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Original Research Article

Potential of floating, parking, and agri photovoltaics in Germany

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ABSTRACT

The innovative use of photovoltaics (PV) on parking lots, water bodies, or agricultural areas reduces land use conflicts by co-using land with renewable PV production. In contrast to conventional open-field PV, their potential role in future energy systems has not been comprehensively defined yet. This study provides a global overview of existing potential analyses on innovative PV technologies and provides a transparent, reproducible, and transferable methodology using land eligibility analyses with a high spatial resolution of 10 m x 10 m, applied for different scenarios in Germany. For current legislation, the potential of floating PV in Germany is 4.7 GW_p but shows a high sensitivity towards the considered water bodies and allowed area coverage of the water bodies. Parking PV has a potential of up to 24.6 GW_p, depending on the minimum number of required parking spaces. The potential of agricultural (agri) PV lies between 3215 GW_p and 5437 GW_p, depending on the crop types considered and the corresponding system designs. While agri PV could significantly contribute to the national PV targets of 400 GW_p by 2040, floating PV and parking PV can only support a maximum of 1.2 % and 6.2 %, respectively. The spatially explicit potentials are openly available and create the basis for further research about the future role of innovative PV technologies, e.g. by energy system modelers.

1. Introduction

Climate change is an urgent and complex challenge that requires a multifaceted response. To contribute to climate change mitigation action, Germany has set the target of greenhouse gas neutrality by 2045 [1]. To achieve this goal, existing studies [2–5] show that a large photovoltaic (PV) expansion of between 230 and 659 GW_p is required. Furthermore, Germany has defined a target of 400 GW_p until 2040 [6]. However, building PV modules on open-field areas could lead to land use conflicts [7]. In a current legislative draft, the Photovoltaic Strategy of Germany's Federal Ministry of Economics and Climate Protection aims to promote the construction of PV in co-used areas [6], including parking, floating, and agricultural PV (agri PV).

Floating PV describes the use of water bodies for PV installations. PV modules are mounted on rafts and are mainly installed on inland still water bodies [8]. In the current German legislation, the expansion of floating PV is restricted to artificial or heavily modified lakes, with a minimum distance of 40 m to shore and a maximum area coverage of 15% of each lake [9]. These requirements are justified by the lack of knowledge about the changes in the ecosystem caused by the shading of PV modules [9]. In addition, the construction on other water bodies is only permitted, if defined by the water management plan [9].

Parking PV describes the co-usage of parking lots for PV, whereby PV modules are constructed on roofs above parking spaces. This co-usage leads to positive effects such as the shading of the vehicles, an easy connection to the electrical grid, and demand proximity because of the urban environment [10]. Five German federal states passed laws for the mandatory construction of parking PV on newly-built parking lots; however, these laws differ with respect to parking lot type and the minimum number of parking spaces. The minimum number of parking spaces is 35 for Baden-Wuerttemberg [11] and North Rhine-Westphalia [12], 50 in Hesse [13] and Rhineland-Palatinate [14], and 100 in Schleswig Holstein [10].

Agri PV describes the co-usage of agricultural land for PV. Land use conflicts can occur between agriculture and energy production as both compete for limited land in two facets. Firstly agriculture competes with ground-mounted PV on arable lands. Secondly, energy crops are grown on arable land and could provide base-load energy in biomass plants but also show a 32 times lower total energy yield than ground-mounted PV in the same area [15]. Agri PV could reduce land use

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conflicts by combining PV and agriculture on the same land; however, the eligibility of crops differs [15–17]. To account for different crop eligibility, the system design of the agri PV plant can be tailored [18]. The system can be differentiated between various options, including horizontally-elevated agricultural PV systems (hereinafter termed horizontal agri PV), where agriculture is carried out beneath the PV modules, and vertically-oriented agricultural PV systems (vertical agri PV), where agriculture is conducted between the agri PV modules (cf. [19]). The construction of agri PV can provide micro-climate benefits for some crops and further protect against extreme weather events such as hail or drought, as well as reduce water consumption in warm regions. However, one challenge of large-scale agri PV deployment is that the design of today's farming machinery is not necessarily compatible with the construction of agri PV systems [20–22].

The German PV strategy [6] considers peatlands PV as another innovative PV technology, however, the rewetting of peatlands is prioritized over the installation of PV [23] and therefore this technology is not further considered.

The future role of the innovative technologies of floating, parking, and agri PV is not yet defined, as it depends, among others, on regional capacity potentials, generation potentials, levelized costs of electricity, environmental impacts, and public acceptance. The technologies are often not considered in energy system models, to the author's knowledge, and not yet integrated in German energy transition studies. To consider these technologies in energy system analyses, adapt policies to enhance the expansion, or define business cases, the transparency of the regional potential is the first step. Due to the geographical scope of regional energy system models or detailed grid expansion planning, high-resolution regionalized potentials are required for further research.

For renewable energy sources such as open-field PV and wind technologies, various potential analyses exist, varying in methodologies and assumptions, e.g., due to different relevant underlying legislation. Typical potential analyses first identify eligible areas for the renewable energy plants of a specific technology by means of, for example, a land eligibility analysis and afterwards derive the technical potential of this area [24]. However, the few potential analyses for innovative PV technologies often lack a reproducible methodology or a data publication or do not comply with current legislation.

Therefore, in this paper, the first overview of existing potential analyses is provided for floating, parking, and agri PV (Section 2). Then, their potential in Germany is estimated for the first time using reproducible land eligibility analyses (Section 3) and the openly published results (Section 4) as base for further research is described. Some of the considered scenarios reflect current legislation and some expand on this with by further calculations. The methodology used to estimate the potential is transferable to further regions. Finally, Section 5 discusses the results and Section 6 presents the conclusion of the study.

2. Previous research on innovative photovoltaic potentials

In the following, existing potential analyses for parking (Section 2.1), floating (Section 2.2), and agri PV (Section 2.3) systems are reviewed. In this section, we refer to geographical potential in km^2, technical potential in kW_p, and economic potential in kW_p. If not otherwise stated, the term 'potential' refers to the technical potential. For a definition of the different potential types in resource assessments, please refer to [7,25].

2.1. Parking photovoltaics

In this section on existing potential analyses for parking PV, the term 'parking lot' is used to describe entire car parks (i.e. access roads, movement areas, etc.), whereas 'parking space' describes the actual spot for vehicle parking. The 'area coverage' refers to the share of eligible area for parking PV in the parking lot.

Table 1
Overview of the parameters in parking PV potential analyses. The capacity density is defined on the potential area for placing PV modules and not the entire parking lot area.

Parameter	Value	Study
Coverage factor [%]	15	[26]
	35	[27]
	50	[10,26]
	75	[26]
	79.4	[33]
Capacity density [MW_p/km^2]	65	[34]
	163	[26]
	170	[34]
	175	[26]
	200	[10]
	202	[27]

On a national level, the parking PV potential is estimated by Quax et al. [26] for the Netherlands and by Wirth [16] for Germany. Another international potential assessment is performed by Julieta et al. [27] for the Canary Islands. Quax et al. [26] analyze the potential for public and non-public parking lots with an area coverage of 50% and 15%, respectively, without further description of the methodology used. Julieta et al. [27] assess open parking lots above $200\,m^2$ on the Canary Islands by means of a photo and geodata analysis. The parking PV potential is derived by an area coverage factor of 35% and a capacity density factor of $202\,MW_p/km^2$ for the remaining area. Wirth [16] identifies a potential of $59\,GW_p$ for the 300,000 largest parking lots in Germany, without elaborating on the underlying methodology.

For Germany, several potential analyses for parking PV are performed at a federal state level. For Schleswig Holstein, Stryi-Hipp et al. [10] estimate the potential for parking lots with more than 100 parking spaces. To identify above-ground hard-surfaced parking lots, data from OpenStreetMap [28] is combined with the real estate cadastre and landscape model of the federal state [29]. A parking lot area of $10.6\,km^2$ and a potential of $1058\,MW_p$ is derived for an area coverage of 50% and an assumed parking space area of $12.5\,m^2$. An additional potential of $40.2\,MW_p$ is estimated for parking lots built until 2030. For Baden-Wuerttemberg a potential of $4.8\,GW_p$ on 16,600 existing public parking lots with more than 40 parking spaces is estimated in another study [30]. An area coverage for parking PV of 40 to 50% is used [30]. For Lower Saxony and Hamburg, Barbara Mussack [31] and Erneuerbare Energien Hamburg Clusteragentur [32] estimate a potential of $3.5\,GW_p$ on a parking lot area of about $30\,km^2$ [31] and $42\,MW_p$ on an area of $0.21\,km^2$ [32], respectively. However, it is unclear whether the area describes the parking lot or that for parking PV, as a description of the methodology is missing for both studies. For Brandenburg, another study [33] identifies a parking lot area of $6.44\,km^2$, of which 24.6% is suitable for parking PV. An area coverage factor of 79.4% is assumed, leading to a potential of $144\,MW_p$. Table 1 provides an overview of the presented parameters used in the presented articles. The area coverage of the parking lot ranges between 15 and 79.4% and the capacity density is between 65 and $202\,MW_p$.

2.2. Floating photovoltaics

In contrast to parking PV, a higher number of studies have investigated floating PV potentials. The regional scope of these studies varies from single locations [35–40], up to the national [27,41–50], continental [51–53], and global levels [54–58]. The water bodies assumed eligible for floating PV also deviate between them: The majority of studies consider the water bodies of dam and hydro power plants [37–43,51–54,56–58], which are – for continental and global studies –

Table 2
Overview of the parameters in floating PV potential analyses.

Parameter	Value	Study
Coverage factor [%]	1	[35,42,43,47,51,53–55]
	2	[35,50]
	4.7	[60]
	5	[38,42,43,48,54,55]
	10	[35,37,41–45,52–55,62]
	15	[43]
	20	[35,36,38]
	25	[37,58]
	27	[46]
	30	[38–40,56]
	40	[27]
	45	[35,62]
	50	[38,51]
	70	[63]
	80	[35]
	100	[45,49,52,53,62]
Capacity density [MW_p/km^2]	60	[62]
	66.82	[58]
	76.11	[64]
	80.97	[27]
	approx. 100	[35,38,42,46,53,54,57]
	118	[62]
	133	[60]
	180	[51]
	120 and 200	[43]

mostly identified by the Global Reservoir and Dam Database [59]. Other studies considered reservoirs [27,35,36,42,44,50,56], artificial/ man-made water [46,47,55], waste water reservoirs [49], 'natural, heavily modified and natural water' [45], or all water bodies [50]. The potential of maritime floating PV is only estimated by Silalahi et al. [48] for Indonesia.

Only a few, non-peer-reviewed, articles are published that address the potential of floating PV in Germany. Wirth [16] states a technical potential of 44 GW_p for artificial lakes. Furthermore, another article [60] estimates a technical potential of 56 GW_p for lignite mining lakes in Germany. To determine the economic potential, areas for recreation activities, tourism, and nature conservation are excluded, as well as lakes with an area of less than 0.01 km^2 and excessive lake depth fluctuation. The exclusions result in a reduction factor of 4.9%, leading to an economic potential of 2.74 GW_p. Weigl [61] estimates the floating PV potential on unused, man-made lakes outside protected areas and competing land uses, e.g., tourism and recreational areas. Only lakes with more than 0.1 km^2 are considered, which results in 469 eligible lakes with an area of 140 km^2. The theoretical potential is 20 to 25 GW_p for Germany and reduces to 4 to 5 GW_p with a coverage factor of 20%.

Other potential analyses for floating PV were conducted at the individual federal state level in Germany: Ilgen [62] estimates three potential scenarios for 69 eligible open-cast mining lakes in Baden-Wuerttemberg. The first scenario assumes 100% area coverage at 60 MW_p/km^2, leading to a potential of 1070 MW_p; the second scenario assumes a 45% area coverage at 118 MW_p/km^2, leading to 1130 MW_p; and the third scenario assumes a 10% area coverage at 118 MW_p/km^2, leading to 280 MW_p. To maintain a shore distance, the area of each considered water body is reduced by 10% in advance. For Brandenburg, a potential of 817 MW_p is identified in another study, but without stating the methodology [33]. Erneuerbare Energien Hamburg Clusteragentur [32] shows that Hamburg has no floating PV potential at all.

Table 2 provides an overview of the assumed coverage factors and capacity densities in the studies presented. The coverage factor covers the full range from 1 to 100% and the capacity density is between 60 and 200 MW_p/km^2.

2.3. Agri photovoltaics

While the majority of agri PV studies focus on the design of single agri PV systems or the eligibility of crops, only a few potential analyses were performed. Yeligeti et al. [65] estimate the global agri PV potential based on the suitability of crops with a geospatial analysis of $10 \times 10\,km^2$ resolution. The geodata of EarthStat and Copernicus Land cover [66,67] are used to geographically identify the arable lands of 18 different crop types. The different crop types are aggregated into two categories (Low and High) according to their suitability for agri PV. Three potential scenarios are estimated resulting in 48 TW_p to 217 TW_p. It should be noted that crop suitability is defined on a global level and is not adapted to regional climatic conditions. Willockx et al. [68] focus on optimal area coverage and economic factors for agri PV in Europe. The study further performs a geospatial potential analysis on potato farmland in Europe. Steadman and Higgins [69] estimate the potential of agri PV with a geospatial analysis along rural highways in Oregon, USA, to support charging stations of electric vehicles. Farming areas with low soil class ratings within a five miles distance are assumed to be eligible for agri PV, whereas protected areas, forests, and wetlands are excluded. The following three studies estimate the agri PV potential with statistical data: Silalahi et al. [48] determine the area potential of agri PV for Indonesia on the arable areas of maize, coffee, and other low-growing crops. An area potential is estimated by statistical data of farming areas and area coverage between 10% and 30%. Tajima and Iida [70] estimate the potential of abandoned farming areas in Japan by using the statistical data of abandoned farms and a capacity density factor of 66.18 MW_p/km^2. Malu et al. [71] use a similar approach for grape farms in India but with a capacity density of 41.72 MW_p/km^2.

Further studies focus on agri PV potentials in Germany: Beck et al. [72] estimate the potential in Germany for crops with statistical data. Crops are considered, which are either positively affected by agri PV (potatoes, lettuce, spinach) or not affected (rape, rye, oats). The technical potential of 533 GW_p on 12.400 km^2 is estimated, and a reduced potential of 10% (53 GW_p) is defined as practical potential. Wirth [16] estimates a potential of 1700 GW_p for highly-mounted agri PV in Germany considering the arable land of shade-tolerant crops and a capacity density of 60 MW_p/km^2. Land with permanent crops (e.g., orchards and vineyards) is fully considered, whereas other arable land (without maize cultivation) is only considered by a third of the area. Furthermore, a potential of 1200 GW_p is estimated for vertical systems on permanent grassland with a capacity density of 25 MW_p/km^2 [15].

Moreover, several studies have been conducted at the federal state level in Germany: Schneider et al. [73] estimate a potential of 79 GW_p for agri PV in Lower Saxony on areas with low biodiversity potential, using a geospatial analysis and a capacity density of 75.6 MW_p/km^2. Unger and Lakes [74] focus on identifying conflict areas for agriculture in Brandenburg. Within the study, possible areas of synergy for agri PV are identified on arable lands with more than 0.1 km^2 on sandy soil outside protected areas. Another study [33] of Brandenburg estimates a potential of either 238 GW_p on arable land and 28 GW_p on grassland if all areas are combined with horizontal PV, or 106 GW_p on arable land and 13 GW_p on grassland for vertical agri PV. These values are derived from open-access landscape data (ALKIS DLM50 [75]) using a geospatial analysis. Protected areas, flood plains, wind acreage, conversion areas, lakes, residential areas, and areas of the open area network are excluded and assigned with buffer distances. Dröschel et al. [76] perform a geospatial potential analysis for Rhineland-Palatinate and Saarland using an area coverage of 31 MW_p/km^2. These areas are geospatially identified by geodata from the European agricultural subsidy [77]. Areas with a slope of more than 20°, flood areas, and forest fringe areas with a 100 m buffer are excluded. In addition, high-growing crops and geographical potentials below 0.1 km^2 are excluded for the economic potential. Scenarios are defined based on legal parameters. In Rhineland-Palatinate, 4734.2 km^2 is identified as a usable area for agri PV. A share of 40% is considered suitable (of which 25%

Table 3
Overview of parameter for agri PV potential analyses.

Parameter	Regional scope	Value	Study
Analysis type	International	Statistical	[48,70,71]
		Geospatial	[68,69]
	Germany	Statistical	[72,78,79]
		Geospatial	[16,33,73,74,76]
Capacity density [MW_p/km^2]	International	41.7	[71]
		66.2	[70]
		75.9	[68]
	Germany	**Vertical**	
		31	[76]
		39.5	[78]
		Horizontal	
		43	[72]
		52	[79]
		60	[16]
		70	[78]
		75.6	[73]
		85	[68]

is preferred), 53% less suitable and 7% not suitable. The economic potential of preferred areas is given as 7.4 GW_p. For Saarland, 509.3 km^2 is classified as a usable area. Of this area, 17% is considered suitable (of which 6% is preferred), 63% as less suitable, and 20% as not suitable. The economic potential of the preferred areas is stated as 1.7 GW_p. Wydra et al. [78] estimate the agri PV potential for Thuringia for arable land without tall-growing crops based on statistical data. Nature conservation areas are excluded. For high-mounted agri PV, a potential of 424 GW_p is determined with a capacity factor of 70 MW_p/km^2 on arable land and permanent crops. Furthermore, a potential of 66.5 GW_p is derived for vertical agri PV on grassland with a capacity factor of 39.5 MW_p/km^2.

Table 3 presents an overview of the methodology used and the capacity density factors in the studies. While international studies use a single capacity density factor, German studies differentiate between vertical and horizontal agri PV.

3. Methodology

The potential of parking, floating, and agri PV in Germany is determined by detailed geospatial land eligibility analyses, as only high resolution geographical potentials fulfill the requirements listed in Section 1. The analyses are performed using the tool TREP [24] for geospatial potential analyses based on the open-source tool GLAES [80] with a resolution of 10 m × 10 m. GLAES performs the necessary geospatial operations to determine potential locations for renewable energy installations. The first step is to initialize the study region for the potential analysis of a technology. The next optional step is defining suitable areas, for example, parking lots for parking PV. All other areas are thereby excluded as potential areas. Subsequently, unsuitable land for construction as natural protection areas are excluded. The remaining area with an optional reduction factor describes the geographically identified potential area of the technology. This reduction factor describes the usage area share of the analyzed area, for example, the share of parking spaces within the parking lot. For a more detailed description refer to Risch et al. [24]. The results are published in the open-access database trep-db [81].

3.1. Parking photovoltaics

The following describes the methodology for estimating the parking PV potential above parking spaces on existing open-space parking lots. Hereby, three scenarios are defined with consideration of parking lots

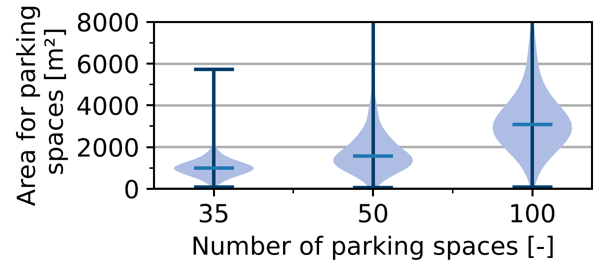

Fig. 1. Area of parking lots with 35, 50, and 100 parking spaces from OpenStreetMap, horizontal light blue line shows the median.

with either more than 35, 50, or 100 parking spaces, in accordance with the legislation of the German federal states. However, in contrast to the legislation that only considers newly built parking lots, the potential of existing parking lots is estimated.

Prior to the potential analysis, relevant assumptions and parameters must be specified. First, parking lots with more than a certain number of parking spaces must be identified. To the knowledge of the authors, there is no dataset with consistent information on the number of parking spaces for all parking lots in Germany. However, OpenStreetMap [28] provides this information for an excerpt of parking lots. OpenStreetMap is therefore used and the data is extracted using the following query per federal state (NAME_OF _FEDERAL_STATE):

```
[out:json];
area[name=NAME_OF_FEDERAL_STATE]->.searchArea;
way["parking"="surface"](area.searchArea);
out geom;
```

As the number of parking spaces is not consequently given in OpenStreetMap, parking lots with more than a specifically defined number of parking spaces are determined by area. To this end, a minimal area for parking lots per scenario is determined and all parking lots are filtered by this. To identify this minimal area, parking lots with information regarding parking spaces are filtered by the defined number of parking spaces, and their area is determined. Fig. 1 shows the area distribution of parking lots with more than 35, 50, and 100 parking spaces, respectively. The median value of each scenario is rounded to 100 m^2 due to the resolution of the land eligibility analysis of 10 m × 10 m. Based on the median, parking lots with more than 35 parking spaces are identified by a minimal area of 1100 m^2, for 50 parking spaces by 1600 m^2, and for 100 parking spaces by 3100 m^2.

To identify the usable area for PV installations, the area coverage factor for parking PV is needed. In the following, solely the roofing of parking spaces within the parking lot is considered, thus requiring the area share of parking spaces in relation to the total parking lot. To define this factor, the OpenStreetMap data is filtered for parking lots with at least the corresponding number of parking spaces. Then, the area share is determined by the number of parking spaces multiplied by the assumed area of 12.5 m^2 per parking space [10] and divided by the total area of the parking lot. Fig. 2 shows the distribution of the parking space share in parking lots per scenario. The median ranges between 41.6% and 42.9%. For all scenarios, the area coverage is therefore set to 42.2%.

Three potential scenarios are analyzed with the determined factors: first, parking lots are extracted and filtered by the determined minimal area. Then, protected areas are excluded based on the world database on protected areas [82] and forests are excluded based on a digital landscape model (Basis-DLM [83]). The queries can be found in Table 5. Then, the area as geographical potential for parking PV is determined by the area coverage factor. Finally, the technical potential can be derived with a capacity density of 200 MW_p/km^2, which is in line with Stryi-Hipp et al. [10] (Section 2.1).

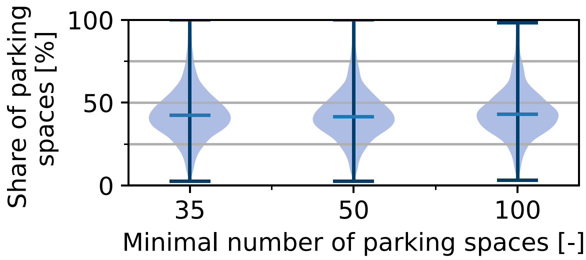

Fig. 2. Share of parking spaces area of parking lot area from OpenStreetMap.

3.2. Floating photovoltaics

The potential of floating PV is estimated on artificial and heavily modified lakes with an area coverage of maximum 15% and a distance of 40 m to shore, which is in line with current legislation. Furthermore, sensitivities for the distance to shore, the maximum area coverage, and the considered lakes are performed. The considered lakes are either 'artificial and heavily modified lakes' or 'all lakes'.

First, datasets are required to either identify artificial and heavily modified water bodies or all water bodies in Germany: to identify all lakes in Germany, the Basis-DLM [83] of the Federal Agency for Cartography and Geodesy is used with the following query:

```
OBJART_TXT = 'AX_StehendesGewaesser'
```

However, the dataset does not contain information about the type of the water body. To this end, the dataset 'Wasserkörper-DE (Wasserrahmenrichtlinie 3. Zyklus 2022–2027)' [84] of the German Federal Institute of Hydrology is used to identify artificial and heavily modified water bodies with the following query:

```
MODIFIED = 'Y' OR ARTIFICIAL = 'Y'
```

Afterwards, protected areas are identified by WDPA [82] and excluded as potential areas. The corresponding queries can be found in Table 5. Additionally, areas closer to shore than the specified distance are excluded depending on the scenario.

As only 15% of a lake is allowed to be used for floating PV in the legislation, two areas are compared for every lake: firstly, the remaining area after all exclusions and, secondly, 15% of the total lake area. The lower of the two values represents the geographical potential as an area of floating PV for the lake.

The technical potential is derived from the resulting geographical potential with a capacity density factor of $100\,\mathrm{MW_p/km^2}$, which is in line with the existing studies (Section 2.2) and used by the floating PV report of the World Bank Group, ESMAP and SERIS [54].

3.3. Agri photovoltaics

The suitability of areas for agri PV varies for different crop types. Therefore, to perform geospatial potential analyses, a dataset is required that locates the agricultural areas of different crops. Basis-DLM [83] also provides geodata for cultivated areas; however, it features low detail on crop categorization. In comparison, Blickensdörfer et al. [85] published a high-resolution dataset of $10\,\mathrm{m} \times 10\,\mathrm{m}$ that classifies 23 crop classes in Germany. This dataset is used in the following to locate the agricultural land of different crop types.

Ten studies [15,18,20,65,68,72,78,86–90] make statements regarding the eligibility of different crop types. These studies are analyzed to define the eligibility of the crop types of the geodata of Blickensdörfer et al. [85]. In addition to the suitability of crops, current machinery design restricts the combination with agri PV for some crops or plant designs (horizontal or vertical orientation), according to experts. In the following, four scenarios based on the crop classes of Blickensdörfer et al. [85] are defined considering crop suitability and accounting for current machinery design:

- Vertical Grassland: grassland areas are considered for vertical agri PV.
- Vertical Grain: the current machinery design for wheat, barley, and rye crops does not support the combination with horizontal agri PV. This scenario therefore considers grains with vertical agri PV.
- Horizontal Conservative: with current machinery design, the crops lupine, soy, grapevine, hops, and orchards are considered eligible based on their shading tolerance for horizontal agri PV.
- Horizontal Innovative: several crop categories are added compared to the Horizontal Conservative scenario. After adapting the machinery design, the grain crops, oats, potatoes, sugar beet, rapeseed, peas, and broad beans allow the combination with agri PV due to their suitable shading tolerance, according to expert opinion. Furthermore, the vegetable category combines several subcategories with diverse eligibility for agri PV. Although vegetables were not considered in the conservative category, they are considered here.

A detailed overview of the crop categories, the crop suitability according to the existing studies, the scenario definition, and the capacity density factors used can be found in Table 4. The total German agri PV potential can be derived from the combination of the scenarios Vertical Grassland, Vertical Grains, and Horizontal Conservative or, alternatively, the combination of Vertical Grassland and Horizontal Innovative.

Comparable to the potential analyses of floating and parking PV, protected areas are excluded, as are peatlands. Today, 7% of agricultural land is located on drained peatlands; however, intact peatlands are an essential greenhouse gas storage [23]. The draining of peatlands, e.g., for agricultural purposes, releases the stored emissions, currently accounting for 7% of Germany's man-made greenhouse gas emissions [23]. Therefore, the rewetting of currently drained peatlands takes priority over PV installation [23]. The dual usage with PV is only permitted on rewetted peatlands, named 'Moor PV' in the current legislation [9,23]. However, as the implementation is not conclusively clarified [91,92], a potential analysis for peatland PV itself is not included in this analysis. In the following, the peatland areas based on the dataset by Tegetmeyer et al. [93] are excluded as potential areas for agri PV. To the knowledge of the authors, it is the only dataset that provides the location of drained and irrigated peatlands. Furthermore, flood plains, water protection areas (water catchment area I and closer protection area II), and biosphere maintenance and core zones are excluded, which is in accordance with previous studies [33,76]. The corresponding queries can be found in Table 5.

After the identification of the geographical potential for the scenarios, the technical potential is derived. In contrast to parking and floating PV, a variable capacity density is used. The capacity density is varied per area with the shading tolerance of the corresponding crop (see Table 4). For horizontal agri PV, the capacity density varies between $60\,\mathrm{MW_p/km^2}$ and $85\,\mathrm{MW_p/km^2}$ depending on the shading tolerance, which is in line with Willockx et al. [68]. For vertical agri PV, a fixed capacity density of $39.5\,\mathrm{MW_p/km^2}$ is assumed, according to Wydra [18].

4. Results

In the following, the results of the potential analyses for parking, floating, and agri PV are presented. These results are published in the open-access database trep-db [81].

4.1. Parking photovoltaics

The technical potential of parking PV on existing parking lots in Germany is $24.6\,\mathrm{GW_p}$ for a minimum of 35 parking spaces, $22.2\,\mathrm{GW_p}$ for a minimum of 50 parking spaces, and $16.5\,\mathrm{GW_p}$ for a minimum of

Table 4
Crops identified by Blickensdörfer et al. [85] and their eligibility for agri PV. (↑: Shade tolerant crop, suitable for agri PV, ↗: Shade tolerant crop, partly suitable for agri PV, →: Neutral effect on crop, ↘: Negative shade tolerant crop, less suitable for agri PV, ↓: shade intolerant crop, not suitable for agri PV, div: Different information for various crops of this group, ●: Included in the analysis, ❍: Not included in the analysis, V: Vertical orientation, H: Horizontal orientation)

Class name	Studies										Scenario					
	Albrecht [86]	Fraunhofer ISE [87]	ISE-modified by Wydra [18]	Fraunhofer ISE guide [15]	Beck et al. [72]	Laub et al. [88]	Yeligeti et al. [65]	Weselek et al. [89] (worldwide)	Wydra et al. [78]	Mamun et al. [90] (worldwide)	Literature average with expert corrections	Assumed capacity density [MW_p/km^2]	Horizontal Conservative	Horizontal Innovative	Vertical Grain	Vertical Grassland
Winter wheat	↘	↘	↘	↘	↘	↘	↑	→	→		H: ↗, V: ↑	H: 60, V: 39.5	❍	●	●	❍
Winter barley		→	→	↘	↑		↘		→		H: ↗, V: ↑	H: 60, V: 39.5	❍	●	●	❍
Winter rye		→	→	↘	→	↘	↑		→		H: ↗, V: ↑	H: 60, V: 39.5	❍	●	●	❍
Springbarley		→	→	↘	↑		↘		→		H: ↗, V: ↑	H: 60, V: 39.5	❍	●	●	❍
Oat		→	→	↘	→	↘	↓		→		H: ↗, V: ↑	H: 60, V: 39.5	❍	●	●	❍
Maize		↘	↘	↘	↘	↘	→	→	↓		↓	–	❍	❍	❍	❍
Potato	↑	→	↑	↑	↑	↘	↑	→	↑	↑	H: ↑	H: 85	❍	●	❍	❍
Sugar beet	↘	↘	↘			↘	↘		↘		H: →	H: 60	❍	●	❍	❍
Rapeseed	→	→	→		↓	→	↘	↑	↑		H: ↗	H: 60	❍	●	❍	❍
Sunflower	↘	↘	↘				↓	→	↘		↓	–	❍	❍	❍	❍
Peas	→	→	→			↘			↗	→	H: →	H: 60	❍	●	❍	❍
Broad beans	↑	↑	↑				↘		↗	↗	H: →	H: 85	❍	●	❍	❍
Lupine	↑					↘					H: ↗	H: 85	●	●	❍	❍
Soy	↑	↑	↑			↘	→		↑		H: ↗	H: 85	●	●	❍	❍
Vegetables	div	div	→		div	↗	div	↑	↑	div	H: ↗	H: 85	❍	●	❍	❍
Cultivated grassland				↑		→			↑		V: ↑	V: 39.5	❍	❍	❍	●
Permanent grassland				↑		→			↑		V: ↑	V: 39.5	❍	❍	❍	●
Grapevine	↑	↘	↗	↑	↑		↑		↑		H: ↑	H: 85	●	●	❍	❍
Hops	↑	↑	↑						↑		H: ↑	H: 85	●	●	❍	❍
Orchard	↘	↘	↘			↑	↑	↑	↑	div	H: ↗	H: 60	●	●	❍	❍
Fallow land	Not considered										–	–	❍	❍	❍	❍
Small woody features	Not considered										–	–	❍	❍	❍	❍
Other areas	Not considered										–	–	❍	❍	❍	❍

100 parking spaces. Fig. 3 shows the potentials on the federal state level in Germany, a detailed overview can be found in Table 6. For all scenarios, North Rhine-Westphalia shows the highest potential, with 5.0 GW_p, 4.5 GW_p, and 3.3 GW_p, respectively. In contrast, Bremen displays the lowest potentials with 210.7 MW_p, 192.2 MW_p, and 159.1 MW_p, respectively.

When comparing the potentials of the federal states to either their areas or populations, no clear correlation can be identified, but a trend can be observed. Larger federal states tend to have higher potential. However, North Rhine-Westphalia has a higher potential than Bavaria, while being half its size. Furthermore, federal states with a higher population tend to have more potential. However, there are also exceptions to this trend, such as the fact that Mecklenburg-Western Pomerania has a higher potential than Hamburg, despite having a lower population. Fig. 4 shows the resulting capacity density in Germany. While the capacity density in the methodology defined the specific capacity per potential area, the resulting capacity density refers to capacity results per region area. This distribution highlights the larger potential in urban areas, such as Hamburg, Berlin, the Rhineland Ruhr area, and Munich. The potential decreases when increasing the minimum number of parking spaces. Compared to a minimum of 35 parking spaces, the potential of the federal states decreases between 8.09% and 13.26% for a minimum of 50 parking spaces, and 28.11% and 42.40% for a minimum of 100.

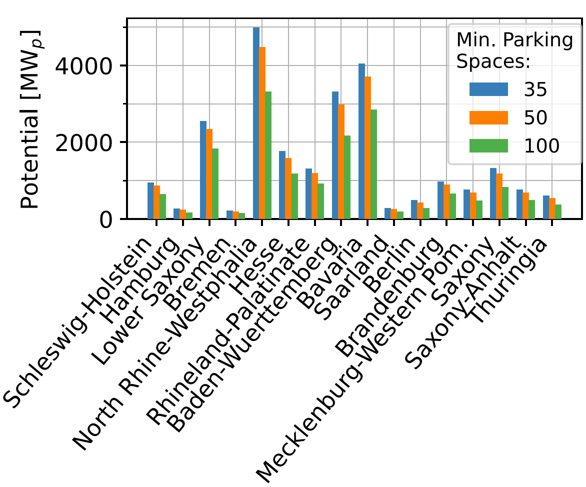

Fig. 3. Technical potential of parking photovoltaics of the federal states for parking lots with a minimum of 35, 50, and 100 parking spaces.

4.2. Floating photovoltaics

The technical potential of floating PV for current legislation in Germany, with a minimum distance to shore of 40 m and a maximum coverage of 15% on artificial and heavily modified lakes, is 4.7 GW_p. Fig. 5 shows the distribution of the resulting potentials by the capacity density in Germany, a more detailed overview of the potential of the federal states can be found in Table 6. The potential is concentrated in a few federal states that have artificial and heavily modified lakes outside protected areas.

Fig. 6 shows the sensitivity analysis of the floating PV potential for the lake coverage between 15% and 90%, with exclusion of areas between 10 m and 40 m to shore and for the usage of either artificial

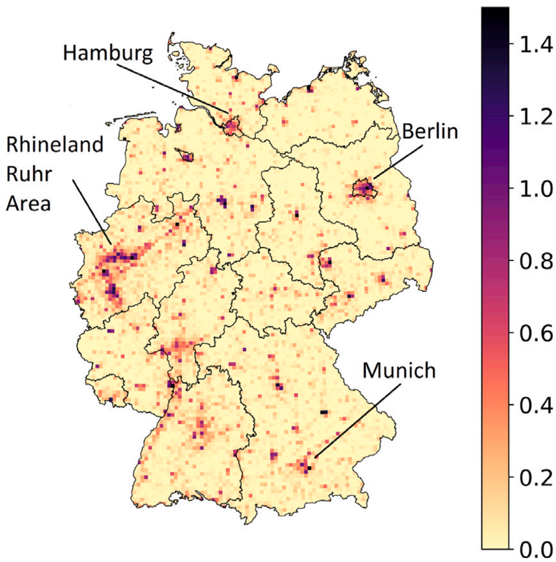

Fig. 4. Capacity density of the technical parking photovoltaics potentials in Germany with a minimum of 35 parking spaces.

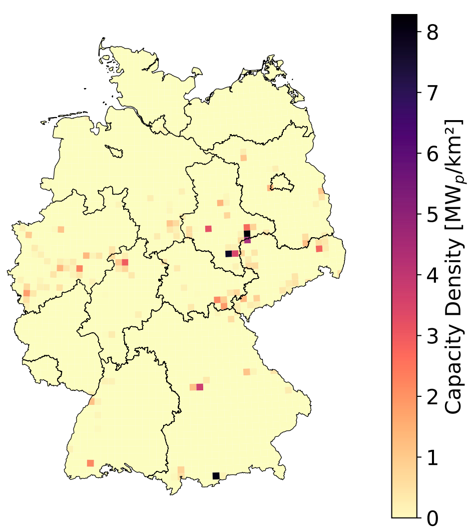

Fig. 5. Capacity density of the technical floating PV potentials in Germany with current legislation restricting floating PV plants to artificial and highly modified lakes with a minimum distance of 40 m to shore and a maximum of 15%.

and heavily modified lakes or all lakes in Germany. For artificial and heavily modified lakes, the decrease in the minimal distance to shore does not lead to a significant potential increase for maximum lake shares below 60%. Even for a coverage of 90%, the potential only increases by 17% if the distance to shore is decreased from 40 m to 10 m. In contrast, by doubling the allowed coverage of the water body from 15% to 30%, the potential increases by 96% This shows the higher impact of changes in legislation on the lake coverage, in contrast to the distance to shore for artificial and heavily modified lakes.

As expected, the potential significantly increases by considering all lakes instead of only artificial and highly modified ones. Considering the same lake share and distance to shore of the current legislation, the potential can be increased by 467% to 22.2 GW_p. Across all sensitivities of distance to shore and area coverage, the capacity for all lakes is between 3.9 and 4.7 times higher than for artificial and highly modified lakes.

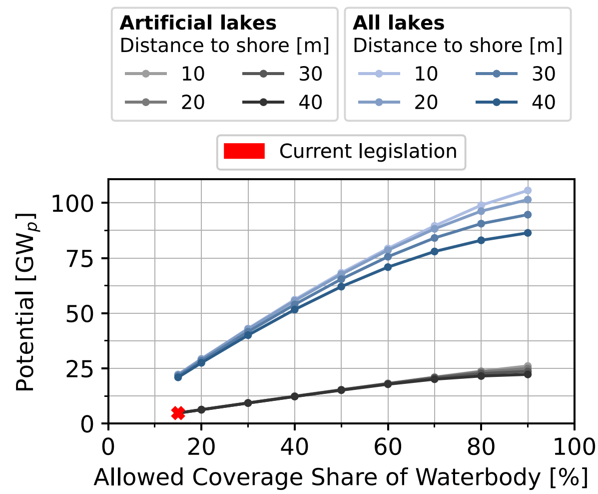

Fig. 6. Sensitivity of the technical floating PV potential for water coverage, distance to shore and usable lake category.

4.3. Agri photovoltaics

The technical potential in the agri PV scenarios highly varies between 232 GW_p for the scenario Horizontal Conservative and 4391 GW_p for the scenario Horizontal Innovative, as is shown in Fig. 7. The main difference between the two scenarios arises from the consideration of grains for horizontal agri PV. As is shown in the Vertical Grain scenario, the combination of grains with vertical agri PV already leads to a potential of 1937 GW_p. The potential of grain arable land is increased by around 50% if it is combined with horizontal agri PV due to its higher capacity density factor. Grassland areas are only considered for vertical agri PV, resulting in a potential of 1046 GW_p.

However, the total agri PV potential in Germany is a combination of the scenario results. Due to the overlapping crop categories considered in the scenarios, only two combinations are possible. The combination of Horizontal Conservative, Vertical Grassland, and Vertical Grains leads to a potential of 3215 GW_p, whereas that of Horizontal Innovative and Vertical Grassland leads to a higher potential of 5437 GW_p.

Fig. 7 shows the potential distribution of the agri PV scenario in Germany. The scenarios Vertical Grassland and Vertical Grains show a complementary distribution of grassland and grains in Germany. In combination, they are more evenly distributed than the potentials in the scenario Horizontal Conservative. The latter are concentrated in a few regions, such as, for example, in Rhineland-Palatinate. Furthermore, the scenario Horizontal Innovative indicates potential hotspots as well, as in Saxony or Mecklenburg-Western Pomerania. Detailed results per federal state can be found in Table 6.

5. Discussion

The following section, first, discusses the results of parking (Section 5.1), floating (Section 5.2), and agri PV separately (Section 5.3). Then, all three technologies are discussed to show the bigger picture (Section 5.4).

5.1. Parking photovoltaics

The results of the presented parking PV potential scenarios can only be compared to the potential analysis of Wirth [16] on a national level. The potentials of the presented scenarios are between 58% and 72% lower than that of Wirth [16]; however, due to the unknown methodology of the study, the differences cannot be explained. Possible factors leading to higher potentials include higher capacity densities

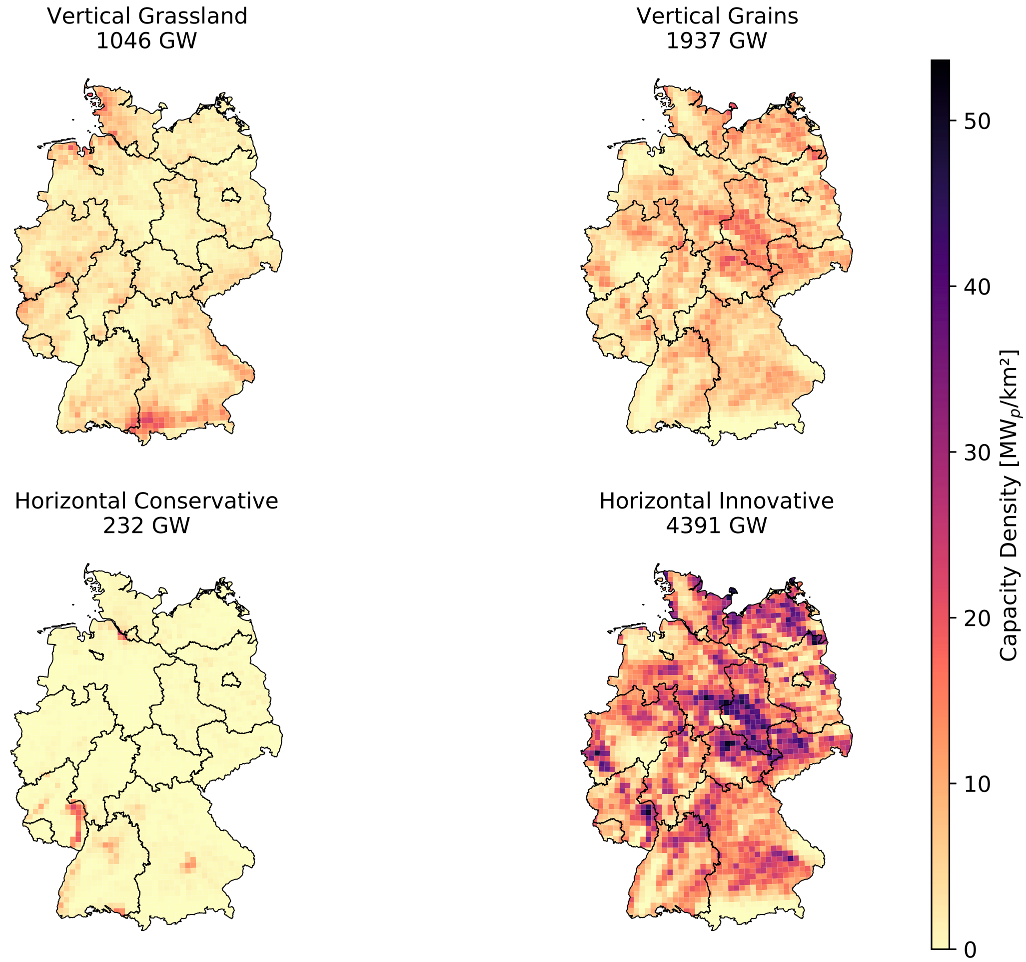

Fig. 7. Capacity density of the technical agri photovoltaics potential in Germany.

or a higher area coverage, e.g., by assuming the roofing of the entire parking lot instead of only the parking spaces.

On the federal states level, the presented results are lower than in studies from the literature for Schleswig Holstein [10], Baden-Wuerttemberg [30], and Lower Saxony [94], however, they are higher for Brandenburg [33] and Hamburg [94]. The comparability is again limited, due to missing descriptions of the methodology in many studies.

Only five of 16 federal states have passed laws that also only apply to newly-built parking lots. The potential according to legislation is therefore only a fraction of the presented results.

In future studies, the potential analysis for parking PV could be improved, e.g., by taking shading aspects into account. For this, 3D building data or tree population data could be incorporated into the analyses. Furthermore, a larger area than only the parking spaces within the parking lot could be considered for parking PV.

5.2. Floating photovoltaics

Two previous studies assess the potential of floating PV on a national scale, but neither aligns with current legislation in Germany. Wirth [16] calculates the economic potential for open-cast lignite lakes, which represents only part of the artificial and heavily modified water bodies. In contrast, Weigl [61] considers man-made inland waters and uses an area coverage of 20%. The potential of 4 to 5 GW_p is comparable to the presented results for artificial lakes, even though the area coverage is higher.

On a federal state level, three studies focus on Brandenburg, Baden-Wuertemberg, and Hamburg: Energieagentur Brandenburg [33] estimates a 242% higher potential for Brandenburg; however, due to the missing description, a comparison is not possible. Ilgen [62] indicates a potential of 280 to 1130 MW_p in different scenarios for quarry ponds. As Ilgen [62] uses only open-cast mining lakes, the results are not comparable due to the different considered water bodies. Erneuerbare Energien Hamburg Clusteragentur [32] identifies no potential for Hamburg, whereas the presented results show 16.6 MW_p.

In addition to the potential according to legislation, several sensitivities are examined. The adaptation of the distance to shore does not have a significant impact on the potential for a maximum area coverage lower than 60%, whereas the potential is highly sensitive towards the maximum area coverage. Furthermore, a high sensitivity to the allowed water body types is demonstrated, as the potential is increased by a factor of four when considering all lakes instead of only artificial and highly modified ones. Adapting the maximum area coverage or allowed water bodies in the legislation would significantly increase the German floating PV potential.

However, two negative aspects could result from such legislative changes. First, the impact of floating PV on biodiversity is unknown, which is one of the reasons why the area coverage in current legislation is set to 15%. Further analyses of biodiversity could therefore be the key to enabling higher area coverage. Secondly, land use conflicts can occur, as many water bodies are used for leisure. Therefore, a political balance must be achieved in each case.

Future potential analyses for floating PV in Germany could evaluate the potential of slow-flowing waters or near-shore maritime floating PV. Furthermore, the potential of the future artificial lakes deriving from phased-out lignite mining sites could be estimated. However, due to the long time required for utilization, these are not relevant for the expansion targets in the next few years [95].

5.3. Agri photovoltaics

The potential of agri PV in Germany largely exceeds the potential of the other innovative PV technologies presented in this study, as well as the potential of rooftop PV and open-field PV [24].

By comparing the results with previous studies, a deviation from Wirth [16] on a national scale can be seen. The horizontal agri PV potential of $1700\,GW_p$ of Wirth [16] is considerably lower than the presented results for the Horizontal Innovative scenario with $4391\,GW_p$. One reason for this is that Wirth [16] only uses a third of certain croplands; however, without a further explanation of this factor. The vertical PV potential on grassland is stated as $1200\,GW_p$ and uses a capacity density of $25\,MW_p/km^2$, whereas the presented results show a capacity of $1046\,GW_p$, with a higher capacity density of $39.5\,MW_p/km^2$. Therefore, the area is around 81% larger, which could be due to a different dataset or to the missing exclusion of protected areas or peatlands. Beck et al. [72] estimate a technical potential of $533\,GW_p$ based on statistical data, which deviates highly from the presented results and Wirth [16].

On the federal state level, the results are only comparable with two other studies [33,78]. For Brandenburg, the presented results are higher than in another study [33], which either uses all arable lands and grassland for vertical or horizontal PV. Thus, a direct comparison is not possible. For vertical grasslands, however, the presented results are around 23% higher. One reason for this could be differences in the dataset used to identify arable land or different capacity density factors. The presented results also deviate from Wydra et al. [78] for Thuringia, in which the capacity for horizontal agri PV is 56% higher than the Horizontal Innovative scenario and around 95% higher for vertical agri PV on grassland. As comparable capacity densities are used, the potential areas differ between the studies. These deviations could arise due to different crop types and different datasets being considered. The results of other studies on the federal state level are not comparable due to different considered areas with a focus on biodiversity [73] and conflict areas [74], or due to non-comparable reduction factors [76].

Another strong impact besides the used areas, crop categories, and capacity densities is the dataset for identifying agricultural and cropland. In the presented methodology, the dataset of Blickensdörfer et al. [85] is used, which to the authors' knowledge is the only dataset with georeferenced crop categories for Germany, and therefore the results are strongly dependent on its quality. The methodology, however, can also be applied to different regions, if geodata for crop areas is available. The dataset Schneider et al. [96], for example, provides full-coverage of some other countries in Europe. Furthermore, the potential analyses could be improved by a further subdivision of plant categories for the fairly generalized vegetable and orchard categories. However, these crops are grown in comparatively small areas and do not have a significant impact on the overall potential.

A limiting condition for the expansion of horizontal agri PV is the current machinery design. As shown with the scenarios Horizontal Conservative and Horizontal Innovative, the potential can be massively increased by adapting the machinery design to be compatible with horizontal agri PV systems. Another challenge for agri PV potential analyses is the alternating cultivation of crops on arable land. The installation of an agri PV system therefore requires compatibility with all crops for the systems' lifetimes. This study only considers a single crop type per land, but it could be advanced in the future to take alternating cultivation into account.

As initially stated, the agri PV plants reduce the land use conflicts between agricultural land and open-field PV plants. Further analyses could estimate the conflict areas via the intersection of the potentials of the two technologies.

5.4. Innovative PV technologies

This study reviews existing potential analyses for the innovative technologies agri PV, floating PV, and parking PV globally with an additional focus on German analyses and shows a wide range of used methodologies and parameters. The presented transparent and reproducible methodology with high geographical resolution is developed for the regional scope of Germany, however, it is transferable to other regions and countries if required land use datasets are available and suitable crops are defined for agri PV. The detailed site-specific localization of the potentials allows further consideration of these technologies for planning processes from a localized regional level up to an aggregated national level and can be utilized for identifying relevant technologies for example for subsidies.

These results, however, are highly dependent on the quality of the geographical datasets. For the analyses of Germany, only the used datasets fulfilled the requirement of high geographical resolution combined with detailed descriptions, such as crop type or parking lot type, to identify relevant areas. Due to the missing comparability, the uncertainty in the used dataset cannot be quantified. For countries and regions with several datasets, the quality of those could be compared as was done in Risch et al. [24] for other renewable technologies.

For Germany as the region examined in the analysis, currently (October 2023), around $22\,GW_p$ of open-field PV plants are in operation [97], which is approximately in the range of parking PV potential on existing parking lots with more than 35 parking lots. Compared to the potential of ground-mounted open-field and rooftop PV [24], parking and floating PV have substantially lower potentials, whereas agri PV exhibits a higher potential. Regarding the PV expansion targets of $400\,GW_p$ until 2040 in Germany, parking PV could have a maximal contribution of 6.15% and floating PV only 1.18% for the current legislation, whereas agri PV shows higher potentials than the defined targets. A quick expansion of agri PV could therefore have a major impact on the German energy system transformation and could be supported by policy adjustments. The distribution of the potentials indicates that parking PV and floating PV show the potential for regionalized contribution, while the agri PV potentials are well spread over Germany.

The potential is, however, a necessary but not sufficient condition for contributing to the future energy system design. In addition to the potential, the possible impact of the technology also depends on the generation potential, levelized costs of electricity, public acceptance, and environmental impact. While the potentials are the first step in determining the role of these technologies in the future, these topics require further research to give a comprehensive overview.

6. Conclusion

Innovative PV technologies constitute a promising approach to increasing renewable energy production by co-usage of land and thereby reducing land use conflicts and are considered in the newest legislation in Germany. However, existing studies show a wide range of methodologies and parameters in the potential analyses of the technologies globally and do not provide reproducible and transparent potentials for Germany.

This study presents the first potential analyses of the innovative PV technologies for parking, floating, and agri PV in Germany, with regionalized results and transparent methodologies, which can be transferred to other countries. The results enable initial insights into the maximum contribution of the technologies to the energy system and set the base for further research, e.g. about local acceptance and economic aspects, to define the future role of these technologies. The analysis of parking PV shows a potential of $24.6\,GW_p$ for existing parking lots with more than 35 parking spaces, $22.2\,GW_p$ for those with more than 50 parking spaces, and $16.5\,GW_p$ for those over 100 parking spaces. As only five federal states currently have legislation for this, which furthermore only applies to newly-built parking lots, the presented scenarios exceed the potentials of current legislation. The current legislation on floating PV leads to a potential of 4.7 GW_p. The potential is only marginally increased by reducing the minimum distance to shore, but significantly by the area coverage and the permitted lake types. To maximize potential contributions, it is necessary to investigate the environmental impact and, if possible, relax legislative restrictions. The analysis of agri PV potentials reveals a high potential in Germany of between 3215 GW_p and 5437 GW_p and can therefore make a major contribution to Germany's target of 400 GW_p of PV for achieving greenhouse gas neutrality in 2045. The methodology can be transferred to other regions globally. Furthermore, the enclosed data publication allows for further evaluation of the potential of innovative PV technologies and consideration in energy system models and planning processes of local and national energy transition strategies in Germany.

CRediT authorship contribution statement

Rachel Maier: Conceptualization, Investigation, Data curation, Methodology, Software, Formal analysis, Visualization, Writing – original draft. **Luna Lütz:** Investigation, Data curation, Methodology, Writing – original draft. **Stanley Risch:** Methodology, Software, Writing – review & editing. **Felix Kullmann:** Writing – review & editing, Supervision. **Jann Weinand:** Writing – review & editing, Supervision. **Detlef Stolten:** Supervision.

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

The regionalized results of the potential analyses are added to [81] in version 1.1.0.

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Appendix

See Tables 5 and 6.

Table 5
Land use exclusions in the land eligibility analysis.

Land use category	Dataset, Institution	Query
National parks	WDPA [82]	Desig='Nationalpark'
Nature protection	WDPA [82]	Desig='Naturschutzgebiet'
Habitats	WDPA [82]	Desig='Site of Community Importance (Habitats Directive)'
Birds	WDPA [82]	DESIG_ENG = 'Special Protection Area (Birds Directive)'
Forests	Basis-DLM [83]	Dataset: veg02_f.shp No query
Peatlands	Tegetmeyer et al. [93]	No query
Water Protection I & II	BfG [84]	Dataset: AM_drinkingWaterProtectionArea-DE.shp Query: WSG_ ZONE in ('1' , '1A', '1B', '2', '2A' , '2a', '2b', '2B', '2B1' , '2B2' ,'GW_ I', 'GW_ II', 'I', 'II', 'IIA', 'IIB', 'IIC', 'qual I', 'qual II', 'TWS I', 'TWS II', 'TWS II/1', 'TWS II/2', 'TWS II/3', 'Zone I', 'Zone II', 'keine Angabe')
	LUBW [98]	ZONE in ('Zone I und II bzw. IIA' , 'Zone IIB')
	LFU-RP [99]	SCHUTZZO_ 1 in ('Zone I' , 'Zone II' , 'Zone II A' , 'Zone II S')
Floodplain	BfG [84]	Dataset: AM_floodplain-DE.shp
	LfU [100]	Dataset: UEGeb_festgesetzt_09 _11 _2021.shp and UEGeb_vor_gesichert _09 _11 _2021.shp
	LUBW [98]	Dataset: Ueberschwemmungsgebiet (M1_M2)_polygon.shp
Biosphere - Core and maintenance zones	BfN [101]	Dataset: Bio_Zonierung2021_3035 Query: ZONIERUNG in ('Kernzone', 'Pflegezone')

Table 6
Results of the potential analysis per federal state and for Germany.

Federal states	Parking PV			Floating PV	Agri PV			
Potentials in MW_p	>35 parking spaces	>50 parking spaces	>100 parking spaces	Current legislation (15% area coverage and 40 m distance from shore)	Horizontal Conservative	Horizontal Innovative	Vertical Grain	Vertical Grassland
Schleswig Holstein	950	862	640	0	11 149	226 073	97 392	83 523
Hamburg	270	235	169	16	1769	3619	713	1382
Lower Saxony	2540	2335	1826	197	19 037	589 280	235 798	117 920
Bremen	210	192	149	0	120	528	158	581
North Rhine-Westphalia	4978	4479	3316	854	7872	394 725	166 840	102 724
Hesse	1768	1586	1173	290	7818	210 691	97 167	53 306
Rhineland-Palatinate	1309	1198	924	0	58 103	231 575	77 208	57 707

(*continued on next page*)

Table 6 (*continued*).

Federal states	Parking PV			Floating PV	Agri PV			
Potentials in MW_p	>35 parking spaces	>50 parking spaces	>100 parking spaces	Current legislation (15% area coverage and 40 m distance from shore)	Horizontal Conservative	Horizontal Innovative	Vertical Grain	Vertical Grassland
Baden-Wuerttemberg	3317	2972	2163	175	52 924	339 927	140 247	115 399
Bavaria	4039	3702	2845	672	48 569	688 916	324 858	301 726
Saarland	283	255	186	0	636	14 422	7212	7244
Berlin	483	421	279	8	23	798	388	253
Brandenburg	970	889	660	337	15 493	298 952	150 439	50 956
Mecklenburg-Western Pomerania	762	687	479	0	9263	392 336	168 361	40 864
Saxony	1316	1175	821	582	5564	291 135	133 862	44 555
Saxony-Anhalt	756	686	489	1183	9605	436 290	208 970	33 168
Thuringia	610	545	370	397	3259	272 190	127 738	34 606
Germany	24 567	22 220	16 488	4717	232 167	4 391 457	1 937 349	1 045 915

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