Rösch and Fakharizadehshirazi
Energy, Sustainability and Society (2025) 15:18
https://doi.org/10.1186/s13705-025-00518-y

Energy, Sustainability and Society

RESEARCH Open Access

Public participation GIS scenarios for decision-making on land-use requirements for renewable energy systems

Christine Rösch[1*] and Elham Fakharizadehshirazi[1]

Abstract

Background The transition to renewable energy is crucial for decarbonising the energy system but creates land-use competition. Whilst there is consensus on the need for local responsibility in achieving climate neutrality, debates continue over where to implement renewable energy plants. The Public Participation Geographic Information System (PPGIS) scenario approach can facilitate these debates and improve equity and procedural and distributive justice.

Results The findings highlight the effectiveness of the PPGIS method in assessing the spatial impact of technologies on agriculture and landscapes. The approach was tested in a rural German municipality to help stakeholders and citizens recognise the potential for land-based solar energy even under strict constraints. These insights were shared to support decision-makers on land-use changes to increase renewable energy production.

Conclusions The findings indicate that the PPGIS scenario approach is valuable for improving equity and mutual understanding in local decision-making processes. Incorporating stakeholders' and citizens' perspectives into renewable energy planning enhances the transparency, legitimacy, and acceptability of land-use decisions. The ability to visualise and quantitatively assess different scenarios makes PPGIS particularly useful for addressing the complexities of public debates on land-use requirements for renewable energy systems.

Keywords Land-use competition, Participation, Bottom-up scenarios, Public acceptance, Decision-making, Public Participation Geographic Information System (PPGIS), Ground-mounted photovoltaics,

Background

Decarbonising the energy system is a primary driver of land-use competition at regional, national, and global levels [1]. The German government aims to achieve climate neutrality by 2045 by increasing the share of renewable energies from 46% of gross electricity consumption today to at least 80% by 2030 [2]. Solar energy must contribute to achieving the target [3]. Photovoltaic (PV) capacity should increase from 65 Gigawatt (GW) to 215 GW by 2030 and 400 GW by 2040. Backcasting the renewable energy target, starting from the preferred normative future and analysing backwards to the present, can lead to various results due to differences and inconsistencies regarding assumptions, methods, and data [4–6]. The scenarios for solar energy are mainly based on two technologies: PV on rooftops and ground-mounted photovoltaics (GM-PV) on fields. Agrivoltaics has not (yet) been considered, although it has significant theoretical potential [7]. According to the scenarios produced by the German Industry Association, PV capacity is expected to increase to 200 TWh for rooftop PV and 4500 TWh for GM-PV. Still, the achievable potential is far lower, with 78 to 130 TWh on rooftops and 140 TWh on fields due to

*Correspondence:
Christine Rösch
christine.roesch@kit.edu
[1] Karlsruhe Institute of Technology (KIT), Institute for Technology Assessment and Systems Analysis (ITAS), Karlstraße 11, 76133 Karlsruhe, Germany

environmental, economic, and acceptability constraints and land-use conflicts [8, 9]. Competition for land use is an issue of controversial public debate and procedural and distributive justice and equity [10, 11]. Despite this evidence, energy scenario development is mainly expert-based and does not directly address local decision-making processes or consider public views [12]. Participatory approaches to developing pathways from the preferred future to the present based on (affected) stakeholders' and citizens' perceptions of land-based solar energy are also rare [13].

Political regulations on different scales determine land use for the energy transition, particularly the German Renewable Energy Sources Act (EEG) and the obligation for the federal states to set aside at least 2% of their land for renewable energies. As every state has individual characteristics, possibilities, and limitations, each has a specific area target for installing solar energy [14]. In the past, the EEG remuneration criteria were changed to phase out GM-PV in 2010 [15], so that the expansion of GM-PV declined in 2011 and 2012 [16]. A few years later, the EEG again provided state-fixed remuneration rates, which were then shifted to a competitive tendering system to increase cost efficiency for PV systems [17]. In addition, specific categories of land, particularly former landfill sites, industrial and military conversion sites, and strips of land alongside motorways and double-tracked railways, were defined as suitable for GM-PV. Land-based solar energy systems have been further promoted by the Open Space Ordinance, which allows the federal states to authorise GM-PV in naturally disadvantaged agricultural areas characterised by unfavourable climatic conditions, poor soil quality, or steeper slopes. Nine of the sixteen federal states use this regulation, including Baden-Württemberg, Bavaria, Hesse, and Rhineland-Palatinate, with favourable conditions for solar energy technologies.

The increase in GM-PV installations contributes to land consumption for settlement and infrastructure development. Existing governance at the state level seems not to foster effective land management at the municipal level to achieve the overarching goals of the European Union, such as "no net land take" [18]. Germany aims to limit land consumption to less than 30 ha per day by 2030, but this target is difficult to achieve, since between 2019 and 2022, 52 ha of land was consumed daily [19]. This goal is not translated to the municipal level, where actual land-use decisions are taken due to municipal planning sovereignty [20]. Some federal states have introduced a PV obligation to alleviate the burden on land use. This makes rooftop PV mandatory for new commercial buildings and 'the rule' for new private buildings. The controversial debates show that burden-shifting can limit the expansion of renewable energies due to their visual impact on the landscape [21]. However, the term 'landscape' has many meanings and can be perceived differently, for example, as a source of livelihood resources, a space for recreation, or a cultural heritage to be protected [22]. A key antagonist of GM-PV is the German Farmers' Association due to the loss of agricultural land and the further fragmentation of agricultural structures. It calls for GM-PV only to be allowed under strictly limited conditions, considering regional differences and agricultural structures [23–25]. In contrast, environmental organisations argue that GM-PV is more environmentally friendly than agriculture and can help preserve biodiversity if adapted to ecological criteria [26]. Other stakeholders and citizens are either convinced by and committed to land-based solar energy systems, or are critical of or even opposed to them because of its aesthetic, ecological, and socio-economic impacts on the immediate environment [27, 28]. As a result, some projects are accepted [27], whilst others face controversial discussions or opposition [29].

At the national level, 76% of the German population consider GM-PV in their neighbourhood (within 5 km) to be 'rather good' [30]. As GM-PV expands, the pressure on land will intensify land-use competition which can change public perceptions at the local level [31]. However, approval at the national level may remain high, a situation which is known as the 'national-local gap' [29]. Despite land-use competition, municipalities can favour GM-PV if they feel the benefits meet their stakeholders' and citizens' needs and expectations [10]. Understanding the contradictions between the public's general support, the difficulties in realising specific projects, and the dynamics of people's responses is crucial for expanding renewable energies [21, 32]. However, analysis is not enough. Instead, social needs, expectations, and normative values must be integrated into the mainly techno-economic development of futures, and potential analyses of renewable energies to better represent social factors in energy modelling and increase the relevance of energy models for informing policymaking [33]. Critical theoretical insights from social and socio-economic sciences can no longer be ignored, and integrated social criteria cannot be reduced to trivial approximations [34]. Natural and social science issues must be combined in decision-making for land-use change [35, 36]. To address conflicts over land use, the views of affected stakeholders must be included in processes, practises, and guidelines [32, 37, 38]. The term 'land-use conflict' refers to social or spatial conflicts of interest between stakeholders over land-use functions. However, it is a vague concept without a coherent understanding and definition of what it encompasses [39–41]. Despite the need to involve stakeholders and citizens in land-use planning for renewable energies, there is a lack of approaches, guidelines, and best practises for stakeholder involvement in decision-making processes [42].

This study aims to fill this gap and involve stakeholders and citizens in decision-making on land use for renewable energy, to help manage controversies and conflicts amongst affected stakeholders, to facilitate negotiation processes and deliberative decision-making, to support consensus building, and to provide scientific support for the development of guidelines for land-use change from food to energy production. The study addresses the national–local gap of the energy transition [29] by analysing land-use restrictions and preferences to support the energy transition in a rural community in southern Germany between 2023 and 2024. To this end, the Public Participation Geographic Information System (PPGIS) scenario approach was used to assess the feasibility of land-use change in favour of energy production with GM-PVs by involving stakeholders and citizens in the development and evaluation of GM-PV scenarios, thus supporting decision-making in the local designation of areas for renewable energy production.

Methods

The association municipality of Kandel (referred to as Kandel) was selected as a case study, because it is located in Rhineland-Palatinate, which has favourable conditions for solar energy and the highest target for expanding GM-PV amongst the German federal states. It is a rural municipality with 16,226 residents covering an area of 69.15 km^2, of which 66% is used for agriculture, 21% for forests, and 10% for settlement and public transport [43]. In 2017, around 60% of the municipality's energy consumption came from renewable sources (PV, wind, biogas cogeneration, and hydropower). This is well above the national average of 36%. Kandel hosts various renewable energy installations, including 927 PV plants (12,258 kW), 11 wind power plants (27,800 kW), and three bioenergy (biogas) plants (1560 kW), with a share in local electricity production of 29%, 67%, and 4%, respectively. Amongst the PV installations, there are two GM-PV plants, each of around 2 ha (Fig. 1). Kandel aims to become an 'Energy Plus Municipality' by 2050 by increasing the use of local renewable resources.

PPGIS is a transdisciplinary format of technology assessment which addresses societal and spatial issues related to the implementation of technologies to broaden public involvement in political decision-making processes [44]. The PPGIS enables the identification of values towards technologies in social and geographical contexts, correlating land use with participants' attitudes and preferences and analysing the causes of land-use conflicts [45]. In contrast to classical technocratic scenario development, which focuses on expert knowledge, the PPGIS scenario approach addresses the socio-technical interface of the energy transition. It enables affected stakeholders

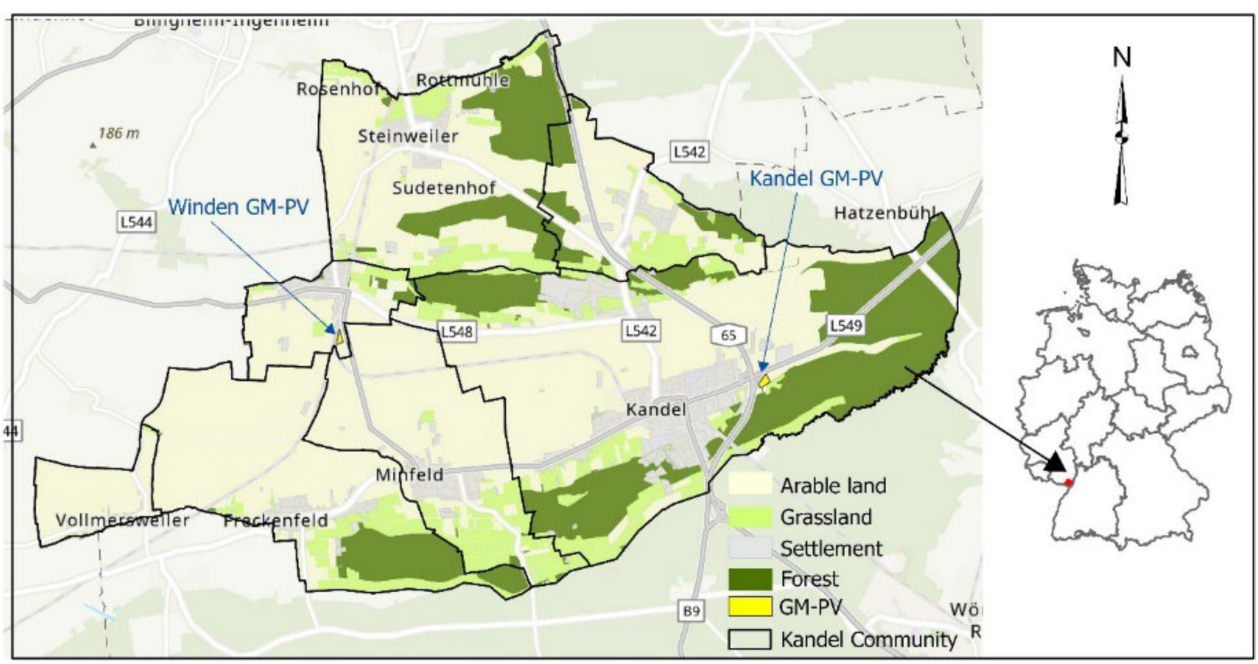

Fig. 1 The geographical position of and land use in the municipality of Kandel, showing the arable land and grassland and its distribution. The blue arrows indicate the location of the existing GM-PVs

and citizens to access the decision-making process and integrate their views and values on renewable energies in planning [44–46]. By considering local knowledge and perspectives, the approach can contribute to procedural and distributive justice and fairness [47]. It combines the PPGIS with the scenario technique to integrate stakeholders' and citizens' views and values in developing possible futures. There are different scenario techniques to develop probable or preferred descriptions of the future [36]. The PPGIS scenario approach was developed using the conceptual framework from [44, 45] and adapted according to [48]. Figure 2 shows the different steps of the PPGIS scenario approach.

First, the goal was defined with a focus on GM-PV. Alternatives, such as increased energy saving and efficiency, rooftop PV, and agrivoltaics [7], were excluded. Based on Wade and Greenberg's concept [49], a social site characterisation was conducted to gather information on stakeholder views and identify relevant stakeholders and citizens to invite to workshops. The cross-section recruitment of key stakeholders and citizens to include various views was conducted on the results of the social site characterisation with the help of the municipality's climate manager and mayor [50]. The scientific project team conceptualised two workshops, held from 5–8 pm in the municipality's town hall. At the first workshop, 27 stakeholders participated: 20 from politics and administration, two from agriculture, two from nature protection, two from citizens' energy cooperatives, and one from the energy supplier. Participants from the first workshop were invited to the second workshop. At the second workshop, 18 stakeholders participated: 12 from politics and administration, three from agriculture, one from nature protection, one from a citizens' energy cooperative, and one from an energy supplier.

The deliberative discussions in the workshops were facilitated by an experienced senior scientist trained as a professional moderator. The moderator's role was to keep the group focussed and allow participants to express their views with minimal interference, to ensure the diversity of voices regardless of background or experience, to explore differences and commonalities amongst participants, to articulate shared issues to enhance awareness and mutual understanding, and to transit to new topics when all arguments had been thoroughly discussed. The moderator clustered similar arguments around an overarching theme and looked for convergences between and across topic clusters. This encouraged exchange between arguments and values in a spirit of mutual understanding, which was integral for the definition of restrictions (land categories to be excluded) and suitability criteria (land categories given priority) for land use by GM-PV and subsequent analysis and interpretation [51]

The first workshop started with an introduction to the PPGIS scenario approach, followed by a presentation of the results of its application to develop national GM-PV scenarios by considering restrictions and suitability criteria drawn from the literature [52]. Then, participants

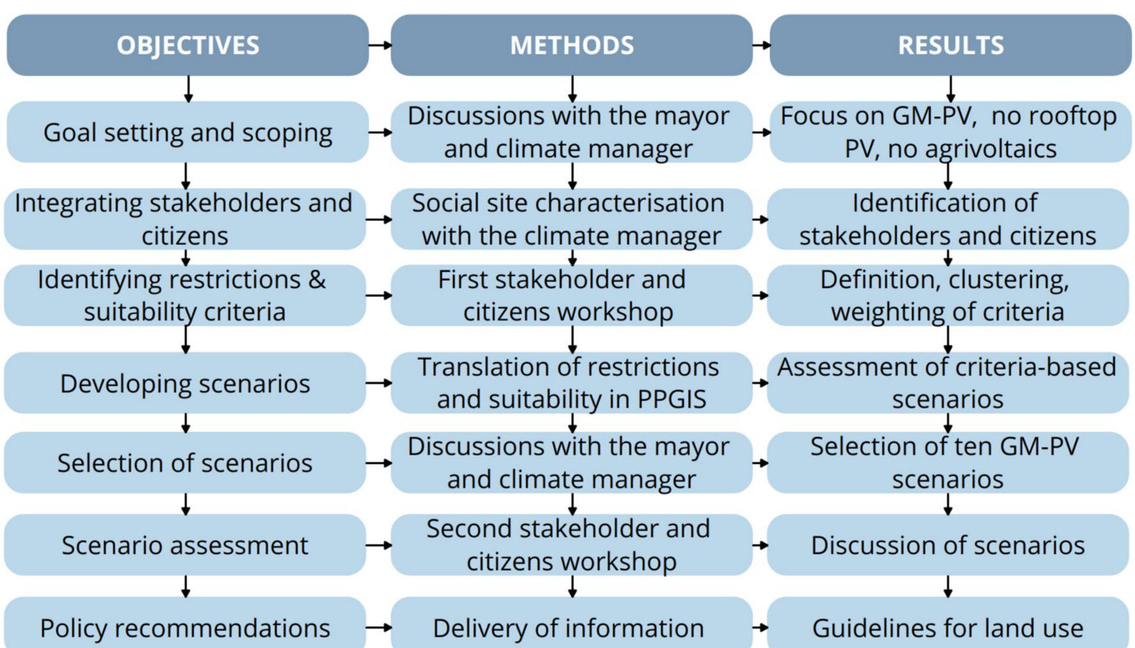

Fig. 2 The study's PPGIS scenario approach

wrote their criteria on cards, presented them, and pinned them to a display board, where they ranked and weighted the clustered criteria, with the possibility of accumulating seven points for each criterion. The discussion was recorded, transcribed, and qualitatively analysed.

The criteria developed in the first workshop were summarised and translated into the PPGIS modelling language and used to assess GM-PV land-use change in different scenarios to visualise the spatial impacts on agriculture and the landscape, reflecting different attitudes to the technology, for example, in terms of biodiversity and farmland protection and distance from residential and commercial areas (see "GM-PV scenarios" section). The scenarios were assessed by integrating the restrictions and suitability criteria. The suitability criteria were prioritised in the Analytic Hierarchy Process (AHP) of the PPGIS using the One-At-a-Time (OAT) sensitivity analysis method [52]. The results were classified into 'particularly suitable', 'highly suitable', and 'moderately suitable' areas to reflect the relative importance of the criteria. Modelling and pre-processing were performed using ArcGIS Desktop 10.8.1, ArcPro-py3, and the Python site package arcpy. The combination of different constraints and preferences results in many scenarios unsuitable for presentation and discussion in a workshop, as they can be tiring and distract from the focus on the main results of the scenarios [53]. The number of scenarios assessed using the PPGIS scenario approach to be presented in the second workshop was therefore limited by selecting, in partnership with the climate manager and the municipality's mayor, the ten most relevant scenarios for the needs and expectations of the municipality.

The second workshop started with a recap of the first workshop, summarising consensus and conflicts on the criteria. The ten main scenarios were presented, followed by a buzz group discussion where participants reflected on the results. Then, a fishbowl discussion was performed involving representatives from five stakeholder groups to discuss the acceptability and feasibility of the scenarios. The discussion was recorded, transcribed, and qualitatively analysed to derive recommendations for the decision-making process. It should be noted that stakeholders and citizens participated in the criteria- and scenario workshops. In contrast, the social site characterisation, the selection of the ten main scenarios to be presented in the scenario workshops, and the recommendations were carried out in collaboration with the municipality's climate manager and mayor. In this way, an environment of trust and accountability was created by involving stakeholders, citizens, administration, and policymakers in the process, and the PPGIS scenario approach and recommendations were not overly academic but transdisciplinary and responsive to local needs and expectations. The results of the two workshops were presented to the participants. The data and algorithms behind the PPGIS scenario tool were handed over to the climate manager and the mayor of the municipality, who will use the tool to respond systematically and responsibly to GM-PV project developers seeking approval for land-use changes based on the results of the transdisciplinary consultation process.

Results

The results section displays the workshop results against and in favour of GM-PV in three sections: GM-PV land-use restrictions, GM-PV land-use suitability criteria, and GM-PV land-use scenarios. Figure 3 shows the aggregated results of the criteria workshop (see Figure S1) translated into English. The cards on the left side of Fig. 3 represent the land categories that were not considered suitable for GM-PV installations and the corresponding reasons. Conversely, the cards on the right side of Fig. 3 indicate the areas that workshop participants considered suitable for GM-PV solar energy production. The initial results of the participatory mapping and scoring process are detailed in Figure S1 in the appendix.

Participants were instructed to use as many cards as necessary to document their land-use restrictions and preferences. Each participant had seven points to distribute amongst the cards, irrespective of whether they pertained to restrictions or preferences. In total, 189 points were allocated, indicating that all points provided to the 27 stakeholders were utilised. Notably, only a quarter of these points (47 points) were assigned to indicate the importance of restrictions. In contrast, a significantly larger portion, quarters of the points (142 points), was used to weight preferences for area characteristics related to GM-PV. Specific land-use criteria were awarded many points, even though only a few cards were classified in the respective land-use category. Conversely, other land-use categories received no points in the scoring process.

GM-PV land-use restrictions

Amongst the GM-PV land-use restrictions, 40% of the total 47 points allocated for land-use restrictions were assigned to "no agriculturally high-quality soils and arable land" (Fig. 2, left). This allocation reflects concerns that local agricultural and food businesses should not be further threatened by losing their foundational resources for production and existence. Additionally, the importance of regional food production for ensuring a secure and sustainable food supply was emphasised, particularly in light of existing and emerging political crises that threaten international food supply chains.

With 32% of the points allocated to nature conservation areas and ecologically valuable regions, participants

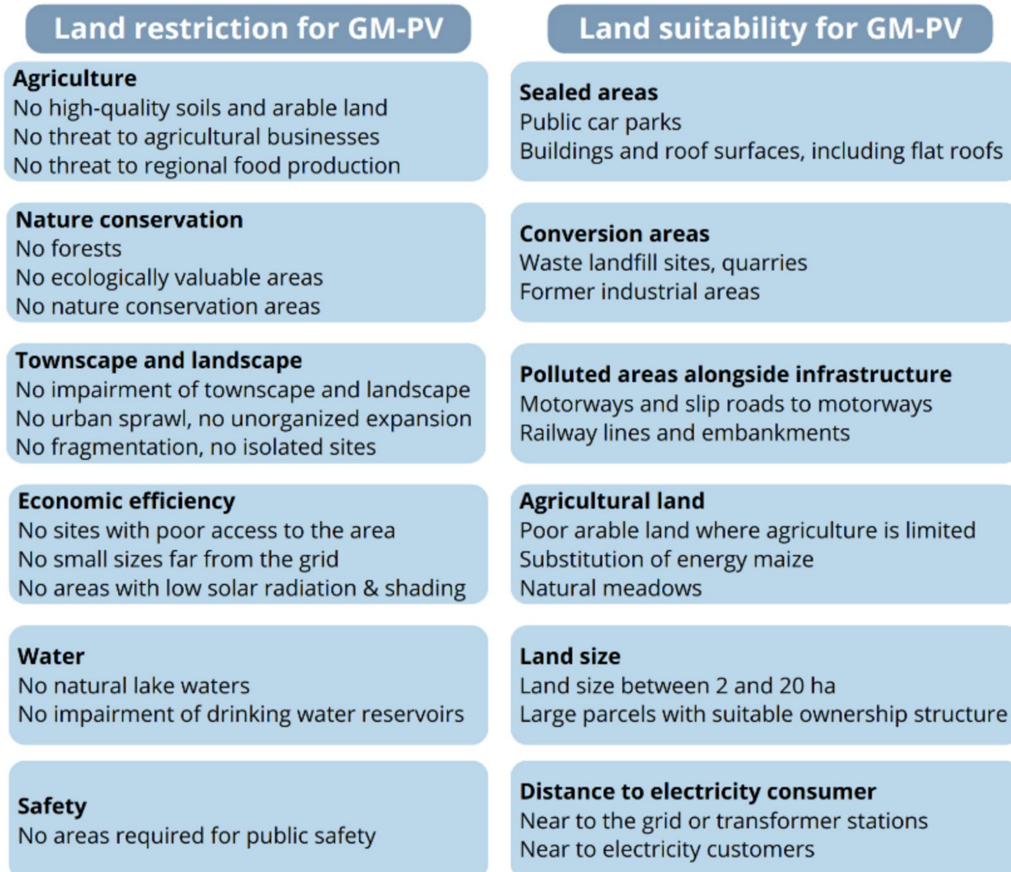

Fig. 3 The results from the first stakeholder and citizen's workshop in Kandel showing the land-use restrictions (left) and preferences (right) for GM-PV

highlighted the necessity of protecting forests and environmentally significant areas to preserve biodiversity. Nearly as many points, 28%, were dedicated to the restriction on townscapes and landscapes. Participants expressed concerns that unregulated GM-PV expansion, following a "first come, first served" approach, could lead to urban sprawl and landscape fragmentation by establishing isolated sites. This could result in a patchwork appearance and undesirable changes to the previously untouched cultural landscape.

Other constraints received lower responses and scores. These include considerations for protecting drinking water reservoirs and natural lakes, as well as techno-economic aspects such as distance to the electricity grid. The importance of these considerations varied from stakeholder to stakeholder, with some criteria receiving many points and others receiving no points in the scoring process. The results on land-use restrictions indicate that agricultural land, nature conservation areas, and areas of townscape and landscape importance are most vulnerable to conflicts in land-use planning for GM-PV.

GM-PV land-use suitability criteria

The cards on the right side of Fig. 3 illustrate the suitability criteria for GM-PV land use. The results show that sealed areas, particularly public car parks, were considered the most suitable, receiving 25% of the 142 points allocated for land-use preferences. Surprisingly, 17% of the points were allocated to agricultural land. In addition, 8% of preferences were given to agricultural land alongside motorways and double-track railways. More specifically, 4% of the land-use preferences were allocated to fields of energy maize for biogas production, as GM-PV is more environmentally friendly and efficient in electricity production and requires less land for energy production than biogas technology. A further 3% was allocated to grassland, which is economically unattractive for agriculture, and 5% to fallow land without agricultural use. One participant pointed out that areas along motorways and double-tracked railways are predominantly high-quality agricultural land. He expressed concern that the EEG supports their use regardless of soil quality and its value for local food production, potentially threatening small farms and local food businesses. Overall, one-third of the preferential votes were allocated to general or specific agricultural land use.

An analysis of the relationship between restrictions and preferences for agricultural land to the total number of points shows that preferences for agricultural land, which accounted for 27%, received significantly more support than restrictions for agricultural land, which received only 10%. The reason is the urgency of expanding renewable energy production to meet local climate change targets, which requires acceptance of GM-PV land use.

Conversion areas, such as landfills and former industrial sites, were considered with 15% of the preference points. Buildings, including flat roofs, received 7% of the preference points. Other criteria highlighted include techno-economic factors such as proximity to the electricity grid, substation, or direct electricity consumer (11%), a preferred GM-PV size between 2 and 10 hectares and simple ownership structures (4%), and flat southern exposure of the area (1%).

GM-PV scenarios

The main restrictions and suitability criteria were integrated into the PPGIS GM-PV model to assess scenarios based on national and regional data. For the scenario development, these restrictions were considered:

1. No agricultural arable land of high quality, which corresponds to a value of arable land quality ≥ 60 according to the Spatial Database Infrastructure Rhineland-Palatinate [54], or no agricultural priority areas according to regional planning [55],
2. No ecologically valuable areas, such as nature conservation areas and biotopes, but Natura 2000 areas are not excluded, and their non-approval should be based on a case-by-case assessment,
3. No areas which are essential for the regional landscape or part of the natural and cultural heritage of significant German landscapes [56],
4. A 200 m buffer zone around residential and 100 m around industrial areas allows future urban growth [57],
5. GM-PV size: minimum 2 or 5 and maximum 10 ha.

Regarding GM-PV land-use suitability, the following criteria were used:

1. Strips along motorways and double-track railways: 200 m privileged [58] and 500 m eligible strips [17],
2. Distance to the electricity grid: ≤ 1 km or 1–3 km,
3. Solar radiation: > 1116 kWh/m^2 and year or 1043–1116 kWh/m^2 and year,
4. Orientation: south or south-east and south-west,
5. Slope: ≤ 5% or 5–15%.

The suitability criteria were combined into classes to identify the most suitable areas:

1. Particularly suitable areas: 500 m strips along motorways and double-track railways
2. Highly suitable areas: solar radiation > 1116 kWh/m^2 and year, distance to electricity grid: ≤ 1 km, south orientation, slope ≤ 5%
3. Moderately suitable areas: solar irradiation 1043–1116 kWh/m^2 and year, distance to electricity grid: 1–3 km, south-east and south-west orientation, slope 5–15%.

Despite the initial focus on GM-PV, scenarios without using agricultural land were developed as the workshop participants prioritised applying rooftops and car parks, already sealed areas, landfills, and brownfield sites. As the PPGIS scenario model was not designed to assess rooftop PV, 3D building data from the Authoritative Topographic-Cartographic Information System dataset [59] were used to evaluate the roof area potential using the equation from Risch et al. [5]. The results show that 90 ha of rooftops are available for PV expansion (Table 1). Exploiting this potential can decrease land use for renewable energy. However, the realisable potential is subject to economic and social conditions as rooftop PV areas are relatively small, in many different hands, and more expensive than GM-PV, which has comparatively lower costs and can mobilise high deployment volumes faster [60]. This challenge with rooftop PV was commented on by a stakeholder, who said that 'a much larger amount of energy will have to come from undeveloped land'. The municipality's eco-account compensation areas (39 ha) were also considered, although GM-PV is not recognised as a compensation measure but requires a compensation measure. The two landfill sites in Kandel (0.3 ha and 0.14 ha) were also considered. However, they are techno-economically unattractive due to their small size and the distance from the electricity grid.

Table 1 Availability of rooftops and car parks for PV in Kandel

Sealed surfaces	Area (ha)	Available PV area (ha)
Sloping rooftop surfaces	102	61
Flat rooftops	45	27
Car parking areas	1.9	1.9
Total area	148.9	89.9

Workshop participants agreed that high-quality arable land (corresponding to numbers ≥ 60) should be retained for food production and restricted to GM-PV. Low-quality arable land is considered, recognising that these soils are not necessarily poor for food production but can be economically valuable for growing certain crops, such as strawberries and asparagus, which are essential for the regional food market and have high economic value for farmers. The assessment shows that the municipality is predominantly characterised by high-quality arable land (Fig. 4).

The assessment of the agricultural land scenario shows that if 500 m and 200 m strips along motorway No. 65 and the double-track railway crossing the territory of Kandel are considered for GM-PV, the potential adds up to 563 and 231 ha of arable land and 208 ha and 70 ha of grassland respectively, which corresponds to 18% and 7% of the municipality's agricultural area. The assessment results confirm the concern that in this scenario, GM-PV would threaten the existence of small-scale farms.

The assessment of the nature conservation scenario considers that only strictly protected nature conservation areas designated under the German Federal Nature Conservation Act [61] are unsuitable for GM-PV, as participants' opinions on Natura 2000 were divided. The disagreement reflects the controversy at the national level, where some federal states allow GM-PV in Natura 2000 areas, whilst others, such as Saxony, Bavaria and Hesse, do not. Workshop participants believe that Natura 2000 sites should be considered in principle for GM -PV and that the specific decision should be made on a case-by-case basis. Whilst nature reserves and biotopes cover 1261 ha in Kandel, a much larger area of 2426 ha is designated as Natura 2000 areas with 765 ha of grassland and 310 ha of arable land (Fig. 5). Therefore, the potential for GM-PV would be significantly greater in this scenario and would take up more agricultural land than in the agricultural land scenario assessed above.

The landscape scenario reflects national preferences based on significant German landscapes, which totals 1648 ha, of which 405 ha is arable land and 345 ha is

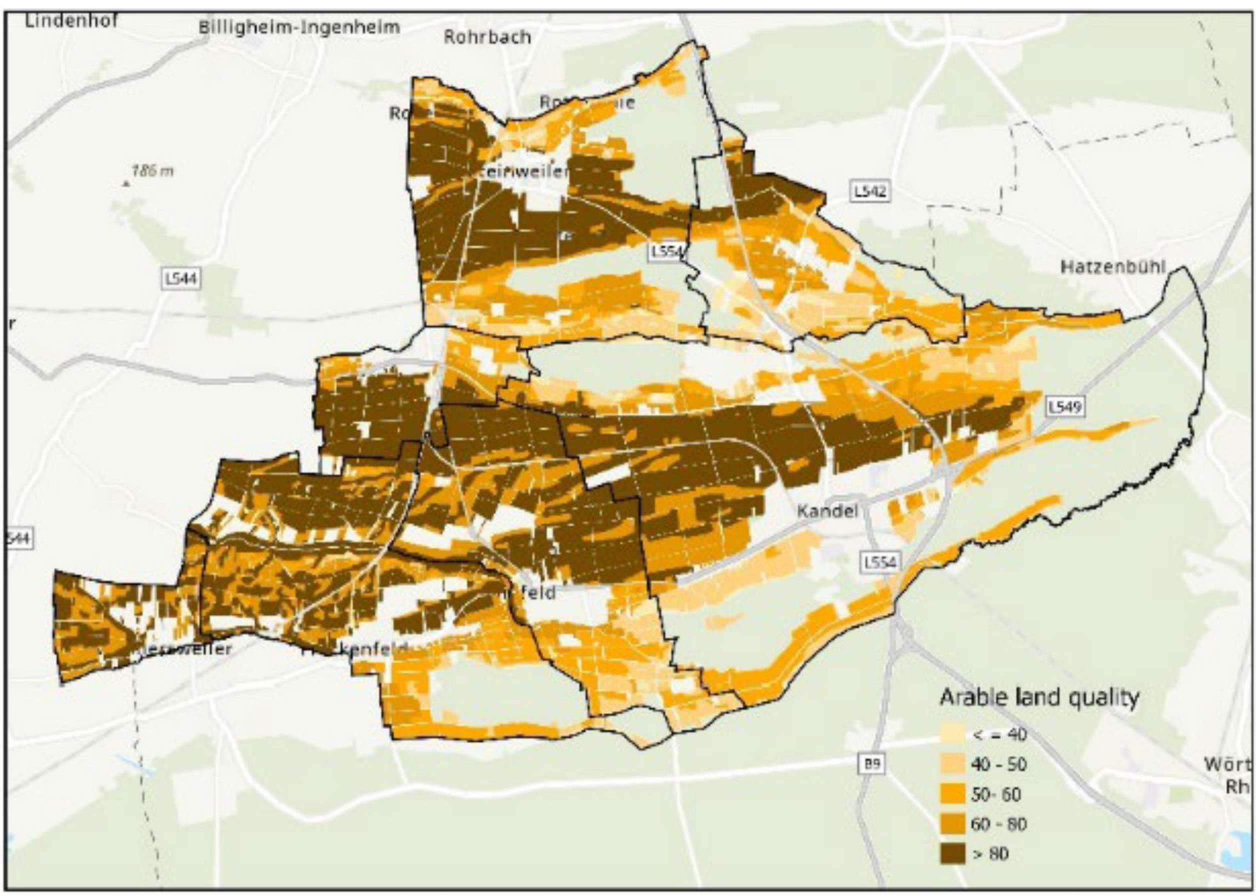

Fig. 4 Arable land quality classes in Kandel showing that the municipality has a high share of high-quality arable land (≥ 60) that should be used for food and not for energy production

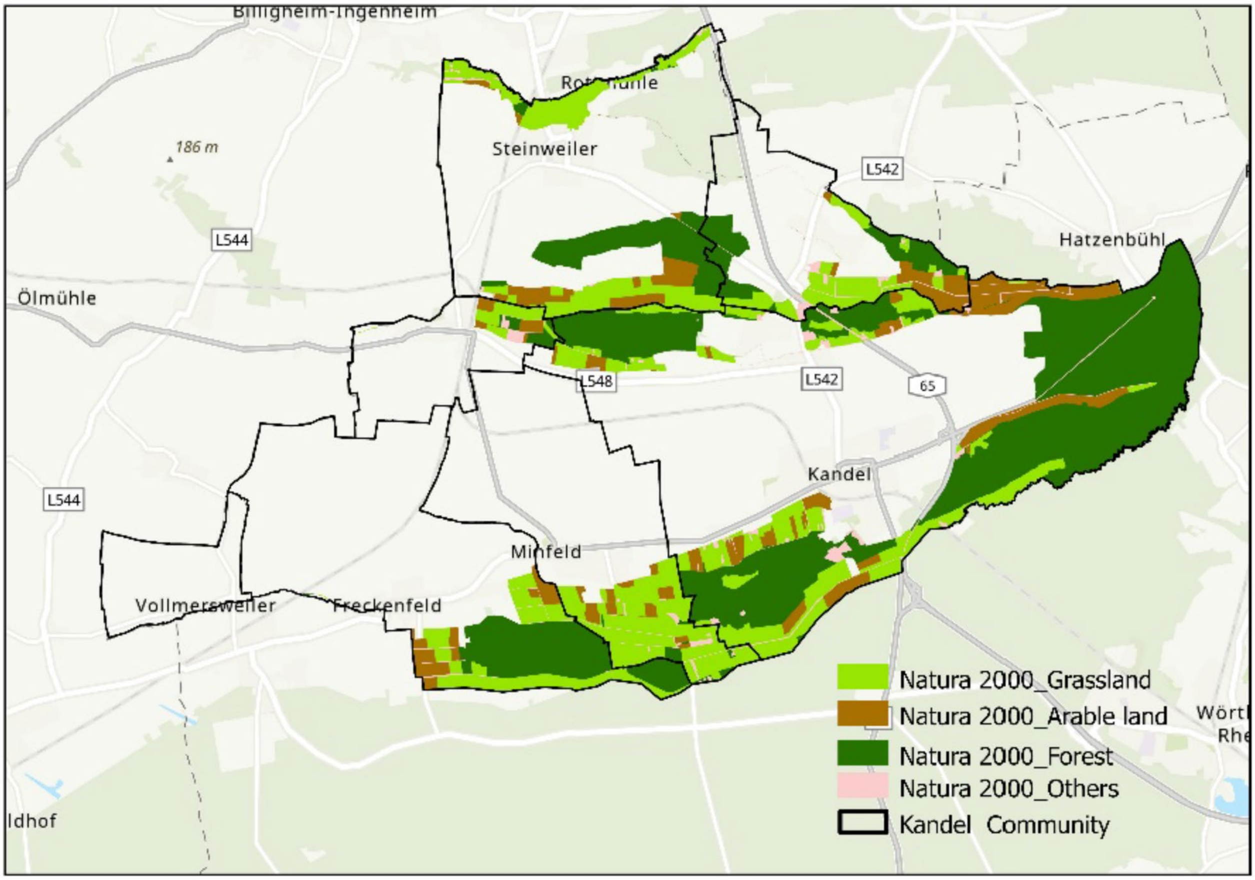

Fig. 5 Natura 2000 areas in Kandel showing that they cover a large area and consist predominantly of grassland, which is considered more suitable for GM-PV by farmers than by nature conservationists

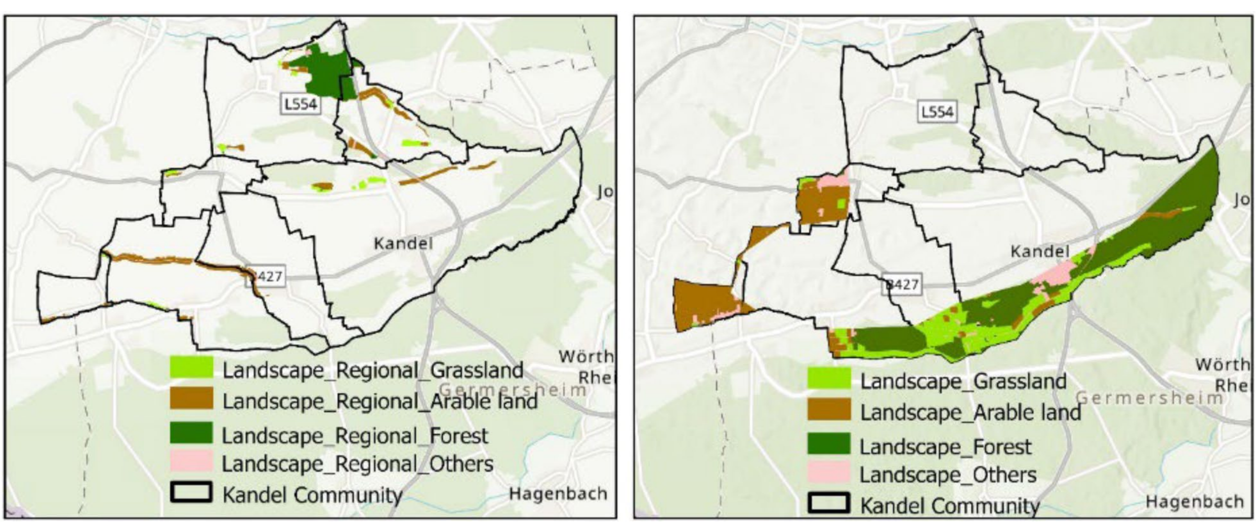

Fig. 6 Significant regional (left) and national landscapes (right) in Kandel showing that this limits the potential for GM-PV to a considerable extent

grassland (Fig. 6, right), and regional preferences based on regional planning, with an area of 414 ha designated to preserving the landscape, of which 172 ha is arable land, and 46 ha grassland (Fig. 6, left).

The scenario restricting GM-PV within 200 m of residential areas considers the restrictions regarding settlement and infrastructure areas, arable land with high soil quality, and nature conservation areas. This totals 6033, which is not applicable for GM-PV (Fig. 7). Considering an additional distance of 100 m around industrial areas increases the excluded area to 6161 ha.

The identified criteria for land-use restrictions and preferences for GM-PV were combined in different ways for the analysis of different scenarios. The characteristics of the 40 scenarios analysed using the PPGIS model are presented in Table S1 in the supplementary material. Together with the mayor and the climate manager of Kandel, it was agreed to present only the results of the ten main scenarios. This was a good compromise between the variety of scenarios calculated using the PPGIS tool and the reasonableness of the number of scenarios that could be presented and discussed in the time-limited framework of the second workshop. Too many scenarios would have led to information overload and confusion amongst the participants and might have been seen as an overly academic approach. These ten scenarios consider the main restriction criteria analysed in the first stakeholder and citizen's workshop. In all scenarios, GM-PV is not installed in settlements or areas to serve infrastructure tasks or in forest areas, because the Federal Forest Act protects the forest from clearing and arbitrary use for other land uses (conversion) (Table 2). The wishes and concerns of the farmers were taken into account, as they are opposed to further utilisation of agricultural land to secure regional food production. This mainly concerns high-quality agricultural areas in the region with an arable land index of over 60. Even areas with a lower arable land index are good soils compared to other regions. They can be of high value for speciality crops such as asparagus or strawberries, which prefer light soils with a low arable land index. As an alternative to the field index, in scenario 10, all priority areas for agriculture defined in the state development plan were excluded from conversion

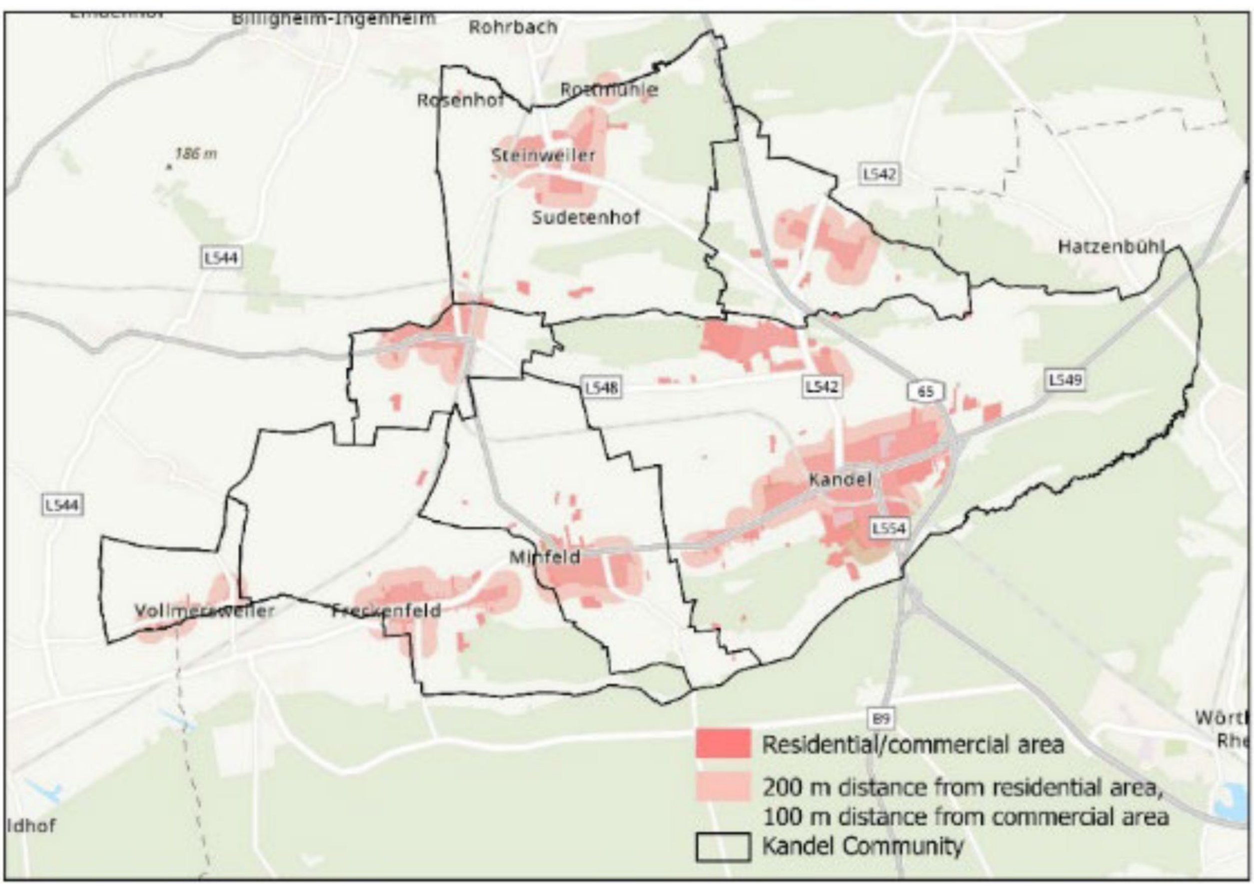

Fig. 7 Considering the distance to residential and industrial areas in Kandel restricts a large share of the municipality area for GM-PV

Table 2 Characteristics of the 10 GM-PV scenarios to be presented in the second workshop

Scenarios	No arable land (quality number ≥ 60)	No nature reserves	Distance to residential areas (m)	Distance to commercial areas (m)	Minimum size of GM-PV area (ha)
1	xl	X	0	0	2
2	x	X	200	0	2
3	x	X	200	100	2
4	x	X	0	0	5
5	x	X	200	0	5
6	x	X	200	100	5
7	x	X	0	0	10
8	x	X	200	0	10
9	x	X	200	100	10
101	yx	X	200	100	10

x: These areas were restricted and excluded from the analyses. y: Instead of high-quality land (≥ 60); all agricultural priority areas are excluded from the analysis

to GM-PV areas to reduce the loss of agricultural land. In the ten scenarios, only nature reserves were excluded in the limitation of the designation of areas that are suitable for GM-PV. In contrast, areas with a less-strict nature conservation character, such as Natura 2000 areas, were not excluded as possible areas for GM-PV in all ten scenarios. Different minimum distances to residential and commercial areas were analysed in the scenarios. Opinions in the workshop were divided on this point, as, on the one hand, proximity to electricity consumers would have economic advantages, but, on the other hand, the designation of new residential and commercial areas should not be 'obstructed', and the townscape should not be 'disfigured'. The scenarios also differ in terms of the size of the GM-PV plants. There was agreement that the plants should not be too small because of the economies of scale and in order not to negatively change the landscape with many small plants. However, these should not be very large either. In the scenarios, sizes of 2, 5, and 10 ha were therefore considered to analyse whether, taking into account the other criteria, areas of the desired size would be available.

The suitability of the areas analysed in these ten scenarios was assessed on the basis of their distance from motorways and double-tracked railways with 500 m strips, which were considered to be particularly suitable areas, because they are already polluted by traffic. Highly suitable areas are those with a southern exposure, the highest solar radiation, a slight slope, and a small distance from the electricity grid (see methodology). The moderately suitable areas have south-east and south-west exposures, less solar radiation, a higher slope, and a greater distance from the grid. The assessment results of the GM-PV scenarios, addressing restriction and suitability criteria, for Kandel are displayed in Table 3. The potential for GM-PV decreases from scenario 1 to 10 due to the increasing restrictions and requirements for suitability. Regarding scenario 10, which has the highest constraints and requirements, 0.4% of the municipality's

Table 3 Particularly-, very-, and moderately suitable areas for GM-PV in ten scenarios

Scenarios	Particularly suitable area (ha)	Highly suitable area (ha)	Moderately suitable area (ha)	Total area (ha)	Share of municipal area (%)
1	162	188	122	472	6.8
2	143	150	98	391	5.7
3	116	115	86	317	4.6
4	56	88	34	178	2.6
5	56	66	34	156	2.3
6	44	49	33	126	1.8
7	23	42	0	64	0.9
8	23	29	0	52	0.8
9	23	18	0	41	0.6
10	11	18	0	29	0.4

area could still be used for GM-PV (Table 3). This finding was a surprise for the workshop participants, which was underlined by a statement from one participant: 'Well, I was positively surprised by what came out of the analysis, that if you apply all these criteria, there are enough areas where it would make sense to have such solar parks'. The fishbowl discussion revealed that despite initial reservations, most workshop participants acknowledged that GM-PV is needed to produce as much renewable energy locally as possible to become an 'Energy Plus Municipality'. The importance of renewable electricity production in supporting local industries was discussed, and concerns were expressed that the factory nearby could close due to the lack of local renewable energy supply. The finding that the preference for large-scale GM-PV to protect the landscape from urban sprawl and achieve economic efficiency still gives considerable room for GM-PV was acknowledged. Farmers, however, adhered to their concerns about giving up arable land for GM-PV and emphasised finding a compromise between agriculture and nature conservation objectives.

Participants discussed the importance of connecting GM-PV to the electricity grid and the economic challenges regarding grid length and available capacity. They identified infrastructure development and grid reinforcement as critical factors for GM-PV deployment. Utility stakeholders highlighted the importance of landowners' willingness to lease or sell their land to implement the scenarios. Ultimately, it is the landowner who decides. If a farmer uses the land for food production, they will not give it up. However, an owner who is no longer involved in agriculture or a large landowner who wants to diversify their income is likely to rent out the land for GM-PV, as the income is more than ten times higher than if leased to a farmer. This shows that the economic framework of the energy transition leads to a complex trade-off for agriculture. However, it cannot be the case that only the landowner decides on the use of the land, collects the profits, and leaves the disadvantages to the public. This is also not possible with construction projects. The responsible political committee decides in which areas this is possible and agrees on the framework conditions. In the future, this should also be the case for the construction of GM-PV plants.

The feedback rounds which took place at the end of each of the two workshops on the process and the results, yielded positive feedback. In general, it was stated that procedural and distributive justice should be taken seriously, and the interests of agriculture, nature conservation, and renewable energy production should be balanced. The participants and the mayor emphasised the importance of the public's early participation in consulting decision-makers. They stated that the PPGIS scenario approach was crucial to finding compromises and moving the energy transition forward. The criteria developed in the PPGIS scenario approach were adopted by the municipal council by a clear majority, with only a few farmers voting against or abstaining. The decision-makers highly praised the work and the results. The establishment of jointly developed, mandatory criteria was considered essential, and a transparent participation process was regarded as indispensable for consensus building in the municipality.

Discussion

The main outputs of the study are the criteria for developing the scenarios themselves. The ten scenarios are not discussed in detail here. The focus is on the methodology, the PPGIS scenario approach and the criteria used to inform policy decisions at the end of the PPGIS scenario process. The PPGIS scenario approach addresses the socio-technical interface of the energy transition. It bridges the national-local gap by empowering affected stakeholders and citizens and facilitating open and transparent decision-making processes [29, 62]. The scenarios eased communication between participants about land-use change for GM-PV and enhanced planning procedures for expanding renewable energies [63]. The PPGIS scenario approach supports societal dialogue on the burdens and benefits of renewable energy production and public participation in consulting decision-makers to increase procedural and distributive justice and fairness [64]. The method enables new insights for a context-based inter- and transdisciplinary assessment of renewable energies and the socio-technical assessment of land-use potential at the local scale [65]. The application of the PPGIS scenario approach is limited due to the required professional and scientific guidance to organise the workshops, so that transdisciplinary scenario development can be meaningful [12, 66]. The process needs an experienced moderator to ensure that the decisive votes of participants from agriculture or renewable energies do not interfere with sharing opinions and developing criteria or dominate the discussions due to their higher levels of technical knowledge and personal conviction [67]. The joint social site characterisation, identification, and invitation of stakeholders and citizens and the municipality's mayor and climate manager facilitated the representative cross-section recruitment of stakeholders and citizens, covering various opinions about the topic [50]. A further advantage of the approach was that the stakeholders and citizens felt that their views were listened to and taken seriously and could actively participate in land-use planning and decision-making. This feeling was confirmed by the fact that the results and recommendations were received with great appreciation and led to the development of a guideline for decisions on converting agricultural land from food to solar energy production. The workshop did not explicitly address landowners, although they may ultimately decide whether to use their land for GM-PV or to give it away (rent or sell it) to GM-PV project developers. However, all the farmers who attended the workshops were landowners. Finding stakeholders who are landowners would be difficult, because there are no statistics on land ownership in Germany, where ownership is a private matter and land registers are not publicly accessible. A recent study by the Thuenen Institute shows that the majority (80%) of agricultural land is owned by individuals, most of whom are not farmers, and that land ownership is predominantly local, with a good two-thirds of agricultural land owned by individuals and companies based in the same municipality as the land. Regardless of their profession or place of residence, landowners need a permit from the local planning authority and an amendment to the zoning plan, which is decided by the local council, to build a solar farm. Local decision-makers appreciate the participatory process of the PPGIS scenarios, because the results have helped them to derive guidelines for future decisions on land-use changes for the installation of GM-PV.

Applying the PPGIS scenario approach to only one municipality limits the study's results about the suitability of the method and the transferability of the results. Yet, the role of energy advocates who belong to energy cooperatives and emphasise local renewable energy production opportunities and citizens' participation in the energy transition consultation process became apparent. There is evidence that their arguments about the benefits for local value creation and income opportunities for landowners, farmers, the municipality, and local businesses to remain competitive and maintain local jobs long-term are transferable to other municipalities if the context is similar. This finding is supported by [68], indicating that members of energy cooperatives act as agents of change by triggering behavioural changes and engaging in participative consultation of energy transition decision-makers. The study shows that, in contrast, mainly farmers and, to some extent, environmental organisations worry that previously 'untouched and unspoiled' landscapes are changed to more 'engineered' landscapes with less recreational and cultural value. This finding is supported by [69, 70]. Similar concerns are raised nationally [25, 71]. These concerns were integrated into the PPGIS scenario approach, because workshop participants decided that the potential for expanding small-scale PV on rooftops and sealed surfaces must be assessed before agricultural land is considered for solar energy production. The finding on the limited potential is supported by an assessment that only 2–3% of urbanised land can be used for PV with reasonable efficiencies [72]. In addition, using non-optimal rooftops increases capital costs for each additional area [73]. Regardless of the techno-economic challenges of exploiting this potential, using it could help to achieve renewable energy targets with less land use [30].

Solar energy potential is constrained by land use, technology conversion, and net energy yield [74]. Agricultural land use for GM-PV has increased due to the limited potential of polluted land, a non-negotiable ban on the conversion of forests and nature reserves [75] and additional land categories eligible in the EEG, such as peatland (to be rewetted), the extension of the eligible strips along highways and double-tracked railways to 500 m and a more flexible Open Space Ordinance. The study shows that these developments have reinforced the disagreement between farmers and energy producers on using agricultural land for renewable energies, which can jeopardise the existence of farms [40, 76, 77]. The German Farmers' Association has called for the same protection for farmland as for forests to protect it from GM-PV [75] and to maintain the soil's ability to capture and store carbon and ensure regional food production [23, 78]. The study's results indicate that not all farmers oppose using land for solar energy but have a differentiated view and consider areas less beneficial to agriculture, such as extensive grassland in less-favoured areas, to be appropriate for GM-PV. However, as extensive grasslands are essential for biodiversity and of high cultural value to the landscape, there is a conflict with nature conservation. Conservationists are calling for a permanent ban on using extensive grassland for GM-PV and for the EEG's funding rules to be amended to ensure that renewable energy does not endanger biodiversity. Despite a general agreement on the value of biodiversity, the study reveals that nature compensation areas for construction projects and Natura 2000 areas are considered suitable for GM-PV as they contribute to climate protection by generating renewable energy. To reconcile GM-PV scenarios with biodiversity conservation, further research is needed to integrate the GM-PVs' impact on ecosystems in the PPGIS scenario approach. Linking climate change and nature conservation can change the scenarios and increase the favourability of renewable energy projects [79]. The study indicates that the participants do not want the landscape to be spoilt by (too many) small and scattered or too large GM-PV plants and consider a size of 2–10 ha to be optimal. This result contrasts with the EEG limit of 100 Megawatt (MW) for the tender bid volume for GM-PV, equivalent to about 100 ha. This finding is supported by a research project in Southern Europe, indicating that citizen satisfaction with solar energy depends on project size, location, and participation [80]. In the study, participants agreed not to use areas for GM-PV which were essential for preserving natural and cultural landscapes. Considering the characteristics of the landscapes, such as vegetation and topography, could help to better investigate stakeholders' and citizens' views on integrating GM-PV into the socio-ecological environment. This finding is supported by wind power results, which show that the (visual) impact on the landscape is the main factor in explaining opposition or support [81]. Nevertheless, adequate scientific methods and procedures have not been implemented or regularly applied, resulting in discrepancies between scientific landscape research and landscape planning practises and needs [82, 83].

The political framework defines renewable energy as an overriding public interest when balancing interests, such as biodiversity, landscape, and soil protection and food production. This can affect the gradual erosion of public acceptance, provoke public opposition to renewable energy projects [84], and reinforce the national-local divide and the gap between attitudes and behaviour, which is often referred to and explained by the concept of "not in my backyard" (NIMBY) [85, 86]. The reasons and mechanisms driving public acceptance or resistance to renewable energy projects are many and complex and go beyond the NIMBY syndrome [87]. In this context, the term 'acceptance' is understood as acceptance by the public rather than social acceptance. [37]. The study's results provide first insights, but more empirically conceptualised and consistent research is needed to understand better the relations between stakeholders and citizens and their views on renewable energy projects [84]. The PPGIS scenario approach addresses procedural and distributive justice and fairness, considering stakeholders' and citizens' interests and the priorities necessary for public acceptance [88]. The results indicate that the conflicts between farmers and energy producers cannot be resolved comprehensively. Even with an overall high level of satisfaction with the PPGIS scenario approach, one farmer did not agree with the results and recommendations. The study did not consider compensation schemes and cooperative business models for the ownership and operation of GM-PV and their benefits for stakeholders and the municipality. Evidence shows that they can create high value [84, 85], and socio-economic compensation schemes can offset the disadvantages of land-use change if designed transparently and with stakeholder and citizen participation [89]. Transparent, participative and fair decision-making processes, as exemplified by the study's approach, can help to avoid conflicts, because socio-psychological aspects, normative values, and perceptions of justice and fairness significantly influence stakeholder responses to land-use change for renewable energies [81].

In response to political and economic conditions, GM-PV plants spring up like mushrooms on arable land. This cannot be stopped by arguing that there are still enough rooftops and non-agricultural areas. On the contrary, this argument does not allow a social discourse to control land conversion in line with social needs and expectations. Given the limited and difficult-to-exploit potential on rooftops and in sealed areas, most participants acknowledge the need for GM-PV to increase the share of renewable energy. However, conflicts exist about whether GM-PV should substitute bioenergy, which is essential for difficult-to-decarbonize energy consumption in areas such as aviation and shipping. The main argument for GM-PV was land-use efficiency, because solar energy produces around 1,000 MWh/ha per unit of land, whilst maize-fed biogas plants produce 10–60 MWh/ha [1, 90]. Converting biogas maize and other bioenergy fields, accounting for 23% of arable land in Germany, into GM-PV would significantly reduce the land demand for energy production and land-use competition [91]. This opinion and environmental concerns about too much biogas maize in the landscape are reflected in the changed political orientation of the energy transition from bioenergy to solar energy and, in particular, by restricting the share of maize permitted as feedstock in biogas plants [17, 92]. Whether bioenergy or solar energy is better suited to producing renewable energy in the field and which agricultural land should be used for energy rather than food production is an emotive debate, also at the regional and national levels [71, 77].

Conclusions

Despite an agreement to take over local responsibility to achieve climate neutrality by increasing the share of renewable energy, controversies exist about which technologies should be used where and to what extent. The PPGIS scenario approach supports procedural and distributive justice and fairness and impacts mutual understanding and the willingness to compromise. The PPGIS scenario approach to integrating stakeholders' and citizens' views on land use for renewable energy is a powerful tool for technology assessment that can facilitate the complex and emotionally charged public debate and improve the acceptability of land-use decisions. It can support local decision-making and land-use planning processes whilst considering social and cultural attachment to land use. It enables pro- and interactive land-use decisions by quantitatively assessing and visualising scenarios which reflect stakeholders' and citizens' views on land-use changes towards renewable energy production. The approach can facilitate dialogue and joint fact-finding between stakeholders and citizens with different opinions and help align land-use planning goals and processes with stakeholders' and citizens' views and values. It is crucial to analyse the context, the ethical values, and the engagement of stakeholders and citizens to increase land-based renewable energy production and reach climate neutrality. Participation increases the legitimacy of the planning process. Still, it does not necessarily increase the public acceptance of renewable energy or infrastructure projects, as this also depends on the specific process, context, facility design, and the willingness of the landowner to change land use in favour of renewable energies.

Abbreviations

EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Sources Act)
GIS	Geographic Information Systems
GM-PV	Ground-mounted Photovoltaics
km	Kilometres
kWh/m^2	Kilowatt-hours per square metre
MW	Megawatt
MWp	Megawatt peak
MWh	Megawatt hours
MWh/ha/yr	Megawatt hours per hectare per year
NIMBY	Not in my backyard
PPGIS	Public Participation Geographic Information System
PV	Photovoltaics
TWh	Terrawatt hours

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-025-00518-y.

Supplementary Material 1

Supplementary Material 2

Acknowledgements
We would like to thank Volker Poß, Jan Pfirrmann and Christina Benighaus for facilitating the workshops, and Julie Cook for editing and proofreading.

Author contributions
CR developed the PPGIS scenario approach and was responsible for stakeholder integration, as well as the organization and analysis of the workshops. She also wrote the manuscript. EF managed the data, conducted the GIS analysis, interpreted the data, and reviewed and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

Received: 3 January 2024 Accepted: 25 February 2025
Published online: 19 March 2025

References

1. Van De Ven D-J, Capellan-Peréz I, Arto I et al (2021) The potential land requirements and related land use change emissions of solar energy. Sci Rep 11:2907. https://doi.org/10.1038/s41598-021-82042-5
2. SPD; Bündnis 90/Die Grünen; FDP (2021) Koalitionsvertrag 2021–2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), BÜNDNIS 90 / DIE GRÜNEN und den Freien Demokraten (FDP). https://www.bundesregierung.de/resource/blob/974430/1990812/1f422c60505b6a88f8f3b3b5b8720bd4/2021-12-10-koav2021-data.pdf?download=1. Accessed 17 Oct 2024
3. Prognos, Öko-Institut, Wuppertal-Institut (2021) Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. https://www.stiftung-klima.de/app/uploads/2021/06/2021_Zusammenfassung_KNDE2045_DEU_1.4.pdf. Accessed 17 Oct 2024
4. Prognos, BCG - Boston Consulting Group, EWI - Energiewirtschaftliches Institut an der Universität zu Köln, et al (2022) Vergleich der „Big 5" Klimaneutralitätsszenarien. Studie für Stiftung Klimaneutralität (SKN), Agora Verkehrswende, Agora Energiewende, Bundesverband der Deutschen Industrie (BDI), Deutsche Energie-Agentur (dena) und Bundesministerium für Wirtschaft und Klimaschutz (BMWK)
5. Risch S, Maier R, Du J et al (2022) Potentials of renewable energy sources in germany and the influence of land use datasets. Energies 15:5536. https://doi.org/10.3390/en15155536
6. Robinson JB (1982) Energy backcasting A proposed method of policy analysis. Energy Policy 10:337–344. https://doi.org/10.1016/0301-4215(82)90048-9
7. Rösch C, Fakharizadehshirazi E (2024) The spatial socio-technical potential of agrivoltaics in Germany. Renew Sustain Energy Rev 202:114706. https://doi.org/10.1016/j.rser.2024.114706
8. BDI (Bundesverband der Deutschen Industrie) (2021) Klimapfade für Deutschland. https://www.vci.de/vci/downloads-vci/media-weitere-downloads/2018-01-18-bdi-studie-klimapfade-fuer-deutschland.pdf. Accessed 17 Oct 2024
9. dena (Deutsche Energie-Agentur) (2021) dena-Leitstudie Aufbruch Klimaneutralität. Eine gesamtgesellschaftliche Aufgabe. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf. Accessed 17 Oct 2024
10. Van Den Berg K, Tempels B (2022) The role of community benefits in community acceptance of multifunctional solar farms in the Netherlands. Land Use Policy 122:106344. https://doi.org/10.1016/j.landusepol.2022.106344
11. Yenneti K, Day R, Golubchikov O (2016) Spatial justice and the land politics of renewables: dispossessing vulnerable communities through solar energy mega-projects. Geoforum 76:90–99. https://doi.org/10.1016/j.geoforum.2016.09.004
12. Wright G, Cairns G, Bradfield R (2013) Scenario methodology: new developments in theory and practice. Technol Forecast Soc Change 80:561–565. https://doi.org/10.1016/j.techfore.2012.11.011
13. Bengston DN, Westphal LM, Dockry MJ (2020) Back from the future: the backcasting wheel for mapping a pathway to a preferred future. World Futur Rev 12:270–278. https://doi.org/10.1177/1946756720929724
14. May J (2023) Raumplanung und Erneuerbare Energien. Flächenbereitstellung für Wind- und Solar-freiflächenanlagen in den Bundesländern. Ausgabe 58, Februar 2023, Agentur für Erneuerbare Energien e.V., Berlin
15. Schrödter W, Kuras M (2011) Auswirkungen des EEG 2010 auf die Planung von Flächen für Photovoltaikanlagen. ZNER 2011. Heft 2:144–151
16. UM BW (Umweltministerium Baden-Württemberg) (2019) Freiflächensolaranlagen Handlungsleitfaden. https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/2_Presse_und_Service/Publikationen/Energie/Handlungsleitfaden_Freiflaechensolaranlagen.pdf. Accessed 17 Oct 2024

17. EEG (2023) Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2023). https://www.gesetze-im-internet.de/eeg_2014/EEG_2023.pdf. Accessed 17 Oct 2024
18. Salvati L, Zambon I, Chelli FM, Serra P (2018) Do spatial patterns of urbanization and land consumption reflect different socioeconomic contexts in Europe? Sci Total Environ 625:722–730. https://doi.org/10.1016/j.scitotenv.2017.12.341
19. Umweltbundesamt (2024) Indikator: Siedlungs- und Verkehrsfläche. https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-siedlungs-verkehrsflaeche. Accessed 17 Oct 2024
20. Meyer MA, Lehmann I, Seibert O, Früh-Müller A (2021) Spatial indicators to monitor land consumption for local governance in Southern Germany. Environ Manage 68:755–771. https://doi.org/10.1007/s00267-021-01460-3
21. Wüstenhagen R, Wolsink M, Bürer MJ (2007) Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy 35:2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001
22. Backhaus N (2011) Landscapes, spatial totalities or special regions? Procedia - Soc Behav Sci 14:193–202. https://doi.org/10.1016/j.sbspro.2011.03.036
23. DBV (Deutscher Bauernverband) (2022) Flächenverluste bei Ackerböden stoppen. Deutscher Bauernverband Pressemitteilung vom 06.12.2022. https://www.bauernverband.de/topartikel/flaechenverluste-bei-ackerboeden-stoppen Accessed 17 Oct 2024
24. DBV (Deutscher Bauernverband) (2023a) Stellungnahme des DBV zum Entwurf der Photovoltaik-Strategie des Bundesministeriums für Wirtschaft und Klimaschutz. https://www.bauernverband.de/fileadmin/user_upload/dbv/positionen/2023/12923_DBV_Stellungnahme_Photovoltaik-Strategie_BMWK__24Maerz23_.pdf. Accessed 17 Oct 2024
25. DBV (Deutscher Bauernverband) (2023b) Photovoltaik vorrangig auf Dächern und Gebäuden ausbauen. https://www.bauernverband.de/topartikel/photovoltaik-vorrangig-auf-daechern-und-gebaeuden-ausbauen. Accessed 17 Oct 2024
26. NABU (Naturschutzbund Deutschland)/BSW e.V. (Bundesverband Solarwirtschaft) (2021) Kriterien für naturverträgliche Photovoltaik-Freiflächenanlagen. https://www.nabu.de/imperia/md/content/nabude/energie/solarenergie/210505-nabu-bsw-kritereien_fuer_naturvertraegliche_solarparks.pdf. Accessed 17 Oct 2024
27. Anderson C, Schirmer J, Abjorensen N (2012) Exploring CCS community acceptance and public participation from a human and social capital perspective. Mitig Adapt Strateg Glob Change 17:687–706. https://doi.org/10.1007/s11027-011-9312-z
28. Zoellner J, Schweizer-Ries P, Wemheuer C (2008) Public acceptance of renewable energies: Results from case studies in Germany. Energy Policy 36:4136–4141. https://doi.org/10.1016/j.enpol.2008.06.026
29. Sütterlin B, Siegrist M (2017) Public acceptance of renewable energy technologies from an abstract versus concrete perspective and the positive imagery of solar power. Energy Policy 106:356–366. https://doi.org/10.1016/j.enpol.2017.03.061
30. Agentur für Erneuerbare Energien e.V (2023) Zustimmung zu Erneuerbare-Energie-Anlagen in der Nachbarschaft des eigenen Wohnorts. https://www.unendlich-viel-energie.de/erneuerbare-energien-in-deutschland-zwischen-akzeptanz-und-unsicherheit. Accessed 17 Oct 2024
31. BMVI (Bundesministerium für Verkehr und digitale Infrastruktur) (Hrsg.) (2015) Räumlich differenzierte Flächenpotentiale für erneuerbare Energien in Deutschland. BMVI-Online-Publikation, Nr. 08/2015. https://www.bbsr.bund.de/BBSR/DE/veroeffentlichungen/ministerien/bmvi/bmvi-online/2015/DL_BMVI_Online_08_15.pdf;jsessionid=C98274E68394473A70B45063997ADEE8.live21301?__blob=publicationFile&v=1. Accessed 17 Oct 2024
32. Batel S (2020) Research on the social acceptance of renewable energy technologies: past, present and future. Energy Res Soc Sci 68:101544. https://doi.org/10.1016/j.erss.2020.101544
33. Grunwald A (2011) Energy futures: diversity and the need for assessment. Futures 43:820–830. https://doi.org/10.1016/j.futures.2011.05.024
34. Bosch S, Schwarz L (2018) Ein GIS-Planungstool für erneuerbare Energien—integration sozialer Perspektiven. https://doi.org/10.14627/537647012
35. Akizu O, Bueno G, Barcena I et al (2018) Contributions of bottom-up energy transitions in Germany: a case study analysis. Energies 11:849. https://doi.org/10.3390/en11040849
36. Börjeson L, Höjer M, Dreborg K-H et al (2006) Scenario types and techniques: towards a user's guide. Futures 38:723–739. https://doi.org/10.1016/j.futures.2005.12.002
37. Wolsink M (2018) Social acceptance revisited: gaps, questionable trends, and an auspicious perspective. Energy Res Soc Sci 46:287–295. https://doi.org/10.1016/j.erss.2018.07.034
38. Wuebben D (2017) From wire evil to power line poetics: the ethics and aesthetics of renewable transmission. Energy Res Soc Sci 30:53–60. https://doi.org/10.1016/j.erss.2017.05.040
39. Fienitz M (2023) Taking stock of land use conflict research: a systematic map with special focus on conceptual approaches. Soc Nat Resour 36:715–732. https://doi.org/10.1080/08941920.2023.2199380
40. Steinhäußer R, Siebert R, Steinführer A, Hellmich M (2015) National and regional land-use conflicts in Germany from the perspective of stakeholders. Land Use Policy 49:183–194. https://doi.org/10.1016/j.landusepol.2015.08.009
41. Zhou D, Lin Z, Lim SH (2019) Spatial characteristics and risk factor identification for land use spatial conflicts in a rapid urbanization region in China. Environ Monit Assess 191:677. https://doi.org/10.1007/s10661-019-7809-1
42. Landesverband Erneuerbare Energien, Niedersachsen, Bremen e.V (2022) Leitfaden für die kommunale Bauleitplanung für Freiflächenphotovoltaikanlagen (FFPVA). https://www.lee-nds-hb.de/wp-content/uploads/2022/07/LEE-Leitfaden-Freiflaechenphotovoltaikanlagen.pdf. Accessed 17 Oct 2024
43. Energieatlas Rheinland-Pfalz (2022) Energiesteckbrief Verbandsgemeinde Kandel. https://www.energieatlas.rlp.de/earp/energiesteckbriefe. Accessed 17 Oct 2024
44. Sieber R (2006) Public participation geographic information systems: a literature review and framework. Ann Assoc Am Geogr 96:491–507. https://doi.org/10.1111/j.1467-8306.2006.00702.x
45. Brown G, Reed P, Raymond CM (2020) Mapping place values: 10 lessons from two decades of public participation GIS empirical research. Appl Geogr 116:102156. https://doi.org/10.1016/j.apgeog.2020.102156
46. Nummi P (2018) Crowdsourcing local knowledge with ppgis and social media for urban planning to reveal intangible cultural heritage. Urban Plan 3:100–115. https://doi.org/10.17645/up.v3i1.1266
47. Denwood T, Huck JJ, Lindley S (2022) Effective PPGIS in spatial decision-making: Reflecting participant priorities by illustrating the implications of their choices. Trans GIS 26:867–886. https://doi.org/10.1111/tgis.12888
48. Starick A, Syrbe R-U, Steinhäußer R et al (2014) Scenarios of bioenergy provision: technological developments in a landscape context and their social effects. Environ Dev Sustain 16:575–594. https://doi.org/10.1007/s10668-013-9495-4
49. Wade S, Greenberg S (2011) Social site characterisation: from concept to application. A review of relevant social science literature and a toolkit for social site characterisation. http://carboncap-cleantech.com/articles/CCS/17%20social-site-characterisation-concept-application.pdf. Accessed 17 Oct 2024
50. Gobo G (2005) Sampling, representativeness and generalizability. In: Gobo G, Gubrium J, Seale C, Silverman D (eds). Qualitative research practice. London, Sage. p. 65–79. https://ggobors.ariel.ctu.unimi.it/repository/ggobors/sage2004.pdf. Accessed 17 Oct 2024
51. Ruiz JR (2017) Collective production of discourse: an approach based on the qualitative school of Madrid. In: Barbour R, Morgan D (eds) A new era in focus group research. Palgrave Macmillan, London. https://doi.org/10.1057/978-1-137-58614-8_13
52. Fakharizadehshirazi E, Rösch C (2024) A novel socio-techno-environmental GIS approach to assess the contribution of ground-mounted photovoltaics to achieve climate neutrality in Germany. Renew Energy 227:120117. https://doi.org/10.1016/j.renene.2024.120117
53. Amer M, Daim TU, Jetter A (2013) A review of scenario planning. Futures 46:23–40. https://doi.org/10.1016/j.futures.2012.10.003
54. Rheinland-Pfalz (2023) Geodateninfrastruktur Rheinland-Pfalz (GDI-RP). https://www.geoportal.rlp.de/. Accessed 17 Oct 2024
55. Verbandsgemeinde Kandel (2016) Gesamtfortschreibung des Flächennutzungsplanes 2025 https://www.vg-kandel.de/vg_kandel/Verwaltung/Bauleitplanung/Bauleitpl%C3%A4ne/FNP-Fortschr.-Begr%C3%BCndung%2002-05-2016_21-10-2016.pdf. Accessed 17 Oct 2024

56. Schwarzer M, Mengel A, Reppin N, Wiechmann S (2022) Bedeutsame Landschaften in Deutschland. Fachbroschüre zur konsolidierten Fassung. https://doi.org/10.17170/KOBRA-202206236391
57. Struth C, Ney J (2020) Leitlinien zu / Kriterien zum Filtern von Eignungsflächen für die Errichtung von Photovoltaik - Freiflächenanlagen (PV-FFA). https://www.vg-suedeifel.de/wp-content/uploads/2023/01/2020-10-26-Leitlinien_Kriterien_PV-FFA_Textfassung.pdf. Accessed 17 Oct 2024
58. BauGB (2023) Baugesetzbuch in der Fassung der Bekanntmachung vom 3. November 2017 (BGBl. I S. 3634), das zuletzt durch Artikel 1 des Gesetzes vom 28. Juli 2023 (BGBl. 2023 I Nr. 221) geändert worden ist
59. BKG (Bundesamt für Kartographie und Geodäsie) (2022) 3D-Gebäudemodelle LoD2 Deutschland. : https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html. Accessed 17 Oct 2024
60. Wirth H (2023) Aktuelle Fakten zur Photovoltaik in Deutschland. http://www.file://C:/Users/uw6875/Downloads/aktuelle-fakten-zur-photovoltaik-in-deutschland-5.pdf. Accessed 17 Oct 2024
61. BNatSchG (Bundesnaturschutzgesetz) (2009) Gesetz über Naturschutz und Landschaftspflege (Bundesnaturschutzgesetz - BNatSchG. 29.07.2009, zuletzt geändert durch Art. 3 G v. 8.12.2022 I 2240. Accessed 17 Oct 2024
62. Hoffmann S, Pohl C, Hering JG (2017) Methods and procedures of transdisciplinary knowledge integration: empirical insights from four thematic synthesis processes. Ecol Soc 22:art27. https://doi.org/10.5751/ES-08955-220127
63. Rall E, Hansen R, Pauleit S (2019) The added value of public participation GIS (PPGIS) for urban green infrastructure planning. Urban For Urban Green 40:264–274. https://doi.org/10.1016/j.ufug.2018.06.016
64. Metze TAP, Van Den Broek J, Van Est R, Cuppen EHWJ (2023) Participatory repertoires for aligning policy and society: an analysis of Dutch stakeholder views on deep geothermal energy. Energy Res Soc Sci 98:103019. https://doi.org/10.1016/j.erss.2023.103019
65. Grunwald A, Rösch C (2011) Sustainability assessment of energy technologies: towards an integrative framework. Energy Sustain Soc 1:3. https://doi.org/10.1186/2192-0567-1-3
66. Schwarz L, Bräuer P (2022) An exploratory PPGIS for the nuclear waste repository siting procedure in Germany—a transdisciplinary approach to enable meaningful participation? GI_Forum 1:77–90. https://doi.org/10.1553/giscience2022_01_s77
67. Kerr A, Cunningham-Burley S, Tutton R (2007) Shifting subject positions: experts and lay people in public dialogue. Soc Stud Sci 37:385–411. https://doi.org/10.1177/0306312706068492
68. Wahlund M, Palm J (2022) The role of energy democracy and energy citizenship for participatory energy transitions: a comprehensive review. Energy Res Soc Sci 87:102482. https://doi.org/10.1016/j.erss.2021.102482
69. Günnewig D, Johannwerner E, Kelm T, et al (2022a) Anpassung der Flächenkulisse für PV-Freiflächenanlagen im EEG vor dem Hintergrund erhöhter Zubauziele. Notwendigkeit und mögliche Umsetzungsoptionen. TEXTE 76/2022 Umweltbundesamt Berlin. https://www.umweltbundesamt.de/sites/default/files/medien/479/publikationen/texte_76-2022_anpassung_der_flaechenkulisse_fuer_pv-freiflaechenanlagen_im_eeg_vor_dem_hintergrund_erhoehter_zubauziele.pdf. Accessed 17 Oct 2024
70. Günnewig D, Johannwerner E, Kelm T, et al (2022b) Umweltverträgliche Standortsteuerung von Solar-Freiflächenanlagen. Handlungsempfehlungen für die Regional- und Kommunalplanung. https://www.umweltbundesamt.de/publikationen/umweltvertraegliche-standortsteuerung-von-solar. Accessed 17 Oct 2024
71. NABU (Naturschutzbund Deutschland) (2021) Der naturverträgliche Ausbau der Photovoltaik Nutzung von Solarenergie in urbanen und ländlichen Räumen, auf Dächern und in der Fläche. https://www.nabu.de/imperia/md/content/nabude/energie/solarenergie/210421-nabu-infopapier-photovoltaik.pdf. Accessed 17 Oct 2024
72. Capellán-Pérez I, De Castro C, Arto I (2017) Assessing vulnerabilities and limits in the transition to renewable energies: land requirements under 100% solar energy scenarios. Renew Sustain Energy Rev 77:760–782. https://doi.org/10.1016/j.rser.2017.03.137
73. Denholm P, Margolis R (2008) Supply Curves for Rooftop Solar PV-Generated Electricity for the United States. https://digitalscholarship.unlv.edu/renew_pubs/25/ Accessed 17 Oct 2024
74. Dupont E, Koppelaar R, Jeanmart H (2020) Global available solar energy under physical and energy return on investment constraints. Appl Energy 257:113968. https://doi.org/10.1016/j.apenergy.2019.113968
75. BWaldG (Bundeswaldgesetz) (1975) Gesetz zur Erhaltung des Waldes und zur Förderung der Forstwirtschaft (Bundeswaldgesetz). https://www.gesetze-im-internet.de/bwaldg/BJNR010370975.html. Accessed 17 Oct 2024
76. DBV (Deutsche Bauernverband) (2015) Situationsbericht Boden Moderne Landwirtschaft – Gesunde Böden. https://www.bauernverband.de/fileadmin/user_upload/dbv/themendossiers/Umwelt_Artenschutz/DBV_Situationsbericht_Boden_2015.pdf. Accessed 17 Oct 2024
77. Landwirtschaftskammer Rheinland-Pfalz (2022) Leitfaden der Landwirtschaftskammer Rheinland-Pfalz zur Beachtung agrarstruktureller Belange beim Ausbau von Freiflächen-Photovoltaik-Anlagen auf landwirtschaftlichen Flächen. https://lwk87.typo3web03.rlp.de/fileadmin/lwk-rlp.de/Weinbau/Presse/Endfassung_Leitfaden_Freiflaechen-Photovoltaik-Anlagen__29.04.2022.pdf. Accessed 17 Oct 2024
78. Lehuger S, Gabrielle B, Cellier P et al (2010) Predicting the net carbon exchanges of crop rotations in Europe with an agro-ecosystem model. Carbon Balance Eur Crop 139:384–395. https://doi.org/10.1016/j.agee.2010.06.011
79. Hübner G, Pohl J, Warode J, et al (2020) Akzeptanzfördernde Faktoren erneuerbarer Energien. Deutschland/Bundesamt für Naturschutz. BfN Schriften 551. doi. https://doi.org/10.19217/skr551
80. Campos I, Brito M, Luz G (2023) Scales of solar energy: exploring citizen satisfaction, interest, and values in a comparison of regions in Portugal and Spain. Energy Res Soc Sci 97:102952. https://doi.org/10.1016/j.erss.2023.102952
81. Wolsink M (2007) Planning of renewables schemes: deliberative and fair decision-making on landscape issues instead of reproachful accusations of non-cooperation. Energy Policy 35:2692–2704. https://doi.org/10.1016/j.enpol.2006.12.002
82. Kompetenzzentrum Naturschutz und Energiewende (2020) Auswirkungen von Solarparks auf das Landschaftsbild.Methoden zur Ermittlung und Bewertung. https://www.naturschutz-energiewende.de/wp-content/uploads/KNE_Auswirkungen-von-Solarparks-auf-das-Landschaftsbild_11-2020.pdf. Accessed 17 Oct 2024
83. Roth M, Bruns E (2016) Landschaftsbildbewertung in Deutschland–Stand von Wissenschaft und Praxis. BfN-Skripten 439. https://www.bfn.de/sites/default/files/BfN/service/Dokumente/skripten/skript439.pdf. Accessed 17 Oct 2024
84. Batel S, Devine-Wright P, Tangeland T (2013) Social acceptance of low carbon energy and associated infrastructures: a critical discussion. Energy Policy 58:1–5. https://doi.org/10.1016/j.enpol.2013.03.018
85. Devine-Wright P (2005) Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy. Wind Energy 8:125–139. https://doi.org/10.1002/we.124
86. Wolsink M (2006) Invalid theory impedes our understanding: a critique on the persistence of the language of NIMBY. Trans Inst Br Geogr 31:85–91. https://doi.org/10.1111/j.1475-5661.2006.00191.x
87. Batel S, Devine-Wright P (2015) Towards a better understanding of people's responses to renewable energy technologies: insights from social representations theory. Public Underst Sci 24:311–325. https://doi.org/10.1177/0963662513514165
88. Otto J, Wegner N (2023) Weiterentwicklung der Außenbereichsprivilegierung von PV-Freiflächenanlagen. Konzeptionelle Möglichkeiten zur Stärkung der Flächenbereitstellung und weiterer Steuerungsziele bei Erhalt kommunaler Gestaltungsmöglichkeiten. Würzburger Berichte zum Umweltenergierecht Nr. 56 vom 16.02.2023. https://stiftung-umweltenergierecht.de/wp. Accessed 17 Oct 2024
89. Stadelmann-Steffen I, Dermont C (2021) Acceptance through inclusion? Political and economic participation and the acceptance of local renewable energy projects in Switzerland. Energy Res Soc Sci 71:101818. https://doi.org/10.1016/j.erss.2020.101818
90. Böhm J (2023) Vergleich der Flächenenergieerträge verschiedener erneuerbarer Energien auf landwirtschaftlichen Flächen – für Strom, Wärme und Verkehr. Berichte Über Landwirtsch - Z Für Agrarpolit Landwirtsch Band 101:April 2023. https://doi.org/10.12767/BUEL.V101I1.462

91. FNR (Fachagentur Nachwachsende Rohstoffe e. V.) (2023) Flächennutzung in Deutschland. https://www.fnr.de/nachwachsende-rohstoffe/anbau. https://www.fnr.de/nachwachsende-rohstoffe/anbau. Accessed 17 Oct 2024
92. BMEL (Bundesministerium für Ernährung und Landwirtschaft) (2022) Ausgangslage der Landwirtschaft und des ländlichen Raums in Deutschland zur Erstellung des deutschen GAP-Strategieplans des Bundesministeriums für Ernährung und Landwirtschaft Art. https://www.bmel.de/SharedDocs/Downloads/DE/_Landwirtschaft/EU-Agrarpolitik-Foerderung/gap-strategieplan_anhang-II.pdf?__blob=publicationFile&v=2. Accessed 17 Oct 2024

Publisher's Note