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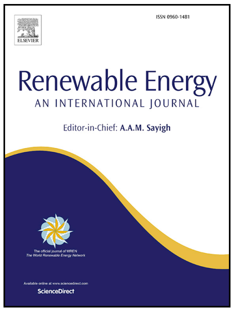

A novel socio-techno-environmental GIS approach to assess the contribution of ground-mounted photovoltaics to achieve climate neutrality in Germany

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Title:

A Novel Socio-Techno-Environmental GIS Approach to Assess the Contribution of Ground-mounted Photovoltaics to Achieve Climate Neutrality in Germany

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A Novel Socio-Techno-Environmental GIS Approach to Assess the Contribution of Ground-mounted Photovoltaics to Achieve Climate Neutrality in Germany

Highlights:

- The model considers climate aspects and integrates socio-technical and ecological criteria.
- The novel approach includes soil erosion and CO_2 release from the decomposition of organic matter.
- Ground-mounted PV meets at least 8.1% of Germany's electricity demand in 2045, using 0.4% of the country's land.
- The innovative approach of the model changes the preferred locations for Ground-mounted PV.
- The model can integrate stakeholders' local preferences and generate region-specific scenarios.

Abstract

The German government's goal of achieving climate neutrality by 2045 and increasing the use of renewable energy, particularly wind and solar power, has public support. However, the local siting of wind and solar farms is highly controversial due to land-use conflicts. We have developed a comprehensive Geographic Information System (GIS) model that integrates criteria from the literature to identify optimal locations for ground-mounted photovoltaic (GM-PV). The model is based on a holistic approach considering energy-related factors and broader environmental and climate considerations. It ensures that the shift in land use from food to energy production is consistent with the economic realities of both the agricultural and energy sectors. The unique feature of the model is its integration of socio-technical and environmental criteria, including a novel approach to achieving a dual land-use climate benefit by protecting erosion-prone soils and conserving soil carbon in areas prone to organic matter decomposition and associated CO_2 release. Our multi-criteria GM-PV model includes 12 restrictions and five suitability criteria representing key socio-technical and environmental aspects. Scenario analysis highlights the sensitivity of Germany's GM-PV potential to defined criteria. In Scenario 1, with minimal constraint, 14.2% of Germany's land is available for GM-PV, decreasing to 1.9% in the highly constrained Scenario 12. Suitable areas (>10 ha) account for 0.4% of Germany's land area, which could cover 8.1% of Germany's electricity consumption in 2045 in the highly restricted scenario. The spatial distribution results show that the innovative approach of the model changes the preference of GM-PV locations based on factors such as solar radiation in the south and soil carbon storage in the north of Germany. Assuming that plant size will become more critical to realise economies of scale in the future, and significantly influences land potential and visual impact on the landscape. The application of restriction and suitability criteria significantly reduces the potential for GM-PV in Germany but also potential pitfalls for decision-makers. The GIS model can be applied in regional and local contexts to integrate local stakeholder values and generate region-specific scenarios, as criteria and thresholds can be easily adapted to local characteristics, preferences, and concerns, including those related to agriculture, biodiversity, and societal acceptance.

Keywords: Energy transition, Climate change, Ground-mounted photovoltaic, Soil erosion, Peatland, Geographic information systems (GIS)

1. Introduction

Germany has set ambitious climate protection targets, aiming for climate neutrality by 2045, with interim targets of a 65% reduction by 2030 and an 88% reduction by 2040 compared to 1990 levels [1]. Seven federal states have additional targets, such as Baden-Württemberg's goal of achieving greenhouse gas neutrality by 2040 [2]. These targets are based on scientific scenario studies, including assessments of energy demand, efficiency, and different technologies (e.g. [3], [4], [5], [6], [7], [8], [8], [9], [10], [11], [12], [13], [14], [15] [17]). In 2022, 46.3% of Germany's electricity will be generated from renewable sources, with wind and photovoltaics contributing 24% and 11% respectively. The share of solar energy has increased from 0.1% in 2003 to 10% in 2021, with Germany having 59.2 GWp of installed photovoltaic capacity. While most solar installations are on rooftops, there's significant untapped potential on roofs, facades, and car parks (e.g. [16]). However, unlocking this potential is challenging due to the higher cost of small rooftop photovoltaic (PV) systems compared to ground-mounted photovoltaic (GM-PV).

In 2022, Germany had a remarkable 46.3% share of renewable electricity in its grid, with wind power contributing 24% and photovoltaics 11%. Despite the slow expansion of wind power due to lengthy approval processes, public protests, and nature conservation concerns, the solar energy sector is growing rapidly. The share of solar power in Germany's total electricity generation will rise from 0.1% in 2003 to an impressive 10% in 2021. With 59.2 GWp of installed photovoltaic capacity, Germany is one of the top countries in the world, alongside China, the US, and Japan [16]. While the majority of Germany's 2.2 million solar installations are currently on rooftops, there is immense untapped potential [17]. Around 400 GWp and 320 GWp could be installed on roofs, facades, and car parks respectively. However, unlocking this potential faces challenges as small rooftop PV systems are costlier and less economically attractive to investors compared to GM-PV.

GM-PV systems are seen as crucial for scalable, low-cost electricity ([17], [18], [19]). They occupy only 0.1% of German farmland, with 78% on arable land, 22% on pasture and 29% on converted military or industrial land. Regulatory changes in 2021 expanded the 'disadvantaged areas' eligible for GM-PV, and increased the size limit for GM-PV systems from 750 kWp to 20 MWp [20]. Solar energy, the world's most cost-effective renewable energy source, experienced an 80% cost reduction between 2010 and 2020 [21]. The future trend includes the deployment of GM-PV through power purchase agreements (PPAs), emphasising factors such as land availability, power lines and feed-in capacity. Project developers favour larger plants (> 20 MWp) for cost savings and profitability [22], leading to increased competition between solar energy and food production for land use [23].

The study attempts to develop an innovative socio-technical, value-based GIS model for the assessment of land constraints and suitability for GM-PV in Germany. The specificity of the model lies in the integration of socio-technical and ecological criteria, including a novel approach to achieve a dual land-use climate benefit by preserving soil carbon in areas prone to organic matter decomposition and associated CO_2 release. This is consistent with environmental considerations, in particular the ecological impact of peatland drainage. The main objective of the model is to facilitate the implementation of new GM-PV installations by harmonising the different interests of stakeholders and addressing public concerns. It also aims to ensure that the shift in land use from food to energy production is consistent with the economic realities of both the agricultural and energy sectors. The overall objective is to establish a comprehensive framework that promotes the sustainable integration of GM-PV systems into the existing socio-economic and environmental landscape. The inclusion of soil erosion as a suitability criterion for GM-PV reflects the holistic approach that considers not only energy-related factors, but also broader environmental and climate considerations. This is in line with the study's commitment to the responsible and sustainable use of renewable energy.

1.1. Literature review

A comprehensive review of both national studies and international literature was conducted to analyse the key parameters influencing the constraints and suitability of GM-PV. The results of this analysis highlighted that restrictive factors and their respective thresholds vary depending on regional characteristics such as infrastructure, legal framework, regulations, climatic conditions, topography and other relevant factors. The dynamic nature of these regional considerations emphasises the need for adaptable and context-specific criteria when assessing the viability of GM-PV installations.

1.1.1. National Studies and the EEG

Research on GM-PV in Germany is mainly embedded in studies that focus on renewable energy scenarios to meet national climate neutrality targets. Many scenarios assume a balanced ratio of 50% between rooftop PV and GM-PV ([14], [24], [25]).

Projections also assume an increase in the installed share of large-scale GM-PV from 34% to 50% by 2040, with some scenarios, such as the Association of German Industries scenario, assuming even higher growth to 83% of total installed PV capacities [26]. Günnewig et al. [17] estimate that to reach a capacity of 107 GWp by 2030, an additional 88,000 ha of agricultural land will be required, which is 0.6% of the German agricultural area. Böhm and Tietz [23] estimate that around 150,500 ha by 2030 and 280,000 ha by 2040, or 1.7% of the German agricultural area, will be required to meet the political targets of 215 GWp and 400 GWp installed capacity by 2030 and 2040 respectively. This assumes a specific GM-PV land use of 0.7 MWp/ha. The German Federal Ministry of Transport and Digital Infrastructure assumes a technical potential of 316,400 ha of unrestricted land for GM-PV, which corresponds to 1.9% of the German agricultural area. Their calculations assume a technical potential of 143 GWp at a density of 0.45 MWp/ha [30]. A study by Kelm et al. [18], which focused on land use regulations for GM-PV, concluded that up to 229,350 ha, or 1.38% of the German agricultural area, could be available for GM-PV. However, this study did not include yield calculations. These different estimates underline the complex and evolving nature of GM-PV land requirements in Germany.

In Germany, the installation of GM-PV is primarily regulated by the Renewable Energy Sources Act (EEG), which sets out suitability and restriction criteria. GM-PV located at least 200 meters from a highway or a railroad with at least two main tracks can be built without a land use planning procedure thanks to their privileged status in the German Building Code [27]. The permissible distance has been extended from 200 [20] to 500 metres [28]. In addition, the EEG 2023 subsidises GM-PV on rewetted peatlands [28]. The EEG addresses agricultural areas at risk of abandonment as defined by the Common Agricultural Policy (CAP). The redefinition of disadvantaged areas significantly increased their size [29]. The Open Space Ordinance (OSO) which was adopted as part of the EEG amendment, allows the federal states to extend the range of areas for GM-PV and to introduce caps to prevent excessive land use [30]. Some federal states, such as Saxony, Bavaria and Hesse, exclude not only protected biotopes and monuments, but also Natura 2000 areas from GM-PV cultivation. The EEG restricts eligibility to GM-PV systems with a capacity of up to 20 MWp [31].

Federal caps, as outlined in the German government's OSO under the EEG, play a role in limiting conflicts between GM-PV and other forms of land use. The introduction of caps helps to manage potential conflicts by placing regulatory constraints on the expansion of GM-PV, particularly in areas eligible for feed-in tariffs. As GM-PV becomes economically viable outside the feed-in tariff scheme, the importance of EEG-based land-use restrictions diminish [32]. Larger solar parks operating outside the EEG sell their electricity through Power Purchase Agreements (PPAs). At up to 8 cents/kWh, PPAs initially offer better returns than the EEG. However, the feed-in tariff under the EEG lasts for 20 years. PPAs have a much shorter term and therefore provide less planning certainty for PV projects. The changing economic landscape of GM-PV is influencing the regulatory considerations related to land use. Some federal states, such as Hesse, are incorporating regional planning principles to allocate a certain percentage of regional land to both wind energy and GM-PV. This supports a broader expansion of renewable energy in line with the state's climate protection goals.

Various national, federal or regional regulations contribute to the spatial deployment of GM-PV in Germany, taking into account environmental concerns, economic feasibility and regional planning considerations. In addition to the EEG, these regulations include land use designations and capacity targets. National, federal and regional regulations play a central role in guiding land use designation for GM-PV. In the area of land use designation for GM-PV, several regulatory measures have been implemented with regard to the principle of regional planning. For example, the state of Baden-Württemberg amended a land area target for GM-PV in 2020 to guide the spatial allocation of GM-PV installations [33]. In Hesse, regional plans require that at least 2% of the regional area be allocated to the use of wind energy and GM-PV (Hessian Energy Act). This allocation is in line with the broader objectives of the Hessian Energy Act and contributes to the expansion of renewable energy to meet the state's climate change targets. In Saarland, an amendment to the ordinance on the installation of photovoltaic systems on agricultural land increased the cap for GM-PV. The cap was increased from 100 MWp in 2022 to 350 MWp in 2025 [34]. This regulatory change corresponds to an expected land consumption of about 500 ha, which is about 0.5% of the agricultural land.

1.1.2. International studies

Numerous studies have examined suitable areas for GM-PV deployment and their potential in various contexts and scenarios. Spyridonidou and Vagiona [35] provide a systematic review of the siting processes for solar plants by analyzing 152 scientific studies and identifying 11 critical parameters including (1) site selection methods; (2) type, number, and exclusion limits of exclusion criteria; (3) type, number, importance, priority, and eligibility classes of evaluation criteria; (4) optimization modules and criteria; (5) geographic locations of studies; (6) spatial planning or reference scales; (7) estimation and analysis of solar radiation data; (8) sensitivity analysis related to the site selection process; (9) participatory planning approaches, groups and input; (10) laws, regulations, and policies related to the site selection process; (11) suitability indices. The international studies evaluated are compiled in Table 1 which shows the factors that limit the construction of GM-PVs. In comparison to the presented study, some other studies looked at a broader range of factors including distance from touristic zones, distance from sand dunes and sandy lands, distance from religious sites, distance from faults, livestock trails, relative humidity, population density, land ownership, land use discount factor, cloudy days, wet days, dusty days.

Furthermore, buffer zones around GM-PV plants have been considered in various investigations depending on the region's conditions due to possible implications, such as visual intrusions in rural settings and resistance among local communities and their residents ([36], [37], [38]). In Table 1, the restriction criteria considered together with the buffer zones are marked with an underlined tick.

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Table 1: Overview of restriction criteria considered in international studies

Reference	Year	Cases study	Roads	Waterways	Protected area	Forests	Agricultural/ Cultivated lands	Settlements	Military zones	Airports	Natural disaster (Flood Area, etc.)
[39]	2022	Germany	✓̲	✓̲		✓̲	✓	✓	×	✓	✓
[40]	2021	Germany	✓̲	×	✓	✓̲	✓	✓̲	✓	✓̲	×
[41]	2019	EU-28	✓	×	✓	✓	✓	✓	×	✓	×
[42]	2022	Germany	✓	✓	✓	✓̲	✓	✓̲	✓	✓	×
[43]	2023	Iran	✓̲	✓̲	✓̲	✓	×	✓̲	×	×	✓
[44]	2013	Western Turkey	×	✓̲	×	×	✓	✓̲	×	✓̲	×
[45]	2021	Libya	✓̲	✓̲	✓̲	✓	✓	✓̲	×	×	×
[46]	2007	Spain	×	×	✓	×	×	×	×	×	×
[47]	2020	Turkey	✓̲	✓̲	×	✓	✓	✓̲	×	×	×
[48]	2021	India	×	×	×	×	×		×	×	×
[49]	2020	Northern Ireland	✓̲	✓̲	×	×	×	✓̲	×	×	×
[50]	2017	Saudi Arabia	✓̲	×	✓̲	×	×	✓̲	×	×	×
[51]	2019	East Spain	×	×	✓	×	×	×	×	×	✓
[52]	2021	Turkey	✓̲	✓̲	×	×	×	✓̲	×	✓̲	×
[53]	2020	Iran	✓	×	✓	✓	×	×	✓	✓	×
[54]	2021	Iraq	✓̲	✓̲	✓̲	×	×	✓̲	✓̲	✓̲	×
[55]	2019	Arizona, USA	✓̲	✓̲	✓̲	×	×	✓̲	✓	×	✓
[56]	2019	Morocco	✓̲	✓̲	✓̲	×	✓̲	✓̲	×	✓̲	×
[57]	2016	Iran	✓̲	✓̲	✓̲	✓	✓	✓̲	✓̲	×	×
[58]	2020	Nigeria	✓̲	✓̲	×	×	✓	✓̲	×	×	×
[59]	2020	Greece	✓̲	✓̲	✓̲	✓̲	✓̲	✓̲	×	×	×
[60]	2021	Mexico	×	✓̲	✓̲	✓̲	×	✓̲	×	×	×
[41]	2021	Peru, South America	✓̲	✓̲	✓̲	✓̲	×	✓̲	×	✓̲	×
[61]	2013	Fujian, China	×	✓̲	✓	×	✓	×	×	×	×
[62]	2021	China	✓̲	✓̲	✓̲	✓̲	✓̲	✓̲	×	✓̲	×
[63]	2021	Turkey	✓̲	✓̲	✓̲	×	×	×	×	×	×
[64]	2018	Iran	✓̲	✓̲	✓̲	✓̲	✓̲	✓̲	×	×	×
[65]	2017	Ukraine	×	×	×	×	×	✓̲	×	×	×
[66]	2008	Spain	×	✓̲	✓	×	×	✓	×	×	×
[67]	2022	Turkey	✓̲	✓̲	✓̲	×	✓̲	✓̲	×	✓̲	×
[68]	2017	Turkey	✓̲	✓̲	✓̲	✓	✓	✓̲	×	×	×

✓̲: with buffer, ✓ without buffer

A compilation of previous international studies used to assess suitability criteria is given in Table 2. These studies typically include a set of five criteria, namely solar radiation, slope, land orientation, and proximity to power lines. The table highlights studies that used the Analytic Hierarchy Process (AHP) to weight suitability criteria, as this method was used in this study. Solar radiation was often the most heavily weighted variable in site selection studies. Easy access to GM-PV was considered relevant for the construction and operation phase [36].

Table 2: Overview of the suitability criteria's rank used in international research[1]

Reference	Year	Case study	Solar radiation	Land orientation	Proximity to power line	Slope
[69]	2017	Morocco	1	3	4	2
[50]	2017	Saudi Arabia	1	3	4	2
[70]	2019	Greece	3	1	3	2
[52]	2021	Turkey	1	2	3	4
[71]	2020	Egypt	1	3	4	2
[72]	2021	Turkey	1	3	2	4
[41]	2021	Peru	1	3	2	4
[47]	2020	Turkey	1	2	3	-
[73]	2021	Serbia	2	3	-	1
[74]	2022	Egypt	1	-	2	3
[65]	2017	Ukraine	-	1	2	3
[56]	2019	Morocco	-	2	1	-
[75]	2021	Iran	1	2	-	-
[76]	2020	Ethiopia	1	-	-	2
[57]	2016	Iran	1	-	2	3
[58]	2020	Nigeria	-	3	1	2
[60]	2021	Mexico	1	2	-	3
[77]	2016	Korea	1	-	2	3
[62]	2021	China	1	-	3	2
[78]	2020	Ukraine	3	-	2	1
[79]	2015	England	1	-	2	-
[80]	2021	Greece	-	-	1	-

[1]Ranking system 1st to 4th derived by AHP

2. Materials and methods

The developed methodology combines geographic information systems (GIS) and multi-criteria decision analysis (MCDA) in a unified process. The definition of restriction and suitability criteria is based on the legal framework, laws, legislation, and findings from the literature review (chapter 1). The process started with restriction scenarios, followed by suitability modelling, integration of the results, and elimination of smaller areas. The Analytic Hierarchy Process (AHP) was used to weight the criteria. Using the One-At-a-Time (OAT) Method. In the suitability model, areas were classified into five classes: 'particularly suitable', 'highly suitable', 'moderately suitable', 'marginally suitable', and 'not suitable', reflecting the relative importance of the criteria. The ultimate step was to estimate the total potential for electricity generation. Modelling and preprocessing were performed using ArcGIS Desktop 10.8.1, ArcPro-py3, and the Python site package arcpy. The overview of the GM-PV site selection workflow is presented in Figure 1

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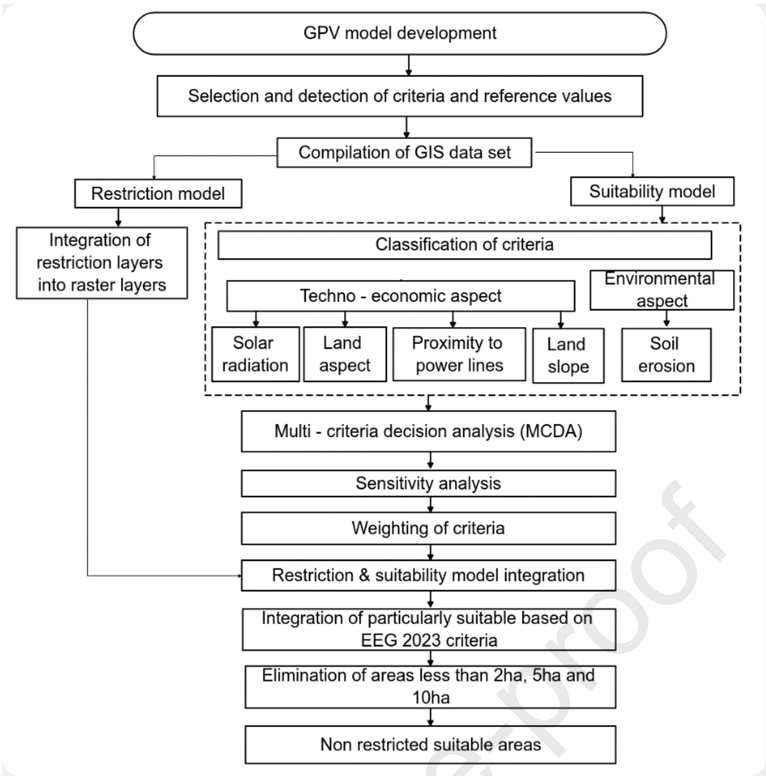

Figure 1: GM-PV model concept and workflow

2.1. Data

Since this model relies on GIS, all data used is geospatial. The quality and resolution of the feature representation in the dataset significantly affect the GIS-based analysis. We used the Official Topographic - Cartographic Information of Germany for the digital topographical geodata (ATKIS[1]) database due to its significantly higher resolution and accuracy. We used the Basis-DLM layers [81] with the relevant topographic objects, and the DGM10 [82]. The information is based on the content of the 1:25000 topographic map but has higher positional accuracy for the essential point and line objects [83]. The basic DLM describes agricultural areas, forests, residential areas, roads, etc. The DGM10 digital terrain model and data with a grid size of 10 meters [84] were used to generate slope and land orientation maps. Table 3 presents the data which are applied in this research.

Table 3: ATKIS (DLM & DGM) data used in the model

Settlement	Traffic	Vegetation	Water bodies	Public-law and other determinations	DGM 10
Residential area Industry & Commercial space Mining operation Open Pit Quarry Mixed use area Area of special functional character Sports leisure and recreation area Cemetery Buildings and facilities in settlement areas Special facilities in settlement areas	Streets (highways, federal, state, and other roads) Railway traffic Railway line Air traffic Ship traffic Structures, installations and facilities	Agriculture Forest Woodland[1] Heide Unland (unused) area without vegetation Moor[2] Sumpf[3] Area undeterminable at the moment Special vegetation features	Running water Watercourse Channel Water axis Harbor basin Standing water body[4] Special characteristics of water bodies	Nature Environment or Soil Conservation Law[5] Protected area according to nature, environment, or soil protection law Monument protection law[6] Miscellaneous Law (soil movement area, fracture field, military training area, military wasteland, sewage field, flood dike, main dike, harbour basin)	Digital terrain model grid width 10 m

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[1]Woodland is an area covered with individual trees, groups of trees, bushes, hedges, and shrubs.
[2]Moor is an uncultivated area whose upper layer consists of peaty or decomposed plant remains.
[3]Sump' is a waterlogged, temporarily submerged area.
[4]'Standing water' is a natural or artificial water-filled hollow form of the land surface enclosed on all sides with no direct connection to 'the sea'.
[5]Nature 2000 (2021 update) was used.
[6] This area is a biosphere reserve, i.e. a legally binding and uniformly designated area to be protected and developed.

German Weather Service (DWD) horizontal global radiation data in Germany-wide raster datasets with 1km resolution were used.

To protect biodiversity, in addition to the protected data from the basic DLM layers [81], which are in accordance with nature, environment and soil protection legislation, Natura 2000 data were also included. Natura 2000 is a coherent network of terrestrial and marine sites protected for the long-term survival of valuable, rare and threatened species and habitats in Europe.

The data on "Significant Landscapes in Germany" are used to identify landscapes of natural and cultural significance and their potential for tourism purposes [85] according to the Federal Nature Conservation Act (BNatSchG) [86]. The compiled national geo data from the Greifswald Moor Centre (GMC) based on the "MoorDialog" (2015-2019) [87] and the national geo map of organic soils [88] were used to model the spatial distribution of peatland in Germany.

The Soil Quality Rating (SQR) method, developed by the Leibniz-Centre for Agricultural Landscape Research (ZALF) and modified by the Federal Institute for Geosciences and Natural Resources (BGR), is used to assess soil suitability and yield potential at national and global scales. The BGR has defined six SQR classes: extremely low, very low, low, medium, high and very high. The SQR data is a freely available raster map [89]. It is important to note that this map includes arable land and excludes grassland.

2.2. The model part “Restriction”

In the "Restrictions" section of the GM-PV model, restriction layers are identified and excluded from the study area, taking into account the preservation of biodiversity, protection of high-quality soils, compliance with water protection regulations, preservation of statutory flood plains and maintaining distances from settlements and infrastructure. Table 4 illustrates the restriction layers, taking into account a buffer zone around a given layer. Biodiversity protection in Germany is regulated by various laws and regulations, in particular §1BNatSchG. Protected areas are designated under the BNatSchG (§23-28, §30 & §32BNatSchG) and include nature reserves, biosphere reserves, landscape conservation areas, nature parks, natural monuments, legally protected biotopes and Natura 2000 sites. Nature reserves and biotopes have the highest level of protection, while Natura 2000 sites have the lowest. The distances to protected areas considered in the different studies ranged from 100 m (e.g. [90]) to 2 km (e.g. [64]). Several studies did not consider specific distances around these areas; as GM-PV may contribute to increasing biodiversity, we did not consider buffer zones around nature reserves, biotopes or Natura 2000 areas. Water protection zones I and II were determined from the Basis-DLM layers [81] in accordance with water law.

Soil quality is of vital importance in the face of climate change and the demand for environmentally friendly, sustainable regional production systems. In our methodology, we explicitly restrict GM-PVs to high and very high-quality soils, which correspond to SQR values between 70 - 85 and SQR > 85 in the BGR classification, so restriction scenarios were developed to exclude arable land using the four remaining BGR classes: SQR > 35, SQR > 50, SQR > 60 and SQR > 70.

GM-PV are subject to considerations of public interest and environmental impact and should not contradict the land-use plan or impair the natural character of the landscape and its recreational value [27]. Compliance with established land-use plans is essential to harmonise GM-PV projects with local development goals. Significant landscapes, as identified by the Federal Agency for Nature Conservation

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(BfN), serve as criteria for landscape restrictions. These landscapes are considered part of the natural and cultural heritage and should be permanently preserved, developed and restored. The significant landscapes in Germany, provided by the BfN, have been used as landscape restriction criteria. These landscapes are part of the natural and cultural heritage and are to be permanently preserved, developed and, if necessary, restored. To avoid conflicts with local residents, the distance from settlements is crucial [91]. Considerations regarding distances from residential or commercial areas include anticipating future urban growth to ensure that GM-PV installations are in line with evolving local development plans. Three buffer zones are applied: 100 [90], 200 [92] and 400 [55] meters from residential areas.

The use of GM-PV is subject to safety regulations, and certain safety distances from various infrastructures are required by existing legislation. Buffer zones around infrastructure are excluded based on the following legislative guidelines: A buffer zone of 40 metres is maintained around motorways according to the Federal Roads Act (FStrG) [93], in particular FStrG §9. For federal roads, a buffer zone of 20 metres is implemented, based on FStrG §10. A safety distance of 4.5 metres is maintained around railways in accordance with the Railway Construction and Operation Regulations (EBO) [94], in particular EBO §10. A safety distance of 1.5 kilometres is maintained around airports in accordance with the Air Traffic Act (LuftVG) [95], in particular LuftVG §10. A buffer zone of 5 metres is maintained around rivers, based on the Water Resources Act (WHG) [96], specifically WHG §10. In addition, military areas are excluded from GM-PV considerations. The security perimeter around these areas is usually taken into account and fenced off by the responsible organisation, so that an additional security perimeter around military areas is not necessary. These exclusion zones ensure compliance with security regulations and minimise potential risks associated with the proximity of GM-PV facilities to critical infrastructure. This approach is consistent with the broader goal of ensuring the safe and orderly deployment of renewable energy infrastructure.

The regional planning of the German state of Rhineland-Palatinate [97] recommends buffer zones around forests with specific distances based on the avoidance of tree shading. The recommended distances are one tree length (30 m) to the north, six tree lengths (180 m) to the south and three tree lengths (90 m) to the west or east. To provide a consistent approach, a buffer zone of 100 m has been chosen to represent the average of the recommended distances. This choice is in line with research conducted by the Reiner Lemoine Institute [40]. The buffer zone is crucial to mitigate shading effects from trees and to ensure optimal solar exposure for GM-PV installations. Table 4 compares the buffer zone applied in the GM-PV model with international values, showing significant differences in the recommended distances. After applying the buffer zone, all layers in the GM-PV model are converted to binary layers. This conversion facilitates the development of a GIS-based restriction model where restriction sites are represented by zero and non-restriction sites by one. The single restriction layer is generated by integrating all relevant layers, providing a comprehensive spatial representation of areas suitable or unsuitable for GM-PV installations based on various criteria, including buffer zones and other restriction factors.

Table 4: Restriction layers and consideration of buffer zones

Restriction geo layers	Buffer zones (m)	
	Current research	International research[3]
Highways	40 [1]	
Federal roads	20 [1]	
Other types of roads	10 [1]	0 - 1,000
Railroads (single tracks)	10.5[1]	
Railroads (double tracks)	15 [1]	
Waterways	5[1]	0 - 2,500
Forests	100	0 - 1,000
Protected areas	-	0 - 2,000
Arable land	-	0 - 1,000

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Settlement areas	100 - 400	0– -5,000
Airports	1,500 around the center	0 - 5,000
Military zones	-	0 - 500

1: The width is not included. 3: based on the research presented in Table 1.

The development of the restriction model is based on different scenarios that vary in the size of the buffer zone around settlements and the SQR threshold for the exclusion of arable land. Considering three buffer zones around settlements and four SQR classes, 12 scenarios (Figure 2) were implemented in the restriction model.

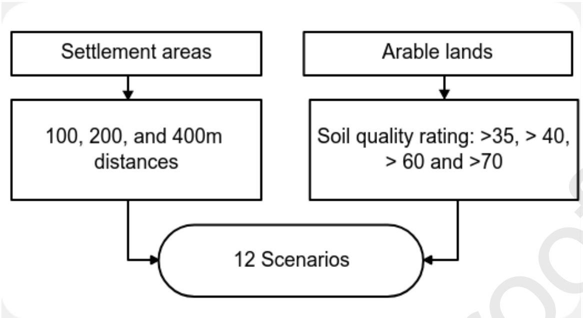


Figure 2: Variation of restrictions scenarios for the GM-PV model

2.3. The model part "Suitability"

This study is the first to analyse suitability in Germany, although several studies have examined the eligibility of land for GM-PV. In the GM-PV suitability part, we considered five aspects: solar radiation, proximity to power lines, land orientation, slope and soil erosion. As the steeper the slope, the higher the investment and running costs, flat land or gentle slopes are the most suitable locations for GM- PV [45]. Areas with a slope >= 15% are considered unsuitable for PV. The distance to the nearest available power line with free capacity is an important aspect of techno-economic suitability ([36], [98]). The greater the proximity to the existing power line, the lower the transmission costs and power losses ([50], [99]). In addition to economic considerations, short distances can limit the impact on nature and landscape. Proximity to roads and average annual air temperature are less relevant due to the generally well-developed road network and moderate temperatures compared to other countries. The average annual air temperature in Germany is below 25°C [100], which is the threshold at which the efficiency of the PV potential decreases. Nevertheless, in certain cases in rural areas and during hot summers, these two parameters may influence the site selection.

The inclusion of soil erosion as a site suitability criterion for GM-PV is a well-reasoned and environmentally conscious decision. It is based on the negative impact on soil fertility and the yield capacity of sites for food production, and is consistent with the study's commitment to addressing critical agricultural and environmental challenges while promoting sustainable renewable energy practices. Inappropriate farming practices, such as the use of heavy machinery and erosion-promoting ploughing on slopes, contribute to these problems. Soil erosion in Germany is estimated at more than three tonnes per year on almost 15% of arable land, and anticipating the exacerbation of soil erosion problems due to climate change underlines the forward-looking approach of the study. By analogy with the more holistic EEG regulations on peatland, GM-PV could also receive additional benefits in the future when installed on soils with an increased risk of erosion. The use of data from the German Federal Institute for Geosciences and Natural Resources (BGR) [101] lends credibility and a scientific basis to the soil erosion suitability criterion, reinforcing the data-driven nature of the study.

The suitability criteria were classified based on different aspects, e.g. geographical characteristics, data distribution, data coverage and expert interviews (Figure 3). The suitability criteria are weighted using a GIS-integrated AHP approach [102] to systematically deal with the different geographical information and ranking criteria and to identify the best sites for GM- PV [50]

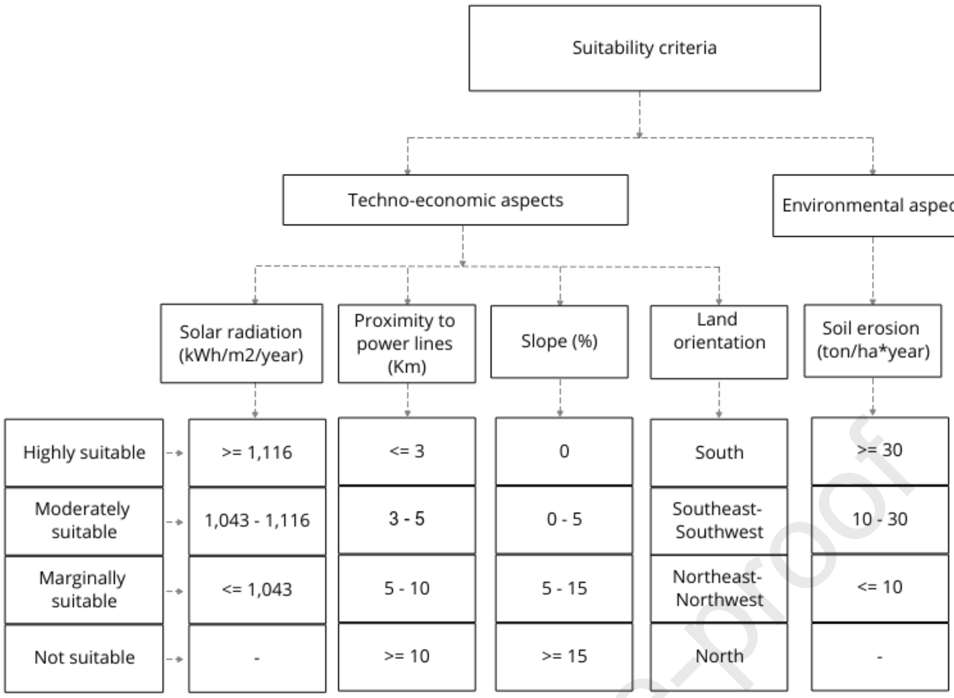


Figure 3: Suitability criteria applied in the GM-PV model and their classification

In addition to the four classes shown in Figure 3, there is a fifth class called "particularly suitable", which is based on the suitability criteria of the EEG 2023 [28] and includes areas within 15 to 500 meters along highways and double-track railroad lines and rewetted peatlands (see chapter 1).

By integrating the restriction and suitability models, we created a geographical distribution map of potential GM-PV sites categorized into five suitability classes: not suitable, marginally suitable, moderately suitable, highly suitable, and partially suitable. The possible GM-PV area was further investigated to analyze the share of the area that belongs to different size classes since economies of scale in equipment and installation costs mean that larger GM-PVs typically result in lower costs per unit of power generated ([103], [104]). Therefore, we excluded areas smaller than 2, 5 and 10 ha. The size of the GM-PV plant (> 2, > 5, > 10 ha) is not a purely techno-economic criterion, but also a social one, because people do not want fragmented GM-PV (many small plants distributed all over) or large GM-PV nor do they want it to be visible from their doorstep or as a fenced-in technical artifact in their recreational surrounding [105].

2.3.1. Sensitivity analysis

Based on the selected suitability criteria classification, most of Germany's agricultural area (except land orientation) have high and moderate suitability classes (+70%), the impacts of changing the weighting of the suitability criteria in the high and moderate suitability classes were investigated. Therefore, the One At a Time (OAT) method [106] was used to perform the sensitivity analysis. This method is commonly used for sensitivity analyses to select sites for PV ([107], [108], [104]). 40 scenarios were examined using eight different weighting schemes (10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80%) for each criterion, with all other criteria equally weighted. To check the impact on the classified suitability criteria, the weighting was changed from 30% to 60% (Table 5). The most meaningful change is +42%, which correlates with soil erosion in the moderately suitable class. Following the soil erosion criterion, the most notable change is linked to the proximity to power lines. The influence of the change in the weight of solar radiation and slope is in the third order of magnitude. The land orientation criterion is the last effective criterion from the sensitivity analysis.

Table 5: Effect of the changes in criteria weights on suitability category areas

Criteria	Moderately suitable			Highly suitable		
	30%	60%	Changes %	30%	60%	Changes %
Slope	66	50	16	9	21	-12
Soil erosion	60	18	42	23	58	-35
Proximity to power lines	60	28	32	23	50	-27
Solar radiation	61	45	16	22	32	-10
Land orientation	67	63	4	16	13	3

However, the reduced sensitivity of the model to changes in solar radiation and the orientation of the ground should not be taken to mean that these factors no longer play a role in the decision-making process. It should be noted that sensitivity analysis is not always the most effective decision-making tool. In GIS-based sensitivity analysis, the characteristics and geographical distribution of the data can influence the results. Although the OAT method provides a simple spatial analysis, it was considered insufficient for determining the final weight of the criteria in this study due to the limited consideration of critical effects. The final weighting in the AHP method was based on the expertise of the authors in the context of the literature and sensitivity analyses and is considered to be more consistent with the risk-free scenario of the same weighting. Approximately 30 studies with different numbers of suitability criteria were analyzed. These were converted to a common five-criteria scale for comparison with the GM-PV model. The average weights of these studies were transformed into a percentage scale. These criteria were weighted as follows: solar radiation 46.7 %, proximity to power lines 22.2 %, land orientation 20.5 %, slope 9.6 %, and soil erosion ~1 %. An initial weighting scheme was established, and weights were adjusted to keep the consistency ratio (CR) below 0.1, considering the sensitivity of each criterion determined by sensitivity analysis. The final weights for the suitability criteria are as follows: solar radiation (0.42), proximity to a power line (0.32), land orientation (0.12), slope (0.09), and soil erosion (0.05).

3. Results

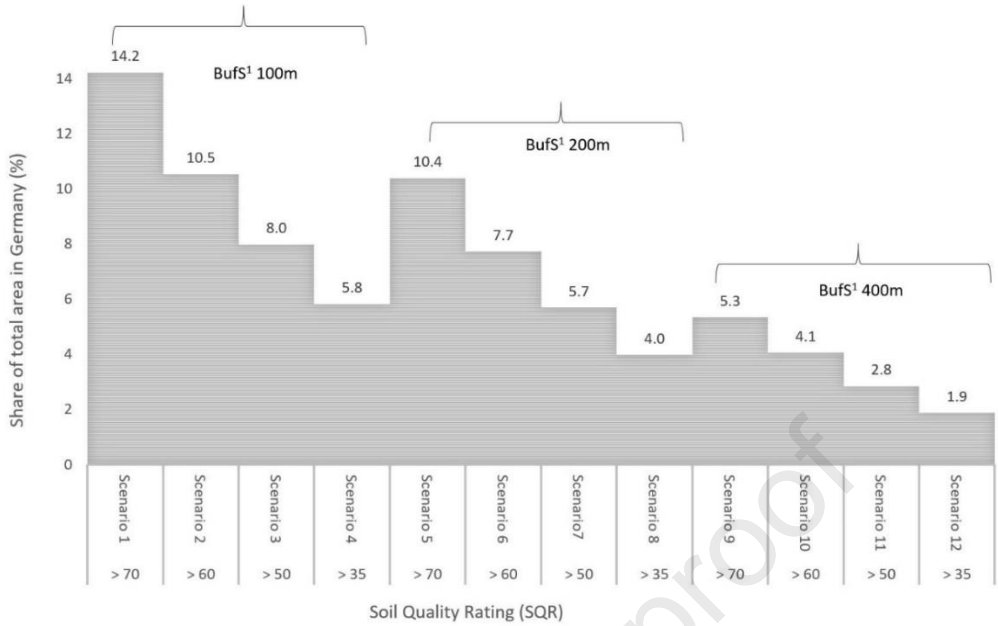
The results for the different restriction factors are shown in Table 6.

Table 6: Share of restriction areas in Germany in total area to the restricted factors[1]

Restriction layers	Scenarios	Restriction area (%)
Roads	-	9.7
Waterways	-	2.3
Forests	-	49.1
Protected area	-	37.1
Arable land	SQR > 70	8.7
	SQR > 60	17.4
	SQR > 50	23.3
	SQR > 35	28.8
Settlement area	Buffer zone 100 m	26.8
	Buffer zone 200 m	40.5
	Buffer zone 400 m	61.9
Airports	-	2.7

1-These restrictions have areas that overlap.

Figure 4 illustrates the assessment results for the 12 scenarios. The figure displays a range between 1.9% (Scenario 12) and 14.2% (Scenario 1) of non-restricted areas.



[1]BufS: Buffer zone around settlement areas

Figure 4: Share of non-restricted areas for GM-PV in different scenarios

To illustrate the reduction in potential GM-PV areas from Scenario 1 to Scenario 12, we have presented five scenarios for comparison. These scenarios are Scenario 1 (weak restrictions, SQR > 70, 100 m buffer zone around settlements), Scenario 12 (highest restrictions, SQR > 35, 400 m buffer zone around settlements), Scenario 3 (SQR > 50, 100 m buffer zone around settlements), Scenario 7 (SQR > 50, 200 m buffer zone around settlements) and Scenario 11 (SQR > 50, 400 m buffer zone around settlements), which represent moderate restrictions. Eliminating areas smaller than 2, 5, and 10 ha leads to a significant reduction in the potential GM-PV area. Across all suitability categories, eliminating parcels smaller than 2, 5, and 10 ha corresponds to reducing the potential GM-PV by approximately 1.7%, 3.1%, and 4.4%, respectively. The results of the scenario assessment show how the restrictions impact the potential of non-restricted suitable areas for GM-PV, considering deleting small areas of less than 2, 5, or 10 ha, (Table 7).

Table 7: Classified suitable areas for GM-PV of total German area (in %)

Suitability classes	Scenario 1	Scenario 3	Scenario 7	Scenario 11	Scenario 12
No elimination					
Particularly suitable	1.96	1.57	1.18	0.64	0.60
Highly suitable	1.79	1.21	0.79	0.33	0.23
Moderately suitable	7.48	3.77	2.70	1.36	0.71
Marginally suitable	0.78	0.26	0.18	0.09	0.07
Areas < 2 ha are eliminated					
Particularly suitable	1.65	1.29	0.97	0.53	0.49
Highly suitable	1.35	0.86	0.54	0.22	0.14
Moderately suitable	6.40	2.95	2.12	1.07	0.49
Marginally suitable	0.60	0.19	0.13	0.06	0.05
Areas < 5 ha are eliminated					
Particularly suitable	1.20	0.90	0.68	0.37	0.34
Highly suitable	0.88	0.53	0.32	0.12	0.08
Moderately suitable	5.20	2.10	1.52	0.78	0.30
Marginally suitable	0.46	0.12	0.08	0.04	0.03
Areas < 10 ha are eliminated					
Particularly suitable	0.76	0.54	0.41	0.23	0.21
Highly suitable	0.43	0.25	0.14	0.05	0.03

Moderately suitable	3.99	1.38	1.01	0.54	0.16
Marginally suitable	0.31	0.07	0.04	0.02	0.01

Figure 5 displays three different restriction scenarios as GIS maps to illustrate the spatial differences in suitable areas for GM-PV between Scenario 1 (weak restrictions), Scenario 7 (moderate restrictions), and Scenario 12 (highest restrictions).

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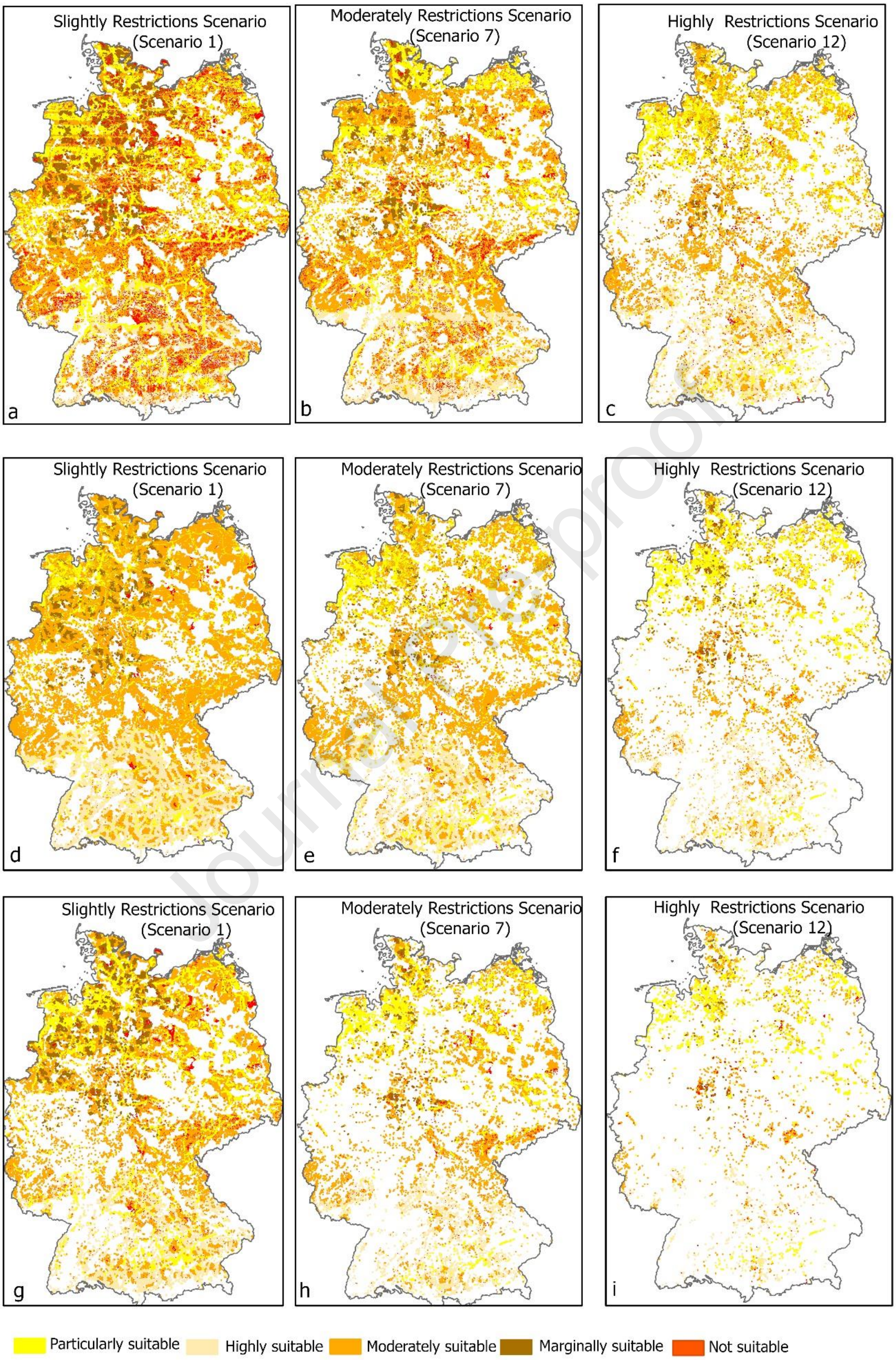

Figure 5: Non-restricted suitable areas for GM-PV in Germany for the scenarios S1, S7, and S12 with deletion of small size areas of < 2 ha (a-c), 5 ha (d-f), and 10 ha (g-i)

The distribution of suitability classes is uniform across all nine maps. Moderate suitability predominates, with scattered areas in central and northern Germany, in Mecklenburg-Western Pomerania and Schleswig-Holstein. Highly suitable areas are found in southern Bavaria, Baden-Württemberg, Rhineland-Palatinate, Saarland, and parts of eastern Brandenburg, where solar radiation is a major determinant. Due to the presence of moors, particularly suitable areas are found in the northwest of Germany. In contrast, other suitability categories are less pronounced in the north-western regions, especially in North Rhine-Westphalia and Saxony. This is due to the distance from the power lines. In the states of Berlin, Bremen, and Hamburg, no areas are suitable for GM-PV in the highly restriction scenarios (Figure 5 c, f & i), mainly due to dense residential development.

Energy production can be easily assessed based on the scenario results. However, there are significant differences regarding the possible electricity production (MWp) per unit of area (ha). These differences are among others based on distances between the module rows and the fence and required compensatory measures. The range in electricity production per hectare (ha) varies between 0.42 [109] and 1.05 MWp [17]. Table 8 displays the potential electricity production based on the assumption of 0.45 MWp/ha [110]. This value corresponds with the integrated land use approach for GM-PV (keyword: biodiversity GM-PV) and acknowledges their potential to provide not only regional renewable energy but also ecosystem services such as promoting biodiversity and landscape integration. Nevertheless, with enhanced technology, the productivity of GM-PV could rise to 1.4 MWp/ha by 2030 [17]. The calculation in Table 8 assumes the generation of about 1,000 kWh of electricity per kilowatt peak (kWp) per year [111].

Table 8: Potential electricity production by GM-PVs in Germany (TWh)

Suitability classes	Scenario 1	Scenario 3	Scenario 7	Scenario 11	Scenario 12
No elimination					
Particularly suitable	315.7	252.7	155.6	103.5	96.1
Highly suitable	287.7	194.3	87.5	52.3	37.0
Moderately suitable	1202.4	606.5	340.3	218.3	114.9
Marginally suitable	125.2	42.6	20.2	13.9	11.0
Areas < 2 ha are eliminated					
Particularly suitable	265.7	206.7	188.4	84.8	78.0
Highly suitable	217.8	138.2	105.0	34.7	23.2
Moderately suitable	1029.6	474.4	272.9	172.3	79.4
Marginally suitable	96.3	29.8	24.7	9.3	7.2
Areas < 5 ha are eliminated					
Particularly suitable	193.5	144.6	108.8	59.9	54.4
Highly suitable	141.7	85.0	51.4	19.5	12.6
Moderately suitable	836.1	338.2	244.1	125.6	48.2
Marginally suitable	73.3	19.8	13.1	5.8	4.3
Areas < 10 ha are eliminated					
Particularly suitable	122.0	87.1	65.6	37.4	33.4
Highly suitable	69.3	39.9	22.3	7.5	4.7
Moderately suitable	641.5	221.7	162.9	86.7	25.2
Marginally suitable	49.4	11.3	7.1	2.9	2.1

In 2021, the electrical energy consumption in Germany was 511.59 TWh, and photovoltaics had a share of 8.8% in generating electrical energy [112]. With the expansion of GM-PV, their percentage in the provision of electrical power under the assumption that the consumption of electrical energy is equal to the year 2021 is presented in Table 9. Under Scenario 1, the least restrictive, GM-PV could not only meet Germany's electricity demand but also facilitate energy transmission to other countries. Based on Scenario 12, the most restrictive, GM-PVs on suitable sites could meet, depending on the GM-PV size, about 12% – 50 % of Germany's electricity demand regarding electric energy compared to energy consumption in 2021 [112].

Table 9: Share of GM-PV electricity production to electricity consumption in 2021 (%)

Suitability classes	Scenario 1	Scenario 3	Scenario 7	Scenario 11	Scenario 12
No elimination					
Particularly suitable	61.7	49.4	30.4	20.2	18.8
Highly suitable	56.2	38.0	17.1	10.2	7.2
Moderately suitable	235.0	118.5	66.5	42.7	22.5
Marginally suitable	24.5	8.3	3.9	2.7	2.2
Areas < 2 ha are eliminated					
Particularly suitable	51.9	40.4	36.8	16.6	15.2
Highly suitable	42.6	27.0	20.5	6.8	4.5
Moderately suitable	201.3	92.7	53.3	33.7	15.5
Marginally suitable	18.8	5.8	4.8	1.8	1.4
Areas < 5 ha are eliminated					
Particularly suitable	37.8	28.3	21.3	11.7	10.6
Highly suitable	27.7	16.6	10.0	3.8	2.5
Moderately suitable	163.4	66.1	47.7	24.6	9.4
Marginally suitable	14.3	3.9	2.6	1.1	0.8
Areas < 10 ha are eliminated					
Particularly suitable	23.9	17.0	12.8	7.3	6.5
Highly suitable	13.6	7.8	4.4	1.5	0.9
Moderately suitable	125.4	43.3	31.9	16.9	4.9
Marginally suitable	9.7	2.2	1.4	0.6	0.4

Given the projection that electricity consumption in Germany will increase by more than 60% by 2045 [113], Table 10 shows the projected percentage of German electricity consumption in 2045 that would be covered by GM-PV electricity generation on the assumption that total electricity consumption in 2045 is 818.5 TWh. The results of all scenarios are available in the supplementary material (Table S 1 to S 4).

Table 10: Share of GM-PV electricity production to electricity consumption in 2045 (%)

Suitability classes	Scenario 1	Scenario 3	Scenario 7	Scenario 11	Scenario 12
No elimination					
Particularly suitable	38.6	30.9	19.0	12.6	11.7
Highly suitable	35.1	23.7	10.7	6.4	4.5
Moderately suitable	146.9	74.1	41.6	26.7	14.0
Marginally suitable	15.3	5.2	2.5	1.7	1.3
Areas < 2 ha are eliminated					
Particularly suitable	32.5	25.3	23.0	10.4	9.5
Highly suitable	26.6	16.9	12.8	4.2	2.8
Moderately suitable	125.8	58.0	33.3	21.1	9.7
Marginally suitable	11.8	3.6	3.0	1.1	0.9
Areas < 5 ha are eliminated					
Particularly suitable	23.6	17.7	13.3	7.3	6.6
Highly suitable	17.3	10.4	6.3	2.4	1.5
Moderately suitable	102.2	41.3	29.8	15.3	5.9
Marginally suitable	9.0	2.4	1.6	0.7	0.5
Areas < 10 ha are eliminated					
Particularly suitable	14.9	10.6	8.0	4.6	4.1
Highly suitable	8.5	4.9	2.7	0.9	0.6
Moderately suitable	78.4	27.1	19.9	10.6	3.1
Marginally suitable	6.0	1.4	0.9	0.4	0.3

4. Discussion

GM-PV planning, taking into account economic, environmental and societal factors, is a highly complex issue and it is therefore important to have a sophisticated and robust model that considers the

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opportunities and challenges associated with the siting and potential of GM-PV installations in Germany, integrating different criteria and taking into account the evolving landscape of legislation and public opinion.

GM-PV is economically preferable to rooftop systems due to its lower levelized cost of energy, which is about half that of rooftop systems, making it more attractive from a techno-economic perspective [114]. There is general agreement that GM-PV should be placed on sealed or contaminated land to avoid further fragmentation of the landscape and competition for land use with food production [115]. Areas not yet used for GM-PV (conversion areas) are considered techno-economically unattractive due to factors such as size and distance from power lines [23]. Public debates at national, regional and local level in Germany are taken into account in the developed GM-PV model, which uses a GIS-AHP method. Criteria include known techno-economic and environmental aspects, as well as novel criteria considering renewable energy production combined with the use of the area as a permanent natural carbon sink.

The German government has established planning guidelines for the allocation of land for wind energy and GM-PV installations and a certain percentage of the country's land area for wind energy and GM-PV. Specifically, 2% of the state's land area is designated for wind energy and GM-PV, of which 1.8% is designated for wind energy and 0.2% for GM-PV. Higher specific federal targets imply fewer restrictions for GM-PV. Under the most restrictive scenario, and considering only particularly and highly suitable sites, GM-PV could cover 0.8% of Germany's land area. If small areas (< 5 ha) are not taken into account, the coverage would be reduced to 0.4% of the area. The land coverage scenarios translate into a share of electricity demand in 2045, with 0.8% covering 16.2% and 0.4% covering 8.1%. The results suggest that under different scenarios and constraints, GM-PV has the potential to cover a percentage of Germany's land area and contribute to a significant share of electricity demand in 2045.

GM-PV installations are a potential solution with a double climate benefit and an option to balance agricultural, environmental and climate considerations in the context of drained peatlands in Germany. Drained peatlands in Germany contribute significantly to greenhouse gas emissions, accounting for 37% of all agricultural emissions, despite occupying only 7% of agricultural land. Drained peatlands release about 53 million tonnes of greenhouse gases annually, which is 7.5% of Germany's total greenhouse gas emissions [116]. Large-scale drainage for settlement, forestry and agriculture, as well as peat extraction for energy production, has turned peatlands from carbon sinks into CO_2 emitters. Germany originally had 1.8 million hectares of peatland, but more than 95% of this has been drained since the 17th and 18th centuries. Two-thirds of Germany's drained peatlands are now used for agriculture, mainly for livestock and fodder production, with significantly higher emissions than traditional mineral soils. About 1.8 million hectares, or 5.14% of Germany's total area, are peatlands, of which about 50% is grassland and 20% is arable land [88]. Agricultural use has led to a tenfold decrease in peatland area, contributing to environmental and climate change. Rewetting of drained peatlands has been proposed as a solution to both the transition to renewable energy and the reduction of greenhouse gas emissions. Germany has set targets for the rewetting of peatlands, aiming to rewet 50,000 hectares per year by 2045. A target agreement was signed in 2021 to reduce annual greenhouse gas emissions from peatlands by five million tonnes of CO_2 equivalents. The EEG 2023 provides government support for peatland GM-PV [28]. Wirth [122] estimated the technical potential of 1.1 million ha of agricultural peatlands for GM-PV, while the current study estimates that 0.1 to 0.2 million ha are suitable for large-scale GM-PV (> 10 ha). The second innovative approach taken in this study introduces peatlands soil erosion as new criteria to address the climate benefits of protecting erosion-prone soils and conserving soil carbon in areas prone to organic matter decomposition and associated CO_2 release, setting it apart from other assessments. While soil erosion is recognised as an eligibility criterion, its low weighting among the five criteria is attributed to initial considerations and lack of public and political support in the EEG. This study serves as an important starting point for incorporating soil erosion into the GM-PV model, with the potential for increased importance in future assessments. These changes are expected to change the GM-PV potential and its spatial distribution in Germany.

The comparison with other studies ([40], [42]) shows differences in assumptions, methodology and selection of criteria, leading to variations in the estimated GM-PV potential. Scenario 4 (SQR < 35, 500 m along highways and railways, 100 m from settlements, size >10 ha) is consistent with their assumptions (SQR < 40, 500 m along highways and railways, minimum size 10 ha). The potential in scenario 4 (about 0.17 million ha) is significantly lower (0.34 million ha), mainly due to the exclusion of restricted areas along motorways and railways. The total of the other suitability classes of Scenario 4 (high, moderate and marginal) is about 0.3 million ha, mainly low-quality arable land and grassland, in contrast to the 0.41 million ha estimated by the Reiner Lemoine Institute [40]. Risch et al. [42] estimated a potential of 0.57 million ha for Scenario 1 with 200 m distance to motorways and railways but no soil quality restriction, 0.16 million ha for Scenario 2 considering SQR < 30 and 0.44 million ha for the combined Scenario 3. A direct comparison of these estimates with our results is not possible because of the different sizes of verges along motorways and railways (200 m compared to 500 m in this study), different SQR thresholds and buffer zones around settlements (10 m compared to 100, 200 and 400 m in this study). In addition, the Reiner Lemoine Institute [40] and Risch et al. [42] did not include peat and erodible arable land in their estimates.

The accuracy of the databases used to analyse the GM-PV potential has a significant impact on the results, as shown by the different results when different land use databases are used. For example, the study by Risch et al. [42] used three land use databases (DLM basic, Open Street Map (OSM) and CORINE Land Cover), showing that the result of the GM-PV potential analysis depends on the land use database used. The Reiner Lemoine Institute [40] used OSM for settlements and Risch et al. [42] used Hausumringe data for buildings. To validate the estimates, scenario 7 (GM-PV > 5 ha) was compared to existing PV installations with >5,000kW [117]. The result of the overlay shows that a significant proportion of these are located outside the areas identified by the GIS model (Figure S 1 in the Supplementary). Although the two datasets are not directly comparable due to their different presentation (polygons for the suitability map and points for the map of installed PV systems), the comparison underlines the need for a regulated, value-based land designation for GM-PV to prevent and regulate otherwise uncontrolled growth, which could quickly lead to declining public acceptance.

Further research is needed to integrate additional criteria, such as agricultural priority areas, into the GM-PV model to address structural and techno-economic demands on land. Challenges include competition for priority areas between agriculture, water protection and renewable energies, and exemptions from restrictions on the use of agricultural priority areas in federal and regional land development programmes [118]. Concerns have been raised about favouring GM-PV at the expense of food production and biodiversity. Legislative changes in some regions allow GM-PV on flood plains if flood protection is ensured. However, legislation is shifting towards prioritising renewable energy production as a "public interest", which has been criticised by nature conservation and farming groups concerned about the impact on food production and biodiversity([119], [120], [121]). There is also ongoing discussion about GM-PV buffer zones around farms for future development to support animal welfare and circular bioeconomy goals. Furthermore, flood plains, which have traditionally been restricted in many German states and in this study, are now defined as possible areas for GM-PV by the Federal Council, which has approved a Bavarian draft amendment to the Water Resources Act (WHG) that allows GM-PV on flood plains if flood protection is guaranteed [122].

The lack of available data at the national level led to a focus on soil quality and the designation of high-quality farmland as a restricted area. The SQR method characterises agricultural soils according to their properties and determines their yield potential on a national and global scale. The SQR expresses the ratio of the yield capacity of a given area to the most productive area, with a value of 100 for arable land and 88 for grassland, based on different parameters for both types of land use. SQR at national level is only available for arable land, so grassland was considered suitable for GM-PV regardless of its value for livestock and feedstock production. Another limitation of this study is that we did not consider that poor soils with low SQR can be of great agro-economic benefit to farmers, as they can grow certain high value-added crops, such as strawberries and asparagus, on these e.g. sandy soils because they warm up quickly in spring. In addition, we have not taken into account a buffer zone around livestock and non-livestock farms, despite the proposals for spatial distance regulations of 400 m and 200 m respectively. To support animal welfare and circular bio-economy goals [97], and to allow for future development of farms, because we did not have access to geospatial data to delineate farms from livestock farms.

GM-PV projects up to the maximum size of 20 MW and above 1,000 kW can participate in the tenders of the Federal Network Agency for EEG funding [28]. This study considers different sizes (>2, >5 and >10 ha) of GM-PV sites, but does not regulate their regional distribution, e.g. by defining a minimum distance between two GM-PV sites to avoid overloading a region with GM-PV projects [123]. The small plant size can generate a reasonable economic return and is of interest to commercial investors. The large plant is limited to 10 MW in order to address public concerns about large-scale GM-PV installations, which have already been taken into account in the size limitation of the EEG 2012 [124]. However, with the amendment of the Energy Security Act in 2022, plants of up to 100 MW can now participate in the tendering process [125]. This increase in the permitted plant size in the EEG is being debated. In the past, as the efficiency of module technologies has increased, the land requirement has decreased from 3.56 ha per MW in 2010 to 2.25 ha/MW in the years 2011 to 2013 [126]. Depending on row spacing, orientation and topography, the value is between 0.9 and 1.4 MW per hectare. Brandenburg is the German state with the most large-scale installations, with 40 installations of more than 20 ha each (eight of which are larger than 100 ha).

The results of the model are a theoretical potential and do not reflect the opportunities and challenges of connecting particularly large-scale GM-PV installations to the grid without overloading and disrupting the capacity, capabilities and constraints of the local grid. A long and new grid cable route, or obstacles such as roads and watercourses, may result in additional costs and jeopardise public acceptance. For the purposes of this study, it was not possible to obtain information from regional grid operators in Germany on available medium-voltage grid capacity and planning for new substations. As a result, we were not able to include these key techno-economic suitability criteria in our model and determine how much energy could theoretically be integrated into Germany's existing power lines and identify opportunities to improve and expand the power system to accommodate energy from future GM-PV installations. The lack of comprehensive planning for the generation and feed-in of GM-PV electricity, coupled with uncertainties about the stability of future power lines, pose challenges. In response to these challenges, German energy companies and municipal utilities are building hybrid plants that combine GM-PV and energy storage.

5. Conclusions

The study presents an innovative GIS model for assessing land restrictions and suitability criteria for GM-PV installations in Germany. The model integrates socio-technical and ecological criteria, addressing stakeholder interests and public concerns while taking into account broader environmental and climate factors. In particular, it introduces a dual climate benefit approach by conserving soil carbon in areas prone to erosion and rewetting of peatlands. The model emphasises the economic realities of the agricultural and energy sectors and modifies GM-PV preferences based on factors such as soil carbon storage. It proves adaptable at a regional level, accommodating different stakeholder values and producing site-specific results. The model provides clarity for decision-makers through restriction and suitability criteria, while reducing potential GM-PV areas. It anticipates future considerations, such as public acceptance, and emphasises the importance of stakeholder involvement in adapting the criteria to local characteristics. While acknowledging the urgency of soil carbon storage issues, the study recognises the evolving importance of the GM-PV installation size and urges consideration of economies of scale. Despite careful selection of criteria, stakeholder involvement is crucial to align criteria with local preferences, food production and biodiversity conservation. The GIS model assists decision-makers and stakeholders in assessing regional potential, with adjustments required based on real-world conditions. Future improvements to the model should take into account landowner considerations, contractual constraints, and existing electricity grid infrastructure and capacity to accommodate future GM-PV electricity production. A shift towards hybrid GM-PV and storage is recommended to improve grid stability in response to the challenges of GM-PV generation and to increase opportunities for local value-added generation.

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Declaration of interests

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

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