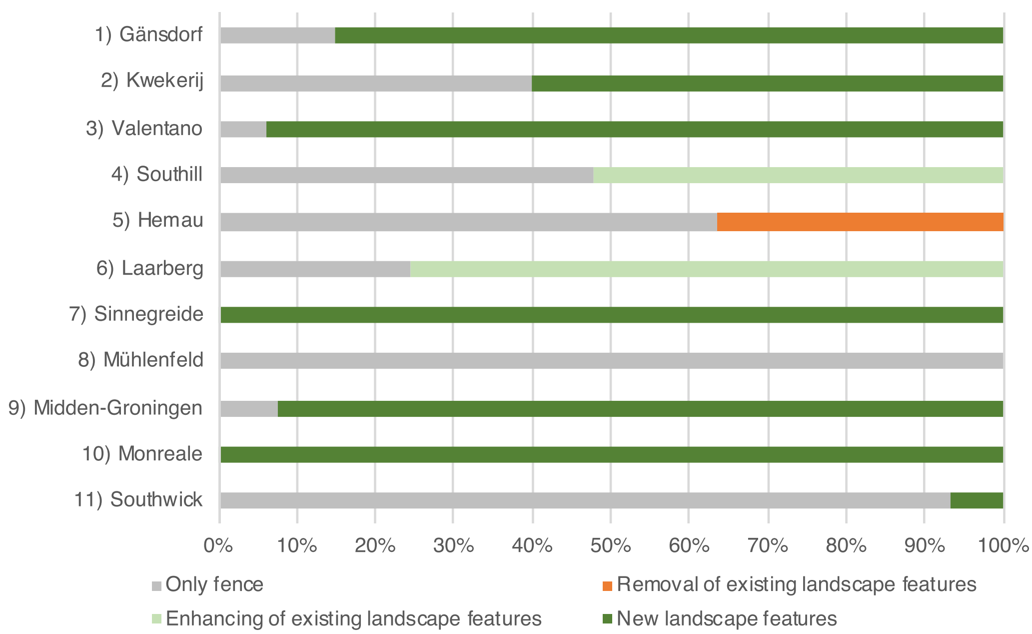
Appendices.



Appendix A. Share of existing eye-level vegetation (e.g. forest patches or hedgerows) along the edge of the solar landscapes.



Appendix B. In addition to fencing, three types of measures were applied along the edge of the solar landscapes: removal of existing landscape features, enhancing existing landscape features and new landscape features.

Appendix C. Presence of functions in the cases following the Common International Classification of Ecosystem Services (CICES) [52]

Section	Division	Code	Simple descriptor	Absolute presence	Relative presence
Provisioning (Biotic)	Biomass	1.1.1.1	Any crops and fruits grown by humans for food; food crops	5	45%
	Biomass	1.1.1.2	Material from plants, fungi, algae or bacterial that we can use	2	18%
	Biomass	1.1.3.1	Livestock raised in housing and/or grazed outdoors	4	36%
	Non-aqueous natural abiotic ecosystem outputs	4.3.2.4	Solar power	11	100%
Regulation & Maintenance (Abiotic)	Transformation of biochemical or physical inputs to ecosystems	5.1.2.1	Natural protection	3	27%
Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	2.1.2.3	Screening unsightly things	9	82%
	Regulation of physical, chemical, biological conditions	2.2.1.3	Regulating the flows of water in our environment	6	55%
	Regulation of physical, chemical, biological conditions	2.2.2.1	Pollinating our fruit trees and other plants	9	82%
	Regulation of physical, chemical, biological conditions	2.2.2.2	Spreading the seeds of wild plants	1	9%
	Regulation of physical, chemical, biological conditions	2.2.2.3	Providing habitats for wild plants and animals that can be useful to us	11	100%
	Regulation of physical, chemical, biological conditions	2.2.4.2	Ensuring the organic matter in our soils is maintained	1	9%
Cultural (Biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.1.1	Using the environment for sport and recreation; using nature to help stay fit	4	36%
	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.1.2	Watching plants and animals where they live; using nature to destress	5	45%
	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.2.1	Researching nature	3	27%
	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.2.2	Studying nature	5	45%
	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	3.1.2.4	The beauty of nature	6	55%
	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting	3.2.2.1	The things in nature that we think should be conserved	7	64%
Cultural (Abiotic)	Indirect, remote, often indoor interactions with physical systems that do not require presence in the environmental setting	6.2.2.1	Things in the physical environment that we think are important to others and future generations	4	36%

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