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Agrivoltaics and landscape change: First evidence from built cases in the Netherlands

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ABSTRACT

The need to advance energy transition has arisen from the global challenge of climate change. Shifts to renewable energy sources, such as solar energy, are crucial for reducing carbon emissions and mitigating climate change. The use of *agrivoltaics*—the combination of food and renewable energy production with photovoltaic technology—is gaining scientific attention. Agrivoltaics is a type of multifunctional energy landscape and thus reduces land use conflicts between energy and food production. However, while agrivoltaics has begun to proliferate at a global scale, the associated landscape changes have so far received little attention. This knowledge gap is critical, as there is clear evidence that landscape change often contributes to low levels of acceptance of solar power installations. To address this gap, this study examines landscape changes brought by agrivoltaic installations in the Netherlands. Four representative built cases were examined making use of key landscape change indicators extracted from the literature and fieldwork. The study revealed varying degrees of landscape change across the examined cases. Changes in the agricultural landscape pattern and openness emerged as prominent landscape changes. Changes in crop type and in historical linear landscape structures—often associated with the implementation of conventional solar power plants—were not identified. Policy attention to the siting and design of agrivoltaic systems in the landscape is needed to positively influence social acceptance of this relatively novel solution and thereby advance energy transition.

1. Introduction

Climate change has emerged as one of the major threats to humanity. In response, the European Union has set a greenhouse gas emission reduction target of 55% by 2030, compared with 1990 levels (EU Council, 2023). One prominent approach to mitigating climate change is the energy transition. Energy transition entails the shift from fossil fuels to renewable energy and is not only a technological or economic transition, but has social, cultural, environmental, political and spatial dimensions as well (Miller et al., 2013; Pasqualetti, 2000; Sovacool, 2014). Population growth and its associated increases in energy and food demand is another motivation for accelerating energy transition at global and local scales (Casares de la Torre et al., 2022).

One of the approaches to addressing these growing challenges and accelerating energy transitions at the local scale is the provision of renewable energy using solar power plants (SPPs) (Oudes et al., 2022). SPPs comprise photovoltaic (PV) arrays that convert sunlight into electrical energy (Ketzer et al., 2020). While the number of SPPs is rapidly growing worldwide, without adequate spatial planning (Hermoso et al., 2023), their implementation often creates land use conflicts with respect to food and energy production (Pascaris et al., 2021). As a result, strategies to minimize these conflicts and preserve agricultural land are required to upscale the deployment of PV systems (Pascaris et al., 2022). Agrivoltaics is a particular type of SPP that combine food and energy production on the same land, giving rise to a novel type of multifunctional landscape (Oudes et al., 2022). Several categories of agrivoltaics can be distinguished, based on the configuration of PV arrays with respect to crop and livestock production (Willockx et al., 2020). Agrivoltaics can be divided into two main categories: configurations with agriculture under PV arrays and configurations with agriculture between PV arrays (DIN, 2021; Willockx et al., 2020). In addition to crop production, the first category also includes livestock grazing if this involves grazing with economic revenue (DIN, 2021). We employ the German DIN definition (DIN, 2021), given its status as a recent agrivoltaic technical specification (Ghosh, 2023) and the inconclusiveness of Dutch policies in defining agrivoltaics (de Ruijter et al., 2023; Rijksoverheid, 2023). This definition acknowledges multiple spatial configurations of the combination of agriculture and

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photovoltaics and therefore supports the case identification. For the purpose of this research, *agrivoltaic system* refers to the technical hardware including PV arrays, while *agrivoltaic power plant* (AVPP) refers to the agrivoltaic system plus the associated land underneath and in between PV arrays.

The implementation of conventional SPPs in landscapes, similar to other renewable power plants, is often met by opposition of local stakeholders (Enserink et al., 2022; Roddis et al., 2020). In the near future, agrivoltaics might encounter similar opposition because of its similarities with conventional SPP. The various types of agrivoltaic systems, each with its own technical characteristics, may change the physical features and the experience of landscapes in a range of ways. Examples are change of the land use, relief and openness of the landscape. In turn, these changes can lead to concerns and even public resistance towards these agrivoltaic systems (Toledo and Scognamiglio, 2021). On the other hand, agrivoltaics may also count on higher rates of public acceptance compared to conventional SPPs due to added value of agricultural production (Pascaris et al., 2022). The latter study showed that 81.8% of respondents would be more likely to support a solar development in their community if it was integrated with agricultural production.

To advance the development and deployment of agrivoltaic systems, it is important to establish land use policies that regulate their implementation, address landscape change and minimize their impact (Pascaris, 2021). Nevertheless, to date policies in the European Union that address agrivoltaics are scarce and often ignore landscape change (Chatzipanagi et al., 2023). One method for measuring landscape change is the use of landscape change indicators (LCIs) (Van Eetvelde and Antrop, 2009). Typically, several LCIs are required to identify different aspects of landscape change (Van Eetvelde and Antrop, 2009).

The objective of this study is therefore to analyze and document landscape changes caused by the implementation of agrivoltaics. As to date relatively little research has been conducted on landscape change with respect to agrivoltaics, it is yet unclear what methods are useful. Consequently, the objective of this research required the development of a comprehensive method for investigating and analysing landscape changes brought by agrivoltaic systems in the Netherlands. This study was guided by the following research question: What are the landscape changes induced by AVPP in the Netherlands and what methods can be used to examine this kind of landscape transformation? Based on our results, we provide recommendations for policy makers to advance policies for the implementation of agrivoltaics.

2. Methods and materials

To conduct this study, we collected case study data on built AVPP in the Netherlands and analysed landscape changes brought by these installations. We adopted a case study approach (Oudes and Stremke, 2021; Yin, 2009) and employed spatial analysis methods to examine and compare landscape changes.

2.1. Data collection

The data collection process was conducted in two stages: case identification and spatial data of selected cases. For the case identification, data was gathered from grey and peer-reviewed literature, including the Google search engine (2023) and two magazines focused on solar energy projects (PVmagazine, 2023; Solarmagazine, 2023). Spatial data of the cases was collected for each case using permit documentation (Ruimtelijkeplannen, 2023), field work, interviews with farmers, orthophotos and satellite images. The interviews were conducted between May 2022 and January 2023 on site with farmers who host agrivoltaic installations. Two sets of orthophotos and satellite images were collected. The first set with a date prior to the implementation of the respective agrivoltaic system and the second set with a date shortly after its implementation.

2.2. Case selection

For this research, we studied built agrivoltaic cases exclusively in the Netherlands due to its recent and rapid rise in agrivoltaic development, the availability of Dutch datasets and the ability to conduct field work. The Dutch AVPP cases have an area up to 5 ha (Table 1), while some international cases with a larger spatial extent exist (e.g. Amador, 2023).

The cases were selected in two stages. First, we identified agrivoltaic installations that met three criteria: already constructed, described in at least one publication prior to 31 January 2023, and matching the above mentioned definition of AVPP. Subsequently, technical details for each agrivoltaic case were collected using orthophotos and satellite images and through a literature review. The study by Sirnik et al. (2023) served as additional data source. Fifteen agrivoltaic cases were identified; Table 1 shows an overview and descriptive statistics for these cases.

Second, we applied additional selection criteria. The chosen AVPPs had to exhibit at least a Technology Readiness Level five (Rose et al., 2017), a nominal power output of least 100 kWp, and a minimum intended project span of five years (Table 1). For photovoltaic installations, Technology Readiness Level five is defined as large scale prototype tested in natural environmental conditions (Rose et al., 2017). These criteria were applied to exclude smaller scale AVPPs and AVPPs pilots with shorter project spans, as those were not considered appropriate for landscape change analysis.

Of these fifteen preliminary cases, four met the selection criteria and were chosen for further analysis: Babberich, Wadenoijen, Almere and Culemborg (Fig. 1). Orthophotos and satellite images of these sites, which are located in the central part of the Netherlands, showed notable landscape changes after the implementation of their respective agrivoltaic systems (Fig. 2).

2.3. Spatial analysis using landscape change indicators

Landscape change refers to the alteration of the physical features and visual appearance of a landscape (Oudes, 2022). To identify and investigate the scale of such landscape changes in the case study areas, we used ten LCIs. The LCIs were chosen to specifically identify and document different physical changes of the landscape. Due to the absence of a list of LCIs for the analysis of agrivoltaics, we combined LCIs from the literature with those identified during field work.

The ten LCIs we employed were derived from three sources (Table 2). These sources are the (1) Dutch National Environmental Assessment Agency (Kuiper and Spoon, 2022) for its focus on monitoring change in the Dutch landscape using LCIs, (2) study by Oudes and Stremke, (2021) for its focus on spatial properties of SPPs, and (3) field work. The Dutch National Environmental Assessment Agency employs eight LCIs (Kuiper and Spoon, 2022). The four LCIs relevant for our study are *land use*, *openness*, *relief* and *historical linear landscape structures*. Oudes and Stremke (2021) examined a series of conventional SPPs that contributed to the understanding of landscape change induced by the development of utility-scale solar power. The LCI *change in the pattern of the agricultural landscape* was selected from that study. Together, these two studies provide a foundation for investigating the landscape changes brought by agrivoltaic applications. The other five LCIs were derived from field work and interviews with farmers.

Two LCIs, *Change in the pattern of the agricultural landscape* and *Change in openness,* require a more elaborate description due to their characteristics. *Change in the pattern of the agricultural landscape* was examined by making use of four types of patch configurations: responsive, irresponsive, split and island. We used the terminology and definition of PV configurations presented in the paper by Oudes and Stremke (2021). The 'responsive type' PV patch mirrors the shape of the plot, maintaining the recognizability of the original parcellation with relatively high coverage (65 – 90%). The 'irresponsive type' is self-referential, resulting in space being left over within the plot and a coverage range of 50 – 75%. The 'split type' is defined by a PV patch that

Table 1

Descriptive statistics of potential agrivoltaic cases including location data and technical details. In the orientation category, E stands for east, S stands for south, W stands for west, vertical refers to vertical PV arrays and single axis refers to single axis tracking systems. Technology Readiness Level (TRL) varies between 1–10, for which 1 indicates 'Basic research, principles postulated and observed but no experimental proof available' and 10 indicates 'Full commercial application, technology available for consumers'. The cases selected for further analysis are indicated in the last column. In the Lochem case, agricultural activity was documented on a small, experimental scale. As a result, the selection criteria "Land underneath and between PV arrays dedicated to agriculture" was not acknowledged.

Name of the agrivoltaic case	Location of agrivoltaic case		Technical details					Selection criteria				Selection
	Latitude	Longitude	Area of agrivoltaics system (ha)	Height of structure (m)	Power output (kWp)	TRL	Orientation of PV arrays	Built case with min. TRL 5	Power output min. 100 (kWp)	Preservation of the structure for minimum five years	Land underneath and between PV arrays dedicated to agriculture	
Babberich	51°53'57.35"N	6° 7'33.95"E	3.20	3.0	2320	8	E-W	X	X	X	X	X
Wadenoijen	51°52'21.76"N	5°21'6.76"E	3.70	3.0	1013	6	E-W	X	X	X	X	X
Almere	52°22'35.95"N	5°17'55.15"E	4.90	2.3	700	5	single axis	X	X	X	X	X
Culemborg	51°56'9.30"N	5°10'31.10"E	0.70	2.9	881	5	vertical	X	X	X	X	X
Lochem	52° 9'54.60"N	6°23'27.84"E	9.50	2.5	6413	9	S	X	X	X		
Haren	53°10'55.06"N	6°37'30.68"E	2.00	1.8	1688	9	S	X	X	X	X	
Someren	51°26'33.83"N	5°39'58.05"E	0.03	2.5	25	4	E-W			X	X	
Stadskanaal	52°59'40.60"N	7° 2'57.48"E	0.14	1.0	118	4	E-W		X	X	X	
Etten-Leur	51°33'44.00"N	4°39'26.18"E	3.00	3.0	2531	9	S	X	X	X	X	
Boekel	51°36'40.52"N	5°42'3.80"E	0.04	2.1	17	6	S	X		X	X	
Oss	51°45'49.80"N	5°28'37.28"E	0.06	1.7	82	5	E-W	X		X	X	
Lelystad	52°32'13.17"N	5°33'42.76"E	0.05	3.5	106	5	E-W	X	X		X	
Randwijk	51°56'13.80"N	5°42'32.12"E	0.11	3.9	30	5	E-W	X		X	X	
Broekhuizen	51°29'15.03"N	6° 9'17.87"E	0.11	2.5	93	5	S	X		X	X	
Sint-Oedenrode	51°34'50.83"N	5°25'36.56"E	0.13	2.1	110	6	E-W	X	X	X	X	

Fig. 1. Images of each selected agrivoltaic cases (Image credit: Dirk Oudes).

matches the plot's shape, but with low coverage (25 – 50%) of the original plot. The 'island type' represents small parts of plot, independent from existing parcellation, covered by PV arrays. The coverage of the original plot is low (35 – 40%).

Change in openness was determined by comparing openness raster layers for the before and after agrivoltaic system conditions for each respective cases. For the pre-implementation spatial condition, input data were digital surface models for the Netherlands (Actueel Hoogtebestand Nederland, 2023). The selected digital surface model dataset was the most recent available prior to implementation. For the post-implementation situation, the height and area of the respective agrivoltaic system was added to the pre-implementation dataset.

We followed Weitkamp's (2011) approach to calculate openness values for the area within a 1200 m radius of each AVPP. For each case, a radius was defined according to maximum viewing distance (Weitkamp, 2011), with the origin point determined as the centroid of the AVPP. Calculations were made using the ArcGIS Viewshed tool (Esri, 2023) with a result of two raster layers containing openness values for 100×100m tiles. Within these analysis circles, we identified the first line of observation from the roads and paths closest to the respective AVPP (see Oudes and Stremke (2021)). We then analyzed *change in openness* by calculating the results for all tiles along this line of observation.

3. Results and discussion

Landscape changes were identified in all four cases, and the results revealed a diversity of identified LCIs across these cases. This chapter discusses the landscape changes identified for each case, followed by a comparative analysis of these changes.

3.1. Landscape changes of overhead soft fruit agrivoltaic case Babberich

The spatial analysis results showed diverse landscape changes on the Babberich site (Fig. 3). In addition to the implementation of a 26,631 m^2 agrivoltaic system, two transformers (total 16 m^2) were added north of the AVPP. These elements were classified under *change of agrivoltaic system structure*. Following the construction of the system, 881 m of hedgerow was removed, which was classified as *change in vertical non-agricultural vegetation*. Babberich is the only case in which hedgerows were removed, most likely due to the shading effect of vegetation and

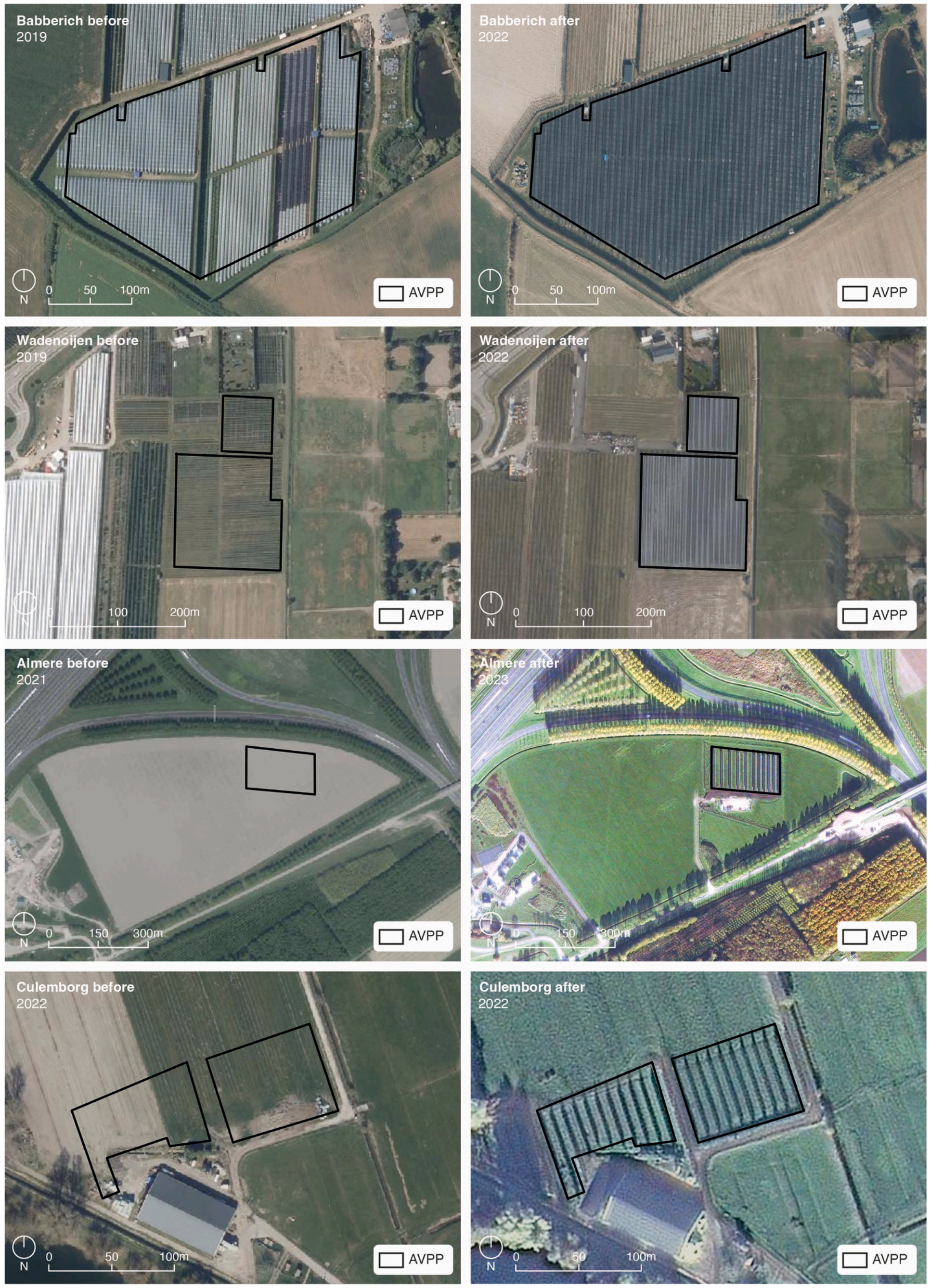

Fig. 2. Orthophotos and satellite images from selected cases before (left column) and after (right column) the installation of an agrivoltaic system (PDOK, 2023; Satellietdataportaal, 2023). AVPP stands for agrivoltaic power plant. Black lines represent AVPP boundaries.

subsequent lower energy production for PV arrays. However, hedgerows also serve agricultural functions, namely as a wind barrier and providing a habitat for pollinators. Depending on the local situation, farmers are potentially confronted with conflicts (e.g. hedgerow shade PV panels) or synergies (e.g. hedgerow reduces visibility of AVPP).

Before the implementation of the agrivoltaic system, a vertical support system of metal structures and plastic foil protected the crop against harmful environmental influences. The removal of this structure was classified as *change in crop support system.* Incidentally, PV arrays offer several advantages compared to plastic foil systems. For example, Sirnik et al. (2023) suggested that agrivoltaic systems look more attractive, and Feuerbacher et al. (2021) found that PV arrays offer better protection against harmful environmental influences such as hail. Further analysis revealed minor changes in the boundaries of the agricultural field, due to the replacement of the existing crop support system. Thus, the identified PV patch configuration was deemed 'responsive' (Oudes and Stremke, 2021) (see Fig. 7).

Another consequence of replacing the crop support system was a relatively minor *change in openness*. This change was identified in the short line of observation compared with the entire observation line (23.4%) and an average change of openness in the observed line of observation (3.1%) (Fig. 8). One possible explanation for this result concerns the existence of perimeter hedgerows prior to the implementation of the agrivoltaic system. Moreover, the openness change was considered minor due to the relatively low height increase of the agrivoltaic system compared with the prior support system.

Table 2
Landscape change indicators used in this study with their corresponding units, descriptions, data sources, and references. The term 'This research' in the reference column refers to landscape change indicators defined during the research process of this study.

#	Landscape change indicator	Unit	Description of landscape change indicator	Data source	Reference
1	Land use change	m^2	Conversion of land use by humans from one state to another.	Land Use Database of the Netherlands (LGN, 2023), orthophotos, satellite images, field work and interviews with farmers	Kuiper and Spoon (2022)
2	Crop change	m^2	Process of altering or shifting crop types grown in an agricultural area	Orthophotos and satellite images, field work and interviews with farmers	This research
3	Change in vertical non-agricultural vegetation	m^2	Change in higher vegetation (such as lines of trees, hedgerows or shrubs) for non-agricultural purposes	Orthophotos, satellite images, field work and interviews with farmers	Kuiper and Spoon (2022) and this research
4	Change of relief	m^2	Change in landscape elevation	Orthophotos, satellite images, digital elevation model (PDOK, 2023), field work and interviews with farmers.	Kuiper and Spoon (2022) and this research
5	Change of historical linear landscape structures	m	Landscape has been formed in the last centuries by intensive interaction of human actions and natural processes. The traces of these actions are still visible in modifications of historical linear structures, including watercourses and roads.	Orthophotos, satellite images and interviews with farmers	Kuiper and Spoon (2022)
6	Change in crop support system	m^2	Change in the support systems of agricultural elements (e.g., plastic foil) that protect crops from harmful environmental factors	Orthophotos, satellite images, field work and interviews with farmers	This research
7	Change of fences	m	Change in perimeter fencing used to prevent human access	Orthophotos, satellite images, field work and interviews with farmers	This research
8	Change of agrivoltaic system structure	m^2	Introduction of technical elements that are part of an agrivoltaic system (e.g., PV arrays, transformers and invertors)	Orthophotos, satellite images, field work and interviews with farmers	This Research
9	Change in the pattern of the agricultural landscape	Responsive, irresponsive, split and island	Change in agricultural landscape pattern due to size, position and/or alignment of a PV patch. Four typical patch configuration types include: responsive, irresponsive, split and island.	Orthophotos, satellite images and field work	Oudes and Stremke (2021)
10	Change in openness	ha	Openness is a characteristic of perceived landscape. It is defined as the amount of space, the field of view of an landscape user at eye-level (1.6 m), perceivable to the landscape user. In this study we study degree of landscape openness before and after the implementation of an agrivoltaic system; determined by the presence of landscape elements above eye-level in the immediate surroundings.	Digital surface models for the Netherlands (Actueel Hoogtebestand Nederland, 2023)	Kuiper and Spoon (2022) and Weitkamp et al. (2011)

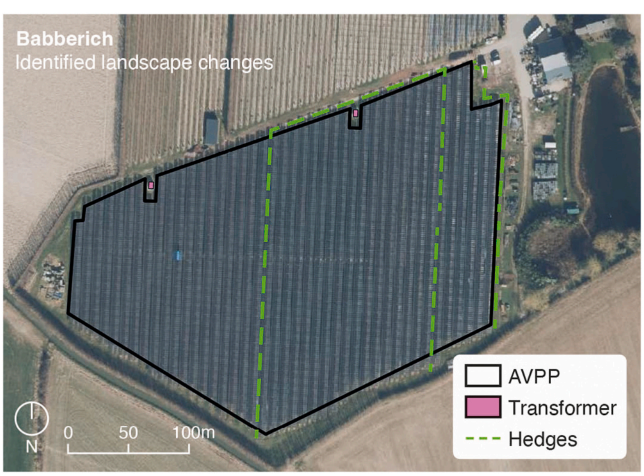

Fig. 3. Babberich site with identified landscape changes. AVPP stands for agrivoltaic power plant. Dotted lines depict the location of hedgerows before removal. Basemap is an orthophoto image from 2022 (PDOK, 2023). Consult Fig. 2 for pre-implementation condition.

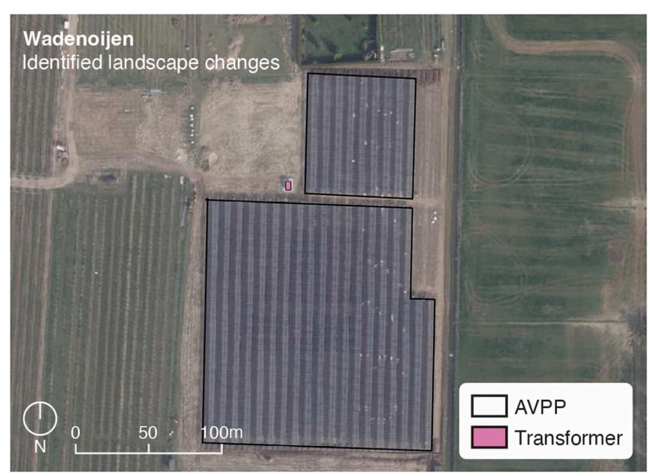

Fig. 4. Wadenoijen site with two identified landscape changes, classified as *change of agrivoltaic system structure*. Consult Table 3 for all identified landscape changes. AVPP stands for agrivoltaic power plant. Basemap is orthophoto image from 2022 (PDOK, 2023).

3.2. *Landscape changes of overhead soft fruit agrivoltaic case Wadenoijen*

For this site, we identified the addition of a 11,849 m^2 agrivoltaic system and a 7 m^2 transformer (Fig. 4). A significant surface of the agricultural field is covered by two PV patches (Fig. 7), and the PV patch configuration is self-referential, meaning that the *change in the pattern of the agricultural landscape* was classified as 'irresponsive' (Oudes and Stremke, 2021). The *change of openness* was relatively high compared with the other three cases, as the results showed a high percentage of affected line of observation (89.1%) and average change of openness in the affected line of observation (7.8%). Here, the absence of vertical structures and relatively low crops (redcurrant) prior to the construction of the agrivoltaic system may explain the relatively high *change in openness* value.

3.3. Landscape changes of agrivoltaic tracking system grassland Almere

Six different landscape changes were found for the Almere site (Fig. 5). The implementation of a 9,495 m^2 agrivoltaic system was classified as *change of agrivoltaic system structure*, and three kinds of *land use change* were identified: (1) from grassland to road (south-west of the AVPP), (2) from grassland to parking lot (south of AVPP), and (3) from grassland to pond (east of the AVPP). The pond potentially serves as an irrigation source for the field underneath the PV. Collectively, these land use changes comprise a 5,737 m^2 area. Another landscape change—a new knoll measuring 3,986 m^2 and 2.3 m high —was also detected to the southeast of the AVPP and was classified as *change of relief*. A metal transparent fence 967 m long and 1.5 m high was also installed around the perimeter of the AVPP. When compared to the other three cases, this relatively large number of added elements suggests significant changes due the implementation of this agrivoltaic system. However, unlike the other sites, these new and altered elements were not located in direct proximity of the AVPP. The furthest element from the Almere installation is the pond, located about 200 m to the east of the AVPP.

The *change in the pattern of the agricultural landscape* was classified as 'island' (Oudes and Stremke, 2021) due to its self-referential nature (Fig. 7). The PV patch covers only a small part of the agricultural field and its shape is independent of the borders of the field. The *change in openness* was 12.2% on average in the affected line of observation, which was the highest *change in openness* among the studied cases (Fig. 8). Moreover, a relatively high affected line of observation of 74.0% was detected, which was the second highest result among the cases. This was due to the implementation of relatively high elements (i.e., a 3.2 m tall PV array) in an open pasture with low crop height.

3.4. Landscape changes of interspace agrivoltaics on grassland case Culemborg

Two new elements were identified in the Culemborg case: the agrivoltaic system itself and a fence (Fig. 6). These elements were classified as *change of agrivoltaic system structure* and *change of fence*, respectively. The surface area of the AVPP is 4,086 m^2, which features integrated inverters. Similar to many SPPs, a beehive was positioned between the PV arrays in the western part of the AVPP (Oudes et al., 2022).

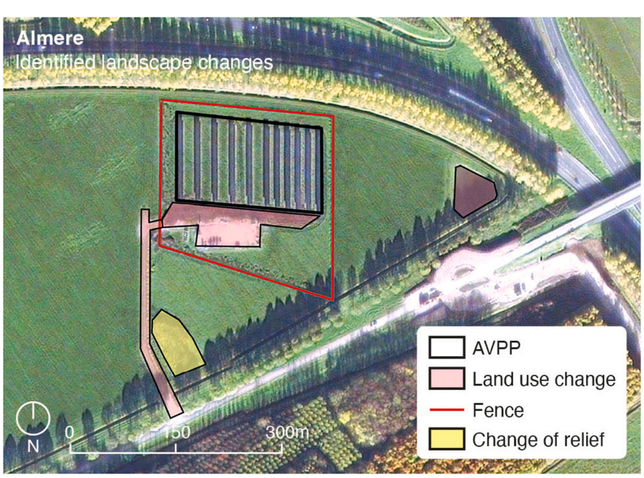

Fig. 5. Almere site with Identified landscape changes. AVPP stands for agrivoltaic power plant. Basemap is a satellite image taken in 2023 (Satellietdataportaal, 2023).

Fig. 6. Culemborg site with identified landscape changes. AVPP stands for agrivoltaic power plant. The basemap is a satellite image taken in 2023 (Satellietdataportaal, 2023).

A 122 m long fence was identified south of the AVPP and was classified as *change of fence.* The 2.9 m tall fence, which visually separates the AVPP from the road and the farmer's residence, is constructed of vertical PV arrays supported by a structure divided into three segments. The other PV arrays largely align with the shape of the agricultural field, yet cover only part of the area (Fig. 7). This, results in a 'split' configuration, which indicates a *change in the pattern of the agricultural landscape*.

The implementation of the 2.9 m vertical PV arrays in the pasture caused an average decrease in *openness* of 1.7% in the affected line of observation (Fig. 8). This *openness change* was somewhat limited due to the presence of buildings to the south, which limit the visibility of these arrays. Without such structures, the openness change caused by the vertical interspatial AVPP is expected to be much higher.

3.5. Overview of landscape changes

Landscape changes were identified in all four cases (Table 3). The maximum number of identified LCI per case was six for the Almere site, followed by the Babberich, Culemborg and Wadenoijen sites with five, four and three LCIs, respectively. The most frequently identified LCIs were *change of agrivoltaic system structure, change in openness,* and *change of pattern of the agricultural landscape*, which occurred in all cases. *Crop change* and *change of historical linear landscape structures* were not identified.

Change of agrivoltaic system structure was identified in all cases and is inherent to the implementation of agrivoltaic systems. The largest area for *change of agrivoltaic system structure* was detected for the Babberich site (26,647 m^2) and the smallest for the Culemborg case (4,086 m^2). The two AVPPs that include fruit crops (Babberich and Wadenoijen) are larger than the two grassland AVPPs (Almere and Culemborg). These grassland AVPPs feature newer technologies, namely vertical bifacial PV and tracking systems. All examined AVPPs are relatively small compared with conventional SPPs (Oudes and Stremke, 2021). This smaller size could be explained by the novelty of agrivoltaic systems (Mamun et al., 2022) in the Netherlands and the relatively higher economic investments for AVPPs compared with conventional SPPs.

Only in Almere *land use changes* were identified, and included a new road, parking area and pond. This is because in Almere the site was an open field without infrastructure prior to the implementation of the agrivoltaic system. By contrast, the agrivoltaic systems on the Babberich, Wadenoijen and Culemborg sites were implemented on existing farms.

The only removal of landscape elements was identified on the

Table 3
Identified landscape change indicators with corresponding intensities for each agrivoltaic case.

#	Landscape change indicator	Agrivoltaic case			
		Babberich	Wadenoijen	Almere	Culemborg
1	Land use change	No change	No change	5,737 m^2	No change
2	Crop change	No change			
3	Change in vertical non-agricultural vegetation	-881 m	No change	No change	No change
4	Change of relief	No change	No change	area = 3,986 m^2, height = 2.3 m	No change
5	Change of historical linear landscape structures	No change			
6	Change in crop support system	-26,631 m^2	No change	No change	No change
7	Change of fences	No change	No change	length = 967 m, height = 1.5 m	length = 122 m, height = 2.9 m
8	Change of agrivoltaic system structure	26,647 m^2	11,856 m^2	9,495 m^2	4,086 m^2
9	Change in the pattern of the agricultural landscape	responsive	irresponsive	island	split
10	Change in openness (average openness change in affected line of observation)	3.1%	7.8%	12.2%	1.7%

Babberich site (i.e., 881 m of hedgerows), which can be explained by the negative effects of shading on both crop yields and energy production. A *change of relief* was identified only for the Almere site, due to the new knoll, which was most likely created using leftover material from the road, parking lot and pond construction. A *change in crop support system* was identified only in Babberich, where the existing agricultural support system was replaced by the agrivoltaic system. A *change of fences* was identified in two cases, Almere and Culemborg, the former for security reasons, and the latter for electricity production.

Four different PV patch configurations were identified across the four cases, illustrating the variety in *change in the pattern of the agricultural landscape* of agrivoltaics (Fig. 7). The 'responsive' PV patch configuration in Babberich is a logical consequence of the replacement of the existing crop support system with the agrivoltaic system. By contrast, the agricultural landscape pattern of the Almere site was largely affected by the creation of an 'island' AVPP.

Change in openness was identified in all cases (Fig. 8) because elements higher than 1.6 m (i.e., at eye level) were implemented (Weitkamp et al., 2011). *Change in openness* depends on the properties of implemented elements (e.g., height and area of element) and the openness of the landscape prior to implementation of a given agrivoltaic system. Thus, *change of openness was* least significant for the Babberich case, as evidenced by its lowest share of affected line of observation (23.4%). This is due to the replacement of the existing crop support system, which was approximately the same height as the new agrivoltaic

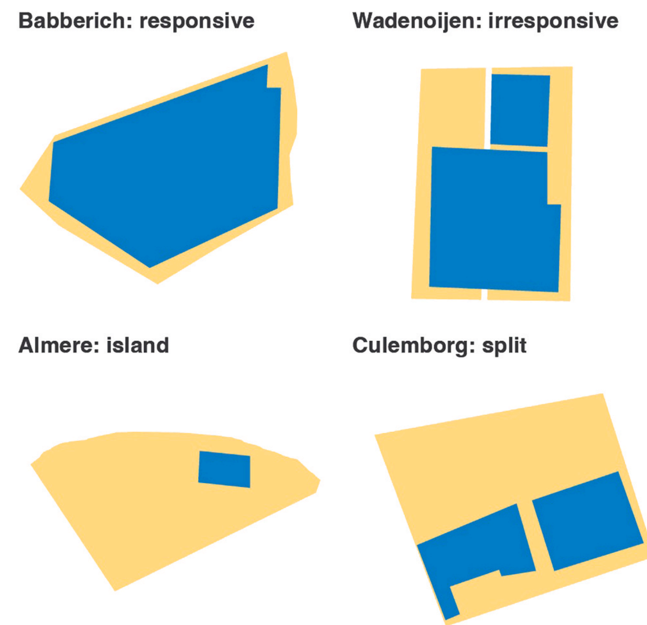

Fig. 7. PV patch configuration by cases representing the change in the pattern of the agricultural landscape. Blue areas represent PV patch and yellow area represents agricultural field. Identified PV patch configuration is stated above each case.

system. A small degree of *change in openness* was also detected for the Culemborg case, largely due to the presence of the tall farm buildings south of the site and a relatively small AVPP area.

The highest percentages of affected line of observation and average *change in openness* of the affected line of observation were detected for the Wadenoijen (89.1% and 74.0%) and Almere cases (7.8% and 12.2%), respectively. The large *change in openness* on the Wadenoijen site is due to the construction of a relatively high AV structure (3 m) in a largely open landscape. The open landscape condition prior to the implementation of the agrivoltaic system is the main reason for the substantial *change in openness* in the Almere case, with a 12.2% change in average openness of the affected line of observation. Here, it is worth noting that the maximum levels of *change in openness* along the line of observation were found in the Wadenoijen (89.1%) and Almere (74.0%) cases. Put differently, for some viewpoints, the landscape user may experience an average decrease in openness of approximately 50%.

In current Dutch legislation, a formal category for agrivoltaics is lacking (de Ruijter et al., 2023). As a result, agrivoltaics has been allowed by some municipalities as replacing existing agricultural support structures, such as plastic foils in the case of soft fruit production. Other municipalities treat agrivoltaics as conventional SPPs. Recent policy in the Netherlands designates agrivoltaics as one of the few exemptions of solar energy on agricultural land (Rijksoverheid, 2023).

3.6. Limitations

Methodological and data limitations may have affected the study presented in this paper. To examine landscape changes induced by the development of AVPP we used ten LCIs, derived from the literature and our own research. Any such selection of LCIs is exposed to potential bias. The choice of LCIs was limited due to the relative dearth of literature on AVPPs in general and on landscape experience of agrivoltaics in particular. Nevertheless, the use of LCIs can be recommended to study landscape changes induced by agrivoltaics. Applying additional LCIs might benefit the further understanding of landscape changes. The limited number of agrivoltaic types that have been examined presents another limitation. Finally, the focus of the research on a single country—the Netherlands – has implications for the generalizability of the

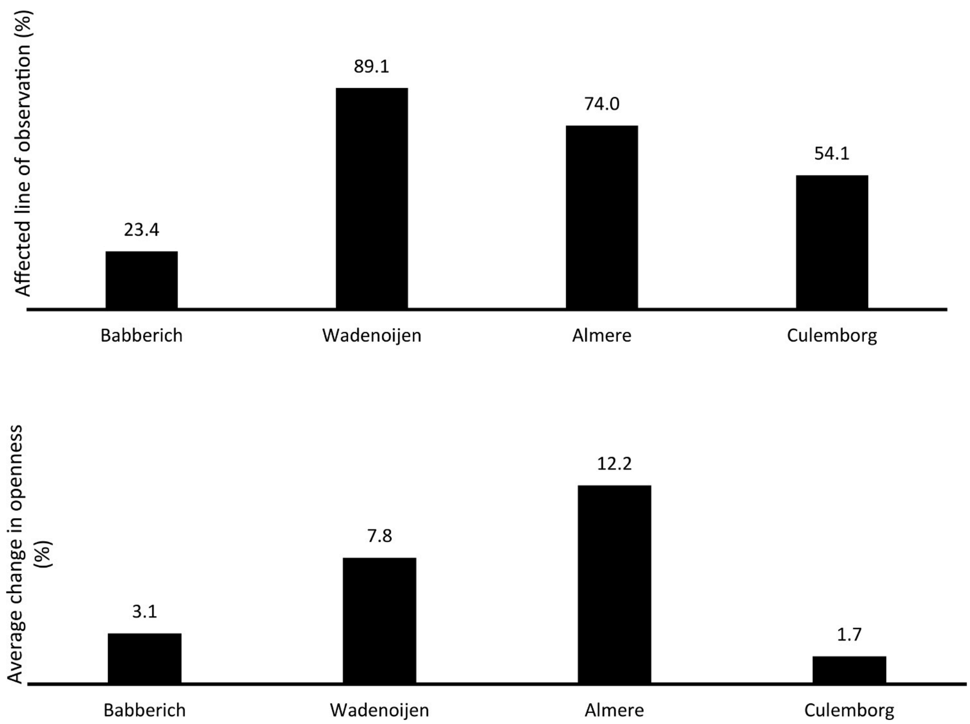

Fig. 8. Openness of studied cases. The top graph shows the percentage of openness-affected lines of observation compared to the entire lines of observation. The bottom graph shows the average change in openness in the affected line of observation.

findings. Comparable studies in other countries are recommended to gain a more comprehensive picture of landscape change by agrivoltaics.

Although the case-study findings are specific for the Netherlands, the presented procedure for the spatial analysis and used LCIs provide a solid basis for studies on AVPP induced landscape change in areas with similar spatial characteristics. It is noteworthy that certain LCIs may be deemed less relevant in landscapes with fundamentally different spatial characteristics. Those landscapes may require the use of additional LCIs. The interview procedure was potentially subject to researcher and respondent bias. This is illustrated, for example, by the inconsistent information on landscape elements that were present prior to the implementation of agrivoltaics (i.e., historical map versus interview data). Finally, available georeferenced land use data were limited both in terms of resolution and accuracy.

4. Conclusion

Agrivoltaics is a promising solution for renewable energy provision and this study highlights the importance of considering landscape during the implementation of agrivoltaics. This work was guided by the following research question: What are the landscape changes induced by AVPP in the Netherlands and what methods can be used to examine this kind of landscape transformation?

To answer this question, we developed an analytical framework comprising ten landscape change indicators (LCIs). Landscape changes were identified in all four cases that were selected for the in-depth case study from the longlist of built AVPP in the Netherlands. The highest number of changes was identified in Almere (six LCIs), and the lowest in Wadenoijen (three LCIs). Based on the results, we provide recommendations for policy makers to limit landscape changes induced by agrivoltaics.

Policy makers are encouraged to establish site selection and design criteria for AVPPs that respond to specific landscape characteristics. Examples of such landscape considerations are emerging, for example in Italy (ENEA et al., 2023). Across all studied cases, changes in the agricultural landscape pattern and landscape openness have been identified. The intensity of these changes strongly depends on the design of the AVPP and the characteristics of the site. For example, the change in landscape openness was considerably lower in cases with existing vertical vegetation, agricultural support structures and in proximity of farmhouses, compared to cases situated in open pastures. These results show that both the site selection and the design of agrivoltaics determine landscape change and support our call for dedicated policies.

Another recommendation for policy makers is to pay attention to temporal aspects of AVPP. Patterns that arise due to the implementation of overhead agrivoltaic systems could become more permanent compared to the relatively dynamic practices of fruit farmers. More permanent changes in cultural landscapes are prone to local resistance (Sherren et al., 2016) and should therefore be considered carefully. For existing crop production sites, AVPP design will likely be aligned with existing landscape patterns. Where AVPPs are introduced in pastures, the actual design and alignment between technology and landscape patterns require more attention.

In this study, landscape changes relating to land use, vertical non-agricultural vegetation, relief, crop support systems and fences showed a high variability among agrivoltaic cases. This variability in landscape change further underlines the importance of considering site selection and design in addition to techno-economic considerations. While the four cases did not reveal changes in crop and historic landscape structure, these indicators can be identified in other agrivoltaic cases. The assessment of agricultural production in relation to landscape change should be an important focal point for future research on agrivoltaics. The measurement of agricultural production may involve fieldwork and interviews, plus the potential use of high-resolution remote sensing (WUR, 2023). Spatial analysis of cases in other countries could contribute to a more complete understanding of landscape change by AVPPs. Finally, future research should also incorporate higher precision imagery, advanced remote sensing techniques and geospatial analysis tools to enhance the accuracy of identifying and quantifying landscape changes brought by agrivoltaic systems.

Agrivoltaics has the potential to become a leading type of solar power plant, contributing to energy transition, meeting environmental targets and reaching several Sustainable Development Goals set by the United Nations (Agostini et al., 2021). More specifically, agrivoltaics is an opportunity to realize multifunctional instead of monofunctional solar energy landscapes. While the multifunctional character of agrivoltaics in itself may positively affect societal acceptance, this study showed that both the siting and the design of AVPP affect the intensity of landscape change. There is evidence from conventional solar power plants that this landscape change negatively affects local acceptance. These developments warrant more attention to landscape by researchers, policy makers and developers in the field of agrivoltaics.

In the Netherlands, among other countries, recent policy gives preference to agrivoltaics over conventional solar power plants. To anticipate for the likely increase of agrivoltaics and potential landscape change, governments are starting to develop spatial policies for agrivoltaics on various legislative levels. Whereas this study focused on physical landscape changes, future research should examine the perceived changes in landscape quality due to the implementation of AVPP (Biró-Varga et al., 2024). Such studies support the understanding of how the siting and design of AVPPs affect local acceptance and inform future policies for a sustainable deployment of this relatively novel type of solar power plant.

CRediT authorship contribution statement

Stremke Sven: Writing – review & editing, Supervision, Methodology. **Oudes Dirk:** Writing – review & editing, Visualization, Supervision, Methodology, Data curation. **Sirnik Igor:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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References

Actueel Hoogtebestand Nederland, 2023. Digital surface model [WWW Document]. URL https://www.ahn.nl/open-data (accessed 6.16.23).

Agostini, A., Colauzzi, M., Amaducci, S., 2021. Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment. Appl. Energy 281, 116102. https://doi.org/10.1016/j.apenergy.2020.116102.

Amador, N., 2023. Engie inaugura in Sicilia il più grande parco agrivoltaico d'Italia [WWW Document]. URL https://www.ilsole24ore.com/art/engie-inaugura-sicilia-piu-grande-parco-agrovoltaico-d-italia-AEIMIFYD?refresh_ce=1 (accessed 11.10.23).

Biró-Varga, K., Sirnik, I., Stremke, S., 2024. Landscape user experiences of interspace and overhead agrivoltaics : A comparative analysis of two novel types of solar landscapes in the Netherlands. Energy Res. Soc. Sci. 109 https://doi.org/10.1016/j.erss.2023.103408.

Casares de la Torre, F.J., Varo-Martinez, M., López-Luque, R., Ramírez-Faz, J., Fernández-Ahumada, L.M., 2022. Design and analysis of a tracking / backtracking strategy for PV plants with horizontal trackers after their conversion to agrivoltaic plants. Renew. Energy 187, 537–550. https://doi.org/10.1016/j.renene.2022.01.081.

Chatzipanagi, A., Taylor, N., Jaeger-Waldau, A., 2023. Overview of the potential and challenges for Agri-Photovoltaics in the European Union. https://doi.org/10.2760/208702.

de Ruijter, F., Helsen, H., Elissen, H., Eerenstein, W., 2023. Producing food and electricity on the same square meter [WWW Document]. URL https://edepot.wur.nl/639135 (accessed 11.21.23).

DIN, 2021. Agri-photovoltaic systems – Requirements for primary agricultural use English translation of Deutsches Institut für Normung SPEC 91434:2021-05 [WWW Document]. URL https://www.beuth.de/en/technical-rule/din-spec-91434/337886742 (accessed 1.10.22).

ENEA, Cuore, U.C. del S., ResmTec, Uni, 2023. Sistemi agrivoltaici - Integrazione di attività agricole e impianti fotovoltaici (UNI/PdR 148:2023) [WWW Document]. URL https://store.uni.com/uni-pdr-148-2023 (accessed 11.21.23).

Esri, 2023. ArcGIS Pro 2.4.3 [WWW Document]. URL https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview (accessed 6.16.23).

EU Council, 2023. Green deal [WWW Document]. URL https://www.consilium.europa.eu/en/policies/green-deal/ (accessed 1.31.23).

Enserink, M., Van Etteger, R., Van den Brink, A., Stremke, S., 2022. To support or oppose renewable energy projects? A systematic literature review on the factors influencing landscape design and social acceptance. Energy Res. Soc. Sci. 91 https://doi.org/10.1016/j.erss.2022.102740.

Feuerbacher, A., Laub, M., Högy, P., Lippert, C., Pataczek, L., Schindele, S., Wieck, C., Zikeli, S., 2021. An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics. Agric. Syst. 192, 103193 https://doi.org/10.1016/j.agsy.2021.103193.

Ghosh, A., 2023. Nexus between agriculture and photovoltaics (agrivoltaics, agriphotovoltaics) for sustainable development goal: A review. Sol. Energy 266, 112146. https://doi.org/10.1016/j.solener.2023.112146.

Google, 2023. Google [WWW Document]. URL https://www.google.com/ (accessed 1.31.23).

Hermoso, V., Bota, G., Brotons, L., Morán-Ordóñez, A., 2023. Addressing the challenge of photovoltaic growth: Integrating multiple objectives towards sustainable green energy development. Land Use Policy 128. https://doi.org/10.1016/j.landusepol.2023.106592.

Ketzer, D., Schlyter, P., Weinberger, N., Rösch, C., 2020. Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – A system dynamics analysis. J. Environ. Manag. 270 https://doi.org/10.1016/j.jenvman.2020.110864.

Kuiper, R., Spoon, M., 2022. Monitor Nationale Omgevingsvisie 2022 [WWW Document]. URL https://www.pbl.nl/publicaties/monitor-nationale-omgevingsvisie-2022 (accessed 5.2.23).

Mamun, M.A.Al, Dargusch, P., Wadley, D., Zulkarnain, N.A., Aziz, A.A., 2022. A review of research on agrivoltaic systems. Renew. Sustain. Energy Rev. 161, 112351 https://doi.org/10.1016/j.rser.2022.112351.

Miller, C.A., Iles, A., Jones, C.F., 2013. The Social Dimensions of Energy Transitions. Sci. Cult. (Lond. 22, 135–148. https://doi.org/10.1080/09505431.2013.786989.

Oudes, D., 2022. Landscape-inclusive energy transition: Landscape as catalyst in the shift to renewable energy. In: Wageningen University. https://doi.org/10.18174/566620.

Oudes, D., Stremke, S., 2021. Next generation solar power plants? A comparative analysis of frontrunner solar landscapes in Europe. Renew. Sustain. Energy Rev. 145, 111101 https://doi.org/10.1016/j.rser.2021.111101.

Oudes, D., van den Brink, A., Stremke, S., 2022. Towards a typology of solar energy landscapes: Mixed-production, nature based and landscape inclusive solar power transitions. Energy Res. Soc. Sci. 91 https://doi.org/10.1016/j.erss.2022.102742.

Pascaris, A.S., 2021. Examining existing policy to inform a comprehensive legal framework for agrivoltaics in the U.S. Energy Policy 159, 112620. https://doi.org/10.1016/j.enpol.2021.112620.

Pascaris, A.S., Schelly, C., Burnham, L., Pearce, J.M., 2021. Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. Energy Res. Soc. Sci. 75, 102023 https://doi.org/10.1016/j.erss.2021.102023.

Pascaris, A.S., Schelly, C., Rouleau, M., Pearce, J.M., 2022. Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities. Green. Technol. Resil., Sustain. 2 https://doi.org/10.1007/s44173-022-00007-x.

Pasqualetti, M.J., 2000. Morality, Space, and the Power of Wind-Energy Landscapes. Geogr. Rev. 90, 381–394.

PVmagazine, 2023. PV magazine [WWW Document]. URL https://www.pv-magazine.com/ (accessed 1.31.23).

Rijksoverheid, 2023. Kamerbrief over aangescherpte voorkeursvolgorde zon [WWW Document]. URL https://open.overheid.nl/documenten/5421fe0d-fb6f-4c83-bb80-f4546457578a/file (accessed 12.6.23).

Roddis, P., Roelich, K., Tran, K., Carver, S., Dallimer, M., Ziv, G., 2020. What shapes community acceptance of large-scale solar farms? A case study of the UK's first 'nationally significant' solar farm. Sol. Energy 209, 235–244. https://doi.org/10.1016/j.solener.2020.08.065.

Rose, A. De, Buna, M., Strazza, C., Olivieri, N., Stevens, T., Peeters, L., Tawil-Jamault, D., 2017. Technology Readiness Level : Guidance Principles for Renewable Energy technologies [WWW Document]. URL https://publications.europa.eu/portal2012-portlet/html/downloadHandler.jsp?identifier=1da3324e-e6d0-11e7-9749-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part= (accessed 1.24.22).

Ruimtelijkeplannen, 2023. Ruimtelijkeplannen [WWW Document]. URL https://www.ruimtelijkeplannen.nl/ (accessed 3.6.23).

Sherren, K., Beckley, T.M., Parkins, J.R., Stedman, R.C., Keilty, K., Morin, I., 2016. Learning (or living) to love the landscapes of hydroelectricity in Canada: Eliciting local perspectives on the Mactaquac Dam via headpond boat tours. Energy Res. Soc. Sci. 14, 102–110. https://doi.org/10.1016/j.erss.2016.02.003.

Solarmagazine, 2023. Solar magazine [WWW Document]. URL https://solarmagazine.nl/home (accessed 1.31.23).

Sirnik, I., Sluijsmans, J., Oudes, D., Stremke, S., 2023. Circularity and landscape experience of agrivoltaics: A systematic review of literature and built systems. Renew. Sustain. Energy Rev. 178, 113250 https://doi.org/10.1016/j.rser.2023.113250.

Sovacool, B.K., 2014. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. Energy Res. Soc. Sci. 1, 1–29. https://doi.org/10.1016/j.erss.2014.02.003.

Toledo, C., Scognamiglio, A., 2021. Agrivoltaic systems design and assessment: A critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns). Sustain 13. https://doi.org/10.3390/su13126871.

Van Eetvelde, V., Antrop, M., 2009. Indicators for assessing changing landscape character of cultural landscapes in Flanders (Belgium). Land Use Policy 26, 901–910. https://doi.org/10.1016/j.landusepol.2008.11.001.

Weitkamp, G., 2011. Mapping landscape openness with isovists. Res. Urban. Ser. 2, 205–223.

Weitkamp, G., Bregt, A., van Ron, L., 2011. Measuring visible space to assess landscape openness. Landsc. Res. 36, 127–150. https://doi.org/10.1080/01426397.2010.549219.

Willockx, B., Uytterhae gen, B., Ronsijn, B., Herteleer, B., Cappelle, J., 2020. A Standardized Classification and Performance Indicators of Agrivoltaic Systems, in: Eu Pvsec 2020. pp. 1–4. https://doi.org/10.4229/EUPVSEC20202020-6CV.2.47.

WUR, 2023. Zonne-energie en grasproductie een win-win? [WWW Document]. URL https://www.wur.nl/nl/nieuws/zonne-energie-en-grasproductie-een-win-win.htm (accessed 12.6.23).

Yin, R.K., 2009. Case study research: design and methods. fourth ed. Thousand Oaks CA Sage 5. https://doi.org/https://doi.org/10.1097/FCH.0b013e31822dda9e.