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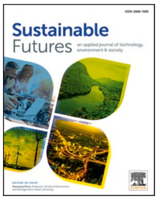

Advancing the renewable energy transition through land prioritisation and advanced photovoltaic technologies: A case study of Germany

Ankita Saxena [a,*], Elham Fakharizadehshirazi [b], Almut Arneth [a,b,1], David Martín Belda [a,1], Calum Brown [a,c,1], Dmitry Otryakhin [a,1], Christine Rösch [b,1], Mark Rounsevell [a,b,d,1]

[a] Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467, Garmisch-Partenkirchen, Germany
[b] Institute of Geography and Geo-ecology, Karlsruhe Institute of Technology, Kaiserstraße 12, Building 10.50, 76131, Karlsruhe, Germany
[c] Highlands Rewilding Limited, The Old School House, Bunloit, Drumnadrochit IV63 6XG, United Kingdom
[d] School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, United Kingdom

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ABSTRACT

Achieving national climate targets while balancing land-use and biodiversity goals is a shared challenge for countries undergoing large-scale solar energy transitions. Strategic deployment of photovoltaic (PV) systems is essential to maximise energy output while minimising land use. This study explores strategies for land-efficient PV deployment by assessing the technical PV potential of ground mounted systems under varying land-use restrictions and PV technology scenarios. Using Germany as a case study, we integrated high-resolution climate data, PV potential modelling, and land suitability assessment across three levels of land-restriction (least, intermediate, most) and three PV technology efficiency levels (low, medium, high) to evaluate how land suitability and technology choices affect energy outcomes. Our results show that deploying high efficiency PV systems can more than double electricity generation from the same land area. Prioritising the most suitable land could produce up to 759 TWh of energy, whereas stricter land-use restrictions could limit this potential to just 97 TWh. We find that energy targets can be met using <1% of Germany's land area, without compromising protected areas or biodiversity objectives, provided PV deployment is targeted to optimal sites and paired with advanced technologies. By aligning PV deployment with high-suitability land and advanced technologies, countries can reduce land demand and environmental trade-offs. This study proposes a scalable pathway to strengthen the renewable energy transition while supporting sustainable outcomes – making it relevant beyond Germany for global land-energy planning.

1. Introduction

The transition to renewable energy is accelerating globally, with countries setting ambitious targets to reduce fossil-fuel dependency and achieve climate neutrality. In 2024, the global renewable energy sector experienced a record capacity expansion of 585 GW, marking the largest annual increase to date and raising total renewable power capacity to approximately 4448 GW. Solar PV alone contributed around 454 GW, accounting for over three-quarters of the new capacity [1]. A 90% decline in solar PV module costs since 2010, rapidly expanding investment flows [2], and favourable policy environments have driven the growth of photovoltaics across many regions. For example, India aims for 280 GW of solar capacity by 2030, the United States targets 50% clean electricity by 2035, and the European Union has committed to doubling solar capacity under REPowerEU plan [3–5]. This surge in solar PV development indicates the pivotal role of PV in meeting near- and long-term climate and energy goals worldwide.

Germany's "Energiewende" remains a leading example of an ambitious energy transition, aiming to source 80% of electricity from renewables by 2030 and 100% by 2035, with the goal of net-zero emissions by 2045 (Renewable Energy Sources Act Erneuerbare-Energien-Gesetz, [6,3]. To meet these goals, the EEG has set specific targets for various renewable technologies. Among these, PV plays a central role with 215 GW of capacity required by 2030 [7], in addition to

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* Corresponding author.
E-mail address: ankita.saxena@kit.edu (A. Saxena).
[1] These authors have made equal contributions to this paper.

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100–110 GW of onshore wind, 30 GW of offshore wind, and 10 GW of hydrogen [3]. As of 2024, Germany's installed PV capacity reached approximately 99.3 GW following a record annual addition of 16.2 GW [8]. Despite this progress, substantial additional deployment is still needed across all renewable technologies particularly PV, wind, hydrogen, and storage, to meet the country's renewable energy targets [9,10].

While Germany has made substantial progress toward its solar PV targets with approximately 100 GW of installed PV capacity by the end of 2024, an additional 115 GW is still required by 2030 to meet the national goal of 215 GW [6,8]. Similar large-scale PV expansion efforts are being pursued in other countries, many of which are facing dual challenges: rapidly scaling up renewable energy supply while managing limited land availability. In regions, such as Brazil, China, and parts of Southeast Asia, tensions have already emerged between solar PV deployment, agriculture productivity and conservation goals [2,11–14]. Simultaneously, global investment in renewable energy reached a new high in 2024, with about USD 807 billion directed toward clean energy technologies, indicating rising policy ambition, technological advancement and economic momentum [15]. Careful planning is therefore needed to optimise PV deployment in the most suitable locations, maximising energy outputs while minimising land requirements. This, in turn, requires a careful consideration of various long-term factors, including climatic, technological, environmental, geographical, economic and regulatory constraints [16]. These constraints must also align with demand-side needs while avoiding negative impacts such as excessive material extraction, waste generation, and biodiversity loss [17,18,19] .

Several studies emphasised the importance of strategic PV deployment in improving energy generation outcomes. For instance, [20] found that many PV farms in Romania were underperforming due to sub-optimal placement. In the German context, [10] showed that PV-suitable areas exhibit contrasting characteristics: with higher solar radiation typically observed in the south, while the north holds greater soil carbon storage potential. These findings underline the need to explore how PV energy performance is influenced by land suitability prioritisation and the adoption of emerging high efficiency PV technologies [21–23]. Germany provides a highly relevant case study due to its ambitious PV capacity targets, dense land-use patterns, and strong environmental protection. The availability of a detailed energy policy framework [6] enables scenario-based analysis under diverse regulatory and spatial constraints. Germany's climatic diversity, from high-irradiance southern regions to lower-irradiance northern areas, making it an ideal case to study the interactions between technology choice, land suitability and energy output.

Land-use policies often restrict PV deployment to designated areas to protect farmland, urban spaces, and natural habitats. While such restrictions are important for conservation and spatial planning, PV potential can vary substantially even within the designated areas [24,25], the failure to account for site-specific PV potential differences may result in sub-optimal PV outcomes [26]. Prioritising highly suitable but otherwise unrestricted land, based on factors such as solar radiation, grid connectivity, and proximity to settlements, can greatly improve the deployment efficiency [27]. In addition, advances in PV technology such as *perovskites* and *III-V multijunction* cells help to rapidly increase efficiency, thus reducing PV area demand [28,29]. Many countries have developed regulatory frameworks that seek to address the land-area conflicts such as California's farmland mapping and monitoring program or China's land classification system, which influence solar siting decisions [30]. Although numerous studies have explored PV performance, deployment barriers or land-use conflicts, an important gap remains is integrating land suitability, technological efficiency, and policy constraints within a single spatially explicit modelling framework. Previous research focussed on technical PV efficiency, land-use constraints, or policy rules in isolation without assessing the combined implications for national-scale deployment [31,32]. Moreover, many studies rely on area-based allocation rules, and ignore how prioritising highly suitable land and deploying advanced PV technologies could reduce the overall PV footprint [29]. Moreover, limited empirical evidence exists comparing energy-target based deployment strategies with conventional land-area based policies. This study addresses these gaps by integrating spatially explicit PV potential modelling with land suitability and policy-based restriction scenarios, and by comparing energy-target based and land-area based deployment approaches. Unlike previous work, this study assesses how land prioritisation and PV efficiencies interact to influence energy outputs, both in absolute terms and relative to energy demand. The study provides a decision-relevant and scalable framework for land-efficient PV deployment under realistic land constraints and policy.

This study adopts an integrated modelling approach that links land suitability, PV technology efficiency, and policy-based deployment constraints. We assess the potential for land-efficient PV energy generation under a combination of land-based restrictions [10] and PV technology scenarios in Germany. We evaluate how land suitability and technology choices interact to influence energy outputs across the country and compare these outputs with existing energy targets and projected demand. Specifically, we address the following research questions using a modelling framework that integrates PV potential estimation [33,34] with land suitability assessment [10] in Germany.

1. What is the potential PV energy generation across different levels of land suitability, and how do these areas contribute to meeting projected energy demands?
2. How do different PV technologies, in combination with varying levels of land-based restrictions, affect total energy generation potential in Germany?
3. Can an energy target-based PV deployment strategy outperform Germany's current land area-based deployment approach?

2. Methods

Germany is located in central Europe and spans a wide range of geographical and climatic conditions. The country experiences a temperate seasonal climate with substantial spatial variation in solar radiation. Southern regions such as Bavaria and Baden-Württemberg receive relatively high solar radiation (1100–1250 kWh/m^2 per year), while Northern states such as Lower Saxony and Brandenburg experience moderate ranges (around 900–1000 kWh/m^2 per year). Despite this variation, even moderate solar radiation levels can yield substantial PV output when combined with high-efficiency PV technologies [3]. In addition to spatial variability in solar radiation, Germany experiences moderate temperature conditions (annual mean around 8–10 °C), which are favourable for PV performance as excessive heat related efficiency losses are limited. Seasonal variability in radiation and temperature was minimised using long-term climatological averages (1990–2014), to represent the baseline conditions. The feasibility of PV deployment in Germany is also supported by sustained policies and declining technology costs which back PV deployment at scale.

We applied the spatial PV potential (PVOUT) modelling framework developed by [33], 2024b) to estimate PVOUT across suitable ground-mounted PV locations in Germany. This method integrates climate variability, panel orientation, and technical losses to produce spatially explicit estimates of PV energy output. The PVOUT modelling framework was selected for its ability to capture spatially-explicit climatic variations and technological influence. We combined this with a land suitability model developed by [10], which classifies land into three suitability categories (high, moderate, and marginal) under three restriction scenarios (least, intermediate, most restricted) based on socioeconomic, environmental, and legal factors. An additional policy-aligned scenario based on the EEG deployment guidelines was also evaluated (more details in Table 1 and 2). PV energy generation was calculated by integrating technical parameters across these scenarios (see Table 3 and 4). The overall methodology used to conduct the study is presented in Fig. 1, with further details provided in subsequent sections. We utilised ArcGIS Pro 3.5 and Python 3.9 for developing code, processing data and analysing the results.

2.1. *Data inputs*

We applied a downscaled climatology dataset for solar radiation and temperature, covering the period 1990–2014 at 1 km resolution (Fig. 2, Fig. A2). Downscaling was carried out using the CHELSA algorithm applied to ISIMIP3b historical climate available at 0.5° [35,36], a semi-mechanistic framework designed to produce high-resolution climate data for temperature, surface incoming solar radiation, and precipitation. The algorithm primarily leverages variations in elevation and lapse rates to derive fine-scale temperature fields. Surface incoming solar radiation was estimated by combining direct and diffuse radiation, factoring in obstructions caused by surrounding terrain that affect light penetration. Mean values over the 1990–2014 period were used as baseline climatic inputs to the PVOUT model ([33], 2024b), which was used to estimate the technical PV potential for Germany at 1 km resolution. The model uses solar radiation, temperature, orientation, and standard PV performance losses (Table 4). Additionally, efficiencies of different PV technologies [28] were applied, from low (*Si*), medium (*perovskites*), to high (*III-V multijunction*) efficiency, forming the basis for low-medium-high technology scenarios (Table 3). These technologies were considered advanced as their efficiencies are substantially higher than the conventional silicon-based systems and their potential for future deployment is technically realistic in the near-term [28].

The PV land suitability model developed by [10] integrated a range of environmental, infrastructural, and economic parameters (details in Table 1), identified land as highly, moderately, or marginally suitable (Fig. 1). The PV land suitability model incorporated these factors due to their crucial role in determining land suitability for PV deployment in Germany. For example, proximity to grid influences connection costs in highly interconnected systems, while slope and aspect determine technical feasibility under Germany's moderate solar conditions. Similarly, soil quality and other land-use constraints reflected national priorities related to agricultural productivity and biodiversity conservation which are central to land-use planning in Germany. Other factors such as economic costs, land ownership, and social acceptance were not included as the focus of the study is spatial and technical suitability at a national scale. These factors may influence local-scale deployment decisions and could be incorporated in future analyses. The model also considers various land-based restrictions that limit panel placement such as conservation areas, settlements, water bodies, and natural parks (further details in Table 2). Collectively, these define the land-based restriction scenarios, categorised into least, intermediate and most restricted scenarios (Table 3). Additionally, EEG guided scenarios were

Table 1
The factors considered for different levels of suitability [10].

Suitability criteria	Highly suitable	Moderately suitable	Marginally suitable
Solar radiation ($kWhm^{-2}yr^{-1}$)	> 1 116	1 043 – 1 116	< 1 043
Distance to power lines (km)	< = 3 k m	3 - 5	5 - 10
Land aspect	South	Southeast, Southwest	Northeast, Northwest, East, West
Slope (%)	0	0 - 5	5–15
Soil erosion in ton $ha^{-1}yr$	> = 30	10 - 30	< 10

Table 2
Land-based restriction scenarios [10]. The grey colour corresponds to criteria that exclude PV installation, while blank corresponds to allowing PV installation.

Restricted factors	Least restricted scenario	Intermediate restricted scenario	Most restricted scenario
Nature reserves (NSG) and legally protected biotopes	Yes	Yes	Yes
NATURA 2000 /FFH fauna-flora habitats, FFH habitat types and bird sanctuaries	Yes	Yes	Yes
Natural monument	Yes	Yes	Yes
Nature parks	Yes	Yes	Yes
Waterways & Waterbody	Yes	Yes	Yes
Drinking water protection areas (zones I and II)	Yes	Yes	Yes
Flood dykes	Yes	Yes	Yes
Forests and wooded areas	Yes	Yes	Yes
Settlement areas with 100 m buffer zone	Yes	Yes	Yes
Settlement areas with 200 m buffer zone	No	Yes	Yes
Settlement areas with 400 m buffer zone	No	No	Yes
Transport routes: Roads	Yes	Yes	Yes
Transport routes: Railway lines	Yes	Yes	Yes
Airports	Yes	Yes	Yes
Military zones	Yes	Yes	Yes
Monument-protected buildings	Yes	Yes	Yes
Soil quality rate (SQR) ≥ 35	No	No	Yes
SQR ≥ 50	No	No	Yes
SQR ≥ 60	No	Yes	Yes
SQR ≥ 70	Yes	Yes	Yes
Significant landscapes (BfN)	Yes	Yes	Yes
Eligible areas for ground-mounted PV systems according to the amended [6]	500 m Marginal strips along highways and double-track railway lines, Former rewetted moorland		

Table 3
Land-restriction scenarios [10] and PV technologies considered [28,33].

PV with different technologies	Low efficiency (Conventional *Si*) 18.5%	Medium efficiency (*Perovskites*) 24.8%	High efficiency (*III-V Multijunction*) 35.8%
Definition of scenarios			
Least restricted scenario	Large-scale PV deployment and energy generation by dedicating extensive land for this purpose, and excluding only areas in close urban proximity (up to 100 m) and very high-quality (SQR ≥ 70) arable land.		
Intermediate restricted scenario	Medium-scale PV deployment by excluding high to very high-quality (SQR ≥ 60) arable land and areas near the intermediate urban periphery (up to 200 m).		
Most restricted scenario	Small-scale PV energy generation by restricting arable land of SQR ≥50 and a large vicinity of urban areas (up to 400 m).		

Table 4
Factors considered in the calculation of PV potential [33].

Parameter	Values//losses
Orientation loss	0.5 (0.1 – 50) (%)
Mismatch losses	0.3 (0.1 – 15) (%)
DC cabling losses	2 (0.5 – 15) (%)
Losses in inverter (conversion of DC to AC)	2.2 (2 – 15) (%)
Availability (Downtime losses)	0.5 (0.1 – 10) (%)
Losses due to dirt and soiling	3.5 (2 – 10) (%)
AC cabling losses	0.5 (0.2 – 3.5) (%)
Transformer losses	0.9 (0.2 – 3.5) (%)
PV module temperature	18.5 °C above ambient temperature at standard test condition (STC)
α – loss for every 1 °C increase above 25 °C of the combined PV module and air temperature	0.4%
The ideal PV module temperature, at which efficiency losses due to heat are negligible	25 °C

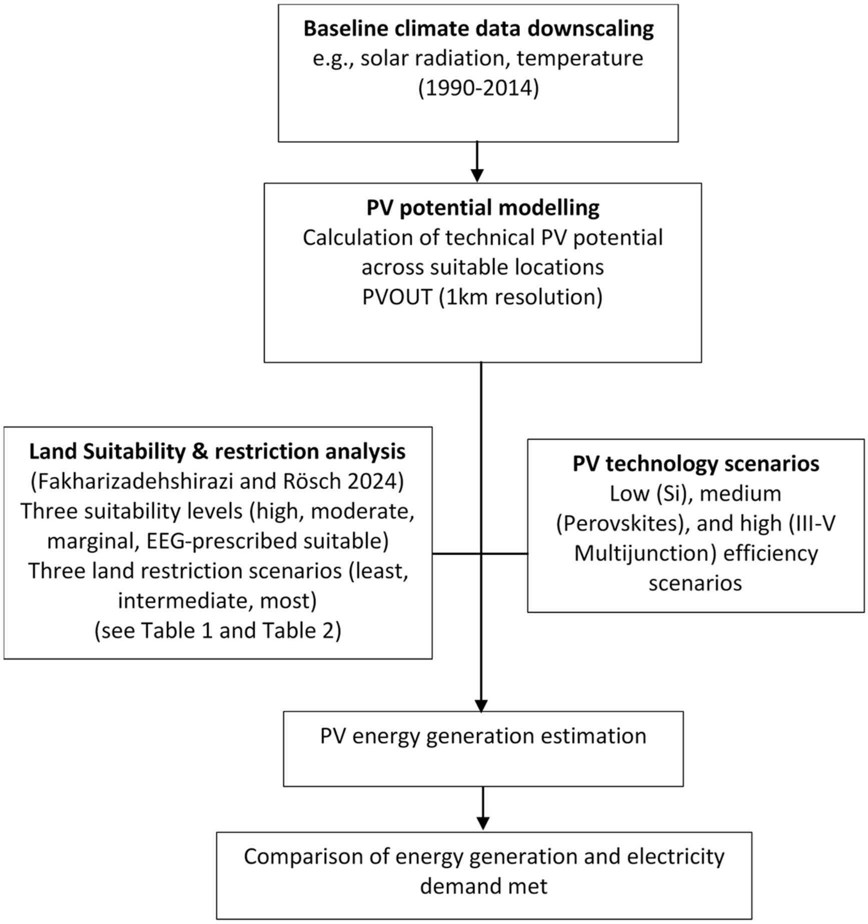

Fig. 1. Overall methodology.

developed to reflect policy-constrained PV deployment under Germany's Renewable Energy Source Act [6] by incorporating 500 m marginal buffer strips along highways and double-track railway lines and rewetted moorland, in line with national deployment policies. These scenarios provided a basis for a direct comparison between theoretical technical potential and policy-constrained deployment in order to understand the trade-offs between land used for PV and energy generation.

2.2. PV potential estimation in suitable land areas

Baseline climate data were used to drive the PVOUT model. The model's outputs were evaluated against existing PV deployment data across Germany (Fig. A1, [37]). The technical PV potential was calculated for each of the three PV technologies i.e., (low (*Si*), medium (*perovskites*), and high (*III-V multijunction*). The outputs from PVOUT model and the PV land suitability model were integrated to compute spatial PV potential under defined deployment scenarios.

2.3. Total PV energy generation in suitable land areas

The PV energy generation model incorporated key technical components of a ground-mounted PV system, including PV module efficiency (η), ground coverage ratio (GCR), system losses (described in Table 4), and temperature dependent performance to reflect realistic system performance under field conditions. Module efficiencies were considered for three technology levels (Table 3), while system-level losses such as orientation, mismatch, cabling, inverter, and soiling losses were accounted for using standard parameter ranges (Table 4). Temperature effects were incorporated using a coefficient-based adjustment to reflect efficiency reductions above standard test conditions.

Total PV energy generation was estimated using Eq. (1), which is based on a spatial aggregation of PV energy output across suitable land areas, combining area, site-specific PV potential (PVOUT), system design parameters, and technology-specific efficiency [33,38].

$$PV\ electricity\ generation_i = \sum_{i=1}^{n} (area_i \times PVOUT_i \times GCR \times \eta) \tag{1}$$

Where i refers to each suitable land unit, n is the total number of such suitable land units, GCR is the ground coverage ratio, and η represents PV module efficiency. The GCR adjusts for shading effects (thus giving the PV footprint), while η varies by PV technology type.

2.4. Energy and electricity demand met by PV energy generation

Total PV electricity generation was compared with national total energy and electricity demand projections for all nine combinations of restriction levels (least, intermediate, most) and PV technologies (low, medium, high). The percentage contribution of PV to energy and electricity demand was calculated using Eq. (2) and 3 [39].

$$Energy\ demand\ met\ by\ PV\ energy = ((PV\ energy\ generation) \times 100) \div (total\ energy\ demand) \tag{2}$$

$$Electricity\ demand\ met\ by\ PV\ energy = ((PV\ energy\ generation) \times 100) \div (total\ electricity\ demand) \tag{3}$$

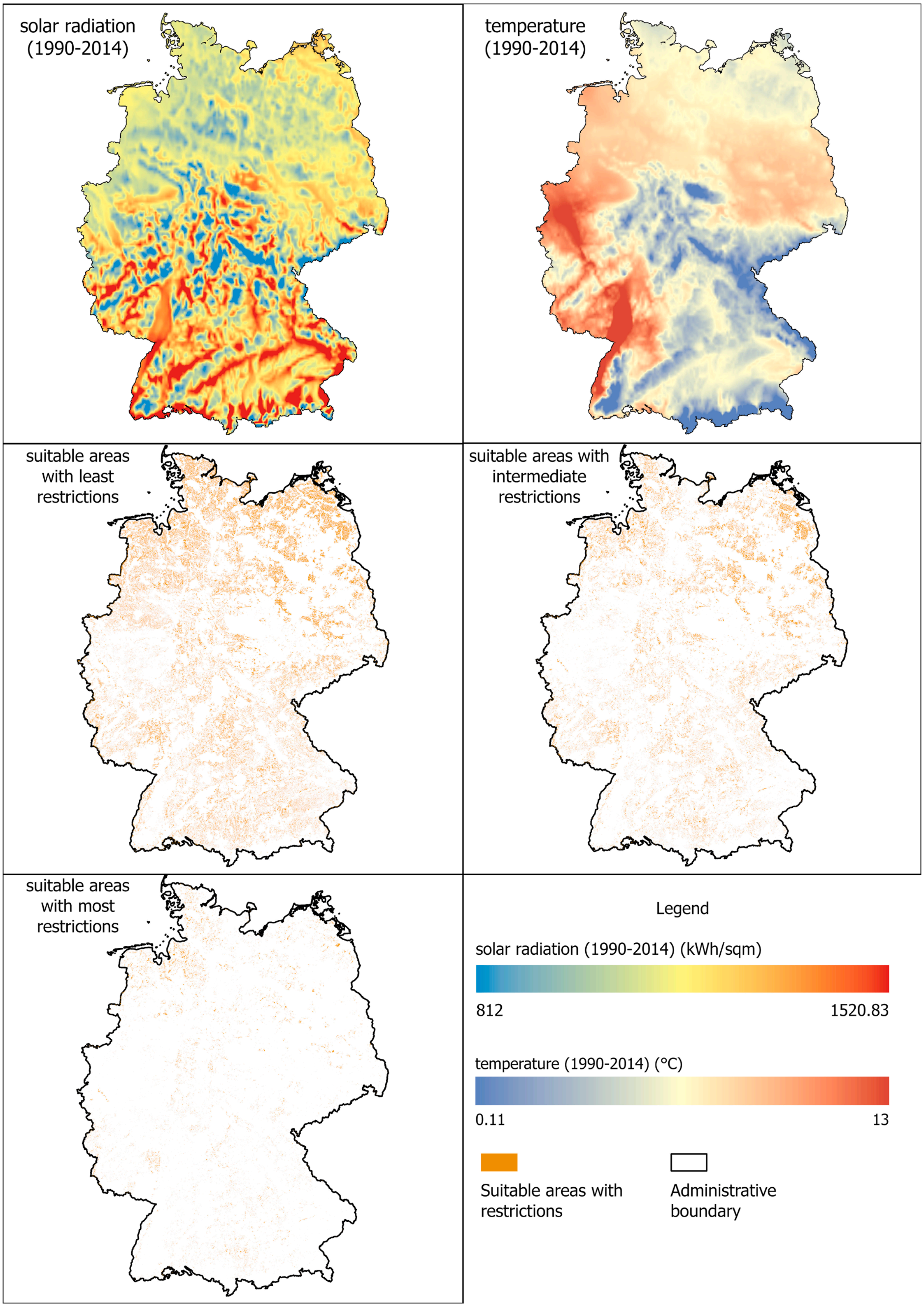

Fig. 2. Input dataset [10,36].

2.5. Role of land suitability in PV energy generation

To assess the influence of land quality on energy output, we compared a least land restricted scenario, where highly suitable land was preferentially chosen for PV deployment, against the most restricted scenario. PV energy generation per unit area was calculated across the three suitability types, progressively moving from land with highly to moderately to marginally suitable land under the least restricted scenario. We calculated the sum up until the point where the highest point of PV energy per unit area was achieved, beyond which it would start levelling off as sites with less PVOUT begin to be included in the sum. We then compared the total area at the point of maximum energy generation per unit area in the least restricted scenario with the total area in the most restricted scenario. This comparison allowed us to analyse the role of different land suitability categories in PV energy generation. The analysis aimed to determine the total land area required to achieve peak energy generation under each scenario.

3. Results

3.1. Spatially-explicit PV potential in Germany

Model validation against observed PV generation data from existing PV installations nationwide [37] showed a good agreement with an r^2 of ca. 0.8 (Fig. A1), indicating satisfactory model performance. The PVOUT model in [33]was parameterised for large-scale PV installations. In contrast, existing PV site data encompassed both small and large-scale installations without detailed spatial parameter variations associated with the losses. While some variations between observed and modelled PV outputs were therefore expected, overall model performance was satisfactory. The model showed a slightly higher mean and narrower range of PV potential compared to the observed at-site PV outputs. The photovoltaic (PV) potential varies geographically across Germany due to differences in solar radiation, topography, and weather conditions (rainfall and cloudiness) with the highest PV potential found in the south of the country due to higher solar radiation.

Bavaria (around 1100–1250 kWh/kW) and Baden-Württemberg (1100 kWh/kW), have the highest annual PV potentials. Likewise, the southwestern states, Rhineland-Palatinate (around 1100 kWh/kW) and Saarland (1050–1100 kWh/kW), also have high potential. The central and eastern states, Hesse (1000–1050 kWh/kW) and Saxony (1000 kWh/kW) have moderate PV potential. While North Rhine-Westphalia (900 – 1000 kWh/kW), Lower Saxony, Brandenburg, and Berlin (950–1000 kWh/kW) have the lowest PV potential, they still offer viable opportunities for PV energy generation (Fig. 3). The existing PV installations across the country currently generate around 61 TWh of PV energy annually [37,40] on 0.23% of the land area (Table A2), with a 12% contribution to Germany’s total electricity demand (Table A2). There is scope for more PV deployment at the most effective locations (Fig. 3).

3.2. PV energy generation across land suitability types and contribution to energy demand

The total suitable land in different categories (i.e., highly, moderately, and marginally suitable) results in different proportions but followed similar patterns across different land-based restriction scenarios. In addition, we also compared these with the EEG-prescribed land areas. In the least restricted scenario, the major proportion of the land area used for PV energy generation based on the PVOUT would come from moderately suitable areas, followed by high, marginal, and EEG-prescribed areas. In the intermediate and most restricted scenarios, the order changes to moderate, high, EEG-prescribed and marginal suitable areas (Fig. 4).

The highly suitable land of 1.8% under the least restricted scenario is alone sufficient to produce PV energy that meets Germany's current electricity demand across all low, medium, and high PV technologies (Fig. 5). In contrast, highly suitable land under intermediate (0.9%) and most (0.2%) restricted scenarios, does not meet the current electricity demand, even with highly efficient PV technologies, except for the *III-V multijunction* technology in the intermediate restricted scenario (Fig. 5).

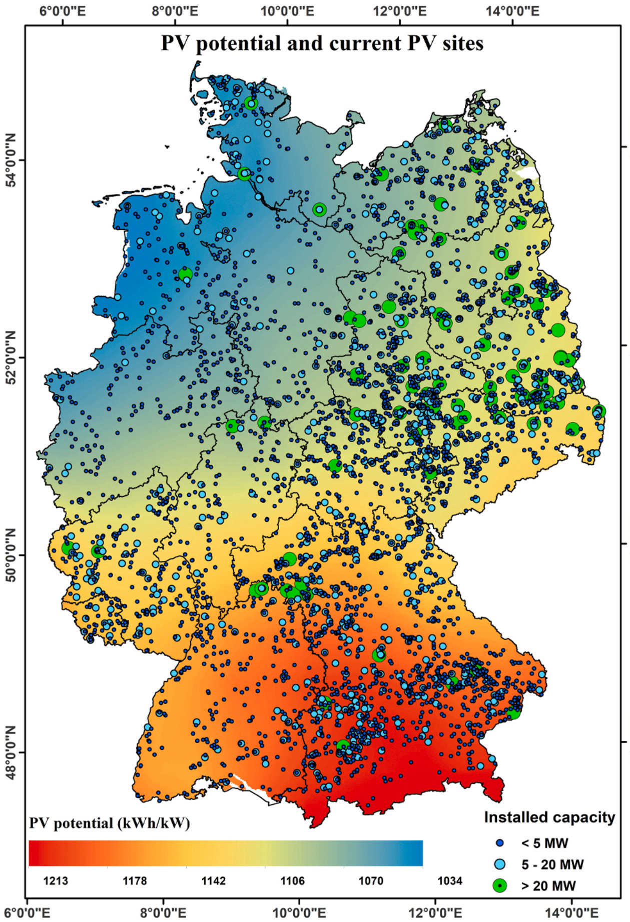

Fig. 3. Baseline PV potential and the current PV sites [37].

PV deployment on moderately suitable land (7.7%) in the intermediate restricted scenario would also meet Germany's total current energy demand. However, none of the types of suitable land alone is enough to meet either the current energy or electricity demands in the most restricted scenario. Only highly or EEG-prescribed suitable land and medium to high PV technologies under the intermediate restricted scenario would meet the current electricity demand, but none of the suitability types would meet the total current energy demand in this scenario (Fig. 5).

3.3. Combined effects of PV technologies and land-based restrictions on energy generation

Even under the most restrictive scenario, which still allows about 2% of Germany’s land area to be used for solar electricity production (see Fig. 6), the deployment of conventional silicon PV technology could generate around 639 TWh. This is equivalent to the current electricity demand (around 600 TWh) in Germany ([3], Federal Ministry for Economic Affairs and Climate Action (BMWK)). Energy output would approximately double to 1237 TWh if higher efficiency PV technologies were to be used on the same land area. In this scenario, PV energy generation would meet 19% to 36% of the total current energy demand, depending on the PV technologies considered. Under more relaxed levels of restriction (intermediate restricted scenario), around 4 to 8 times the current electricity demand could be generated on 7% of

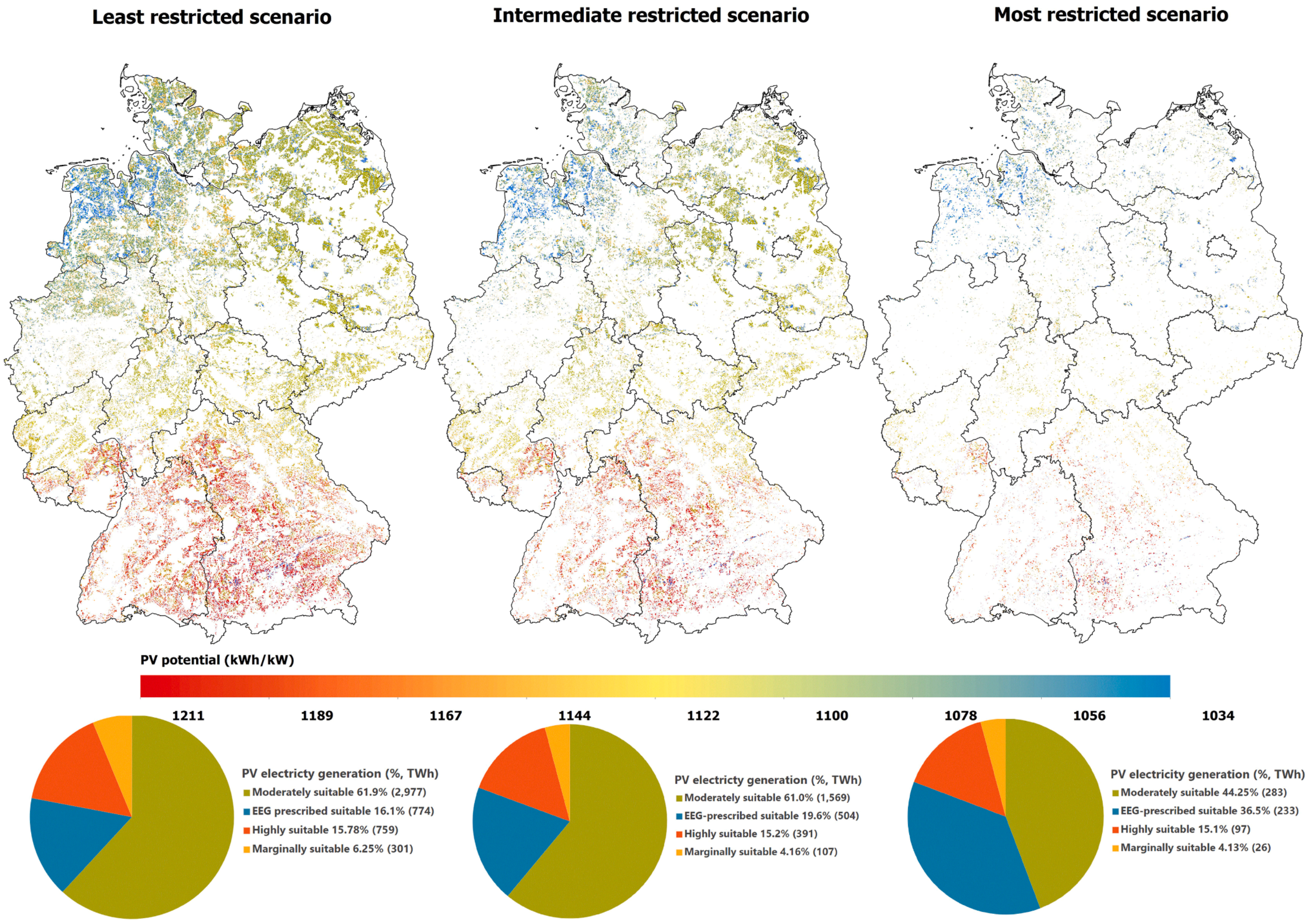

Fig. 4. PV potential in least, intermediate and most restricted scenarios (upper panel) and electricity generation share on different levels of suitability (lower panel).

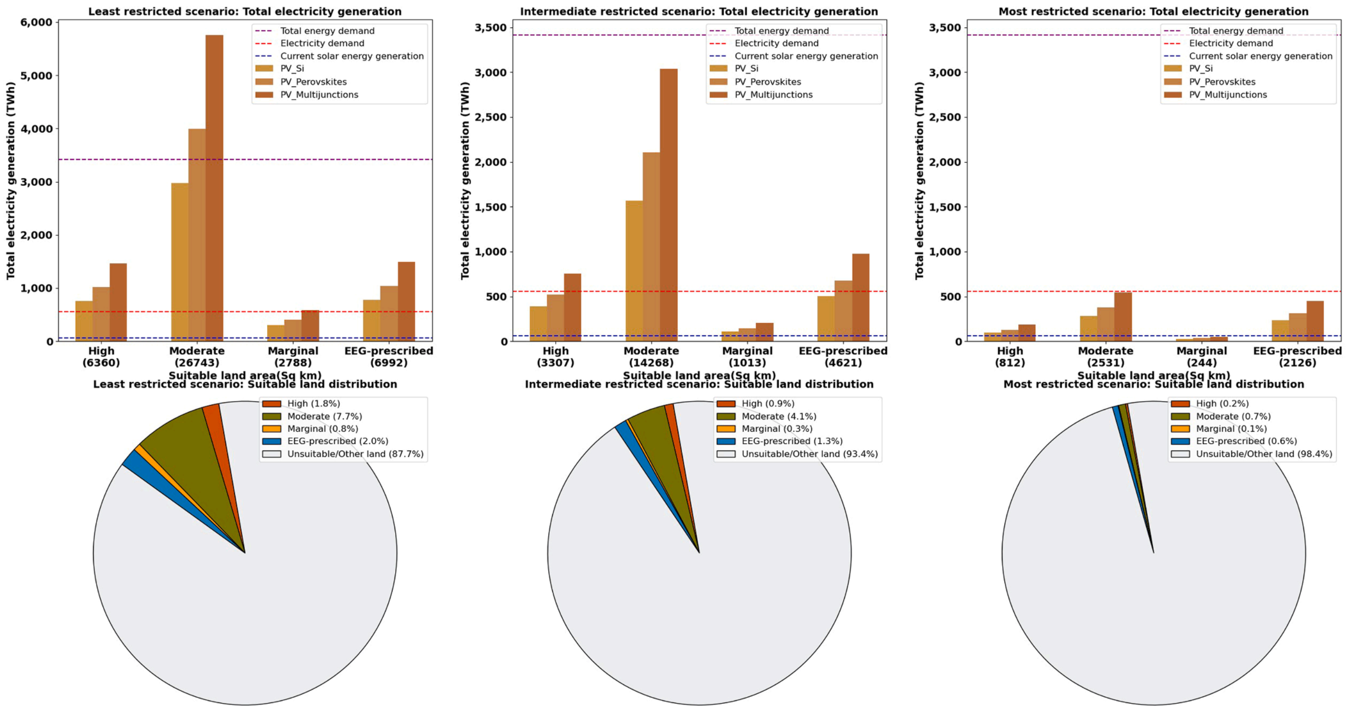

Fig. 5. Total electricity generation using different PV technologies across land-suitability categories for various levels of PV-suitable land under least, intermediate and most restricted scenarios.

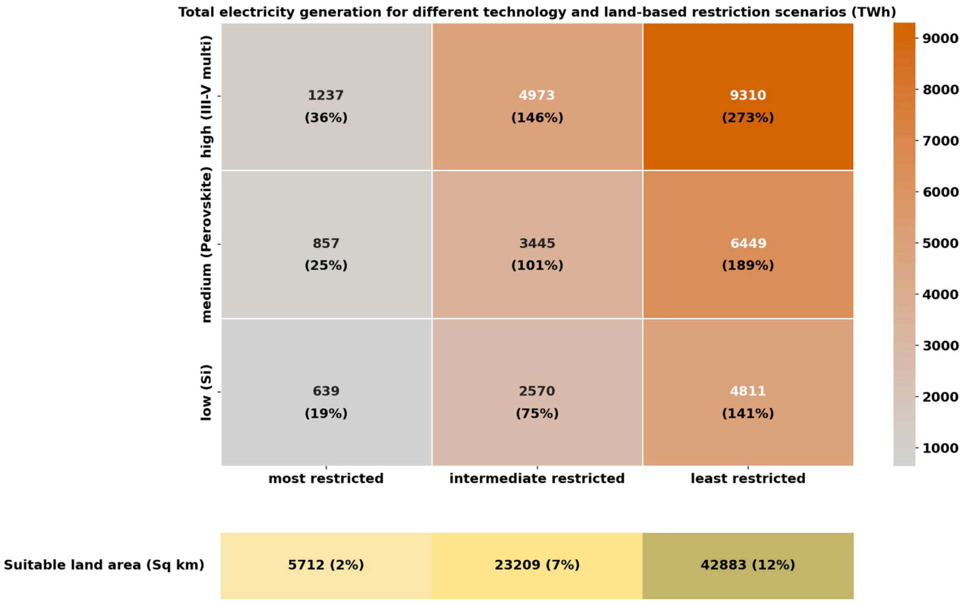

Fig. 6. Total electricity generation for different technologies (low – Si, medium – perovskites, high – III-V multijunctions) across various land-based restriction scenarios (least, intermediate, most restricted). The percentage values in brackets (%) for energy generation indicate the proportion of Germany's total energy demand that would be met. The values for land area (from [10]) in brackets (%) represent the percentage of Germany's total land area that potentially could be utilized for PV installations.

Germany's land area, meeting 75% to 146% of the total current energy demand depending on the type of technology used. The least restricted scenario would produce 8 to 15 times the current electricity demand, meeting 141% to 273% of the total current energy demand on 12% of Germany's land area (Fig. 6). By utilising highly efficient PV technologies, it is possible to not only meet the electricity demand but also to generate an excess supply of energy. This surplus could be redirected to fulfill the overall energy demand including electricity and other industrial needs and heating.

3.4. Comparison between energy-target based and land-area based deployment approaches

The PV energy generation per unit area shows a declining trend when adding land gradually, starting with highly suitable land, followed by moderately, and marginally suitable land (Fig. 7). The highly suitable land (1.8% of total land area) in the least restricted scenario is more efficient than the total suitable land (1.9% of total land) in the most restricted scenario; producing 120 TWh more and surpassing Germany's

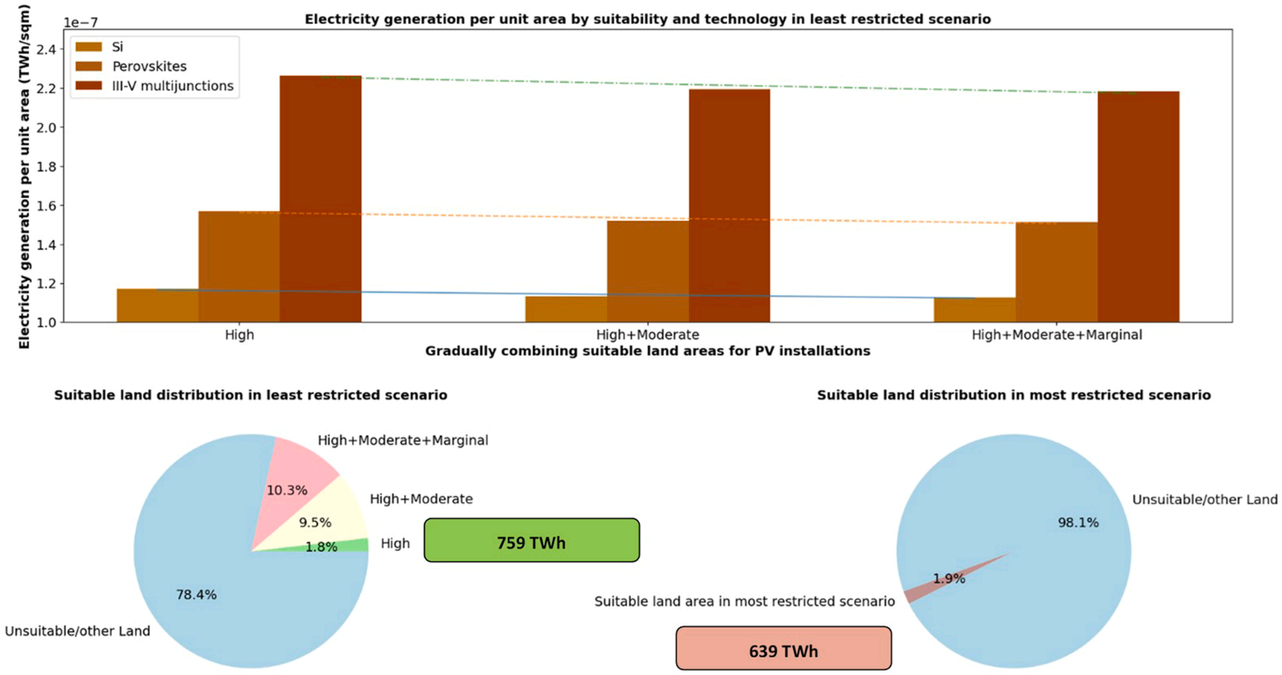

Fig. 7. Electricity generation per unit area by gradually combining suitable land areas by suitability and technology in the least restricted scenario. The lines in the upper panel show a declining trend as less suitable areas are added. The lower panel compares PV energy production between least and high restricted scenarios using different levels of suitable land.

total electricity demand (Fig. 7). Although the differences are limited, and even in the most restricted scenario the PV energy has substantial potential to contribute its share in Germany's renewable energy targets.

The EEG-prescribed areas (0.6%) in the most restricted scenario could contribute to renewable energy targets through its share of PV energy generation i.e., 233 TWh (52% of the 80% of total electricity demand which is the current renewable target) while in the least restricted scenario it produces around 774 TWh (Table A1). To achieve the 215 GW of PV installed capacity target by 2030, it would require an additional around 1270 sq km (around 0.6% of land), which might vary with the technology and design specifics considered (Table A2).

4. Discussion

To accelerate large scale PV deployment, strategic planning is essential to ensure efficient use of land, given the competition with other land uses and spatial variation in PV potential. In Germany, most high-capacity PV sites are concentrated in the north and northeast, despite relatively higher solar radiation in the south. The EEG guidelines identify areas suitable for PV deployment to support the energy transition; however, they often lack detailed consideration of the PV potential and site suitability factors. Our study shows that prioritising highly suitable land with high PV potential can substantially reduce the total land area required to meet energy targets. Highly suitable land areas for PV deployment in Germany are primarily characterised by high solar radiation, low slope, favourable aspect, proximity to grid network and low agricultural and ecological values (Table 1). Southern regions exhibit relatively higher photovoltaic potential. However, land-efficient PV deployment can be further enhanced by complementing these areas with marginal lands, transport corridors, and previously disturbed areas (e.g., brownfields) under policy constraints. Additionally, integrating advanced PV technologies with high-potential land could effectively address land constraints [29] by increasing yield per unit area. This improvement depends on the higher conversion efficiencies without influencing the physical system size. Advanced PV technologies, such as *perovskites* and *III-V Multijunction* systems generate more electricity per unit area compared to conventional *silicon*-based system, thereby reducing the total land required to meet energy targets. For instance, deploying high-efficiency PV panels (e.g., *III-V multijunction*) could reduce land requirements by up to 50% while still achieving national energy targets. Surplus electricity generated through advanced technologies could also support energy-intensive sectors such as heating, with the excess managed through energy storage systems that help balance demand and supply ([41], Germany Trade & Invest). However, the large-scale commercial deployment of these advanced PV technologies has several challenges associated. For example, *perovskites* face issues related to long-term stability and environmental sensitivity, while deployment of *III-V Multijunction* is impeded by high material and manufacturing costs. Nevertheless, ongoing research and rapid technological advancements could improve the stability and scalability of these technologies in the near future [28].

Our estimates (97 TWh) are derived from a PV potential model that incorporates spatial and technological parameters while [10] and Clean Energy Wire [40,42,43] quoted around 37 TWh and 61 TWh respectively by using more generalised methods (Table A2). This discrepancy highlights the importance of accounting for land suitability and PV technology differences in assessing deployment potential.

Land-based restrictions on ground mounted PV deployment are necessary to balance PV expansion with ecological, environmental and land-use concerns [44]. Large-scale ground mounted PV deployment can lead to competition with agricultural and ecosystem services, and potentially affect food security [45] and local biodiversity [46,47]. Encouraging PV deployment along roadsides, railways, and on marginal lands (e.g., brownfield sites, landfills and industrial wastelands) [48,49], while avoiding ecologically sensitive zones, provides a balanced path forward. PV deployment on rewetted moorlands may also offer co-benefits for PV energy production along with conserving ecology and biodiversity [50], but timing and installation before rewetting is essential to realise these synergies. However, land restrictions may exclude some of the most efficient land for PV energy generation. Our results show that the least restricted scenario with high-suitability land could generate 759 TWh, while the most restricted scenario could limit this to just 97 TWh (Fig. 5).

The prospective electrification of various sectors in Germany including industry, transport, heat, and rising household income is projected to increase electricity demand by up to 700 TWh by 2030 [40]. To meet this growing demand, prioritising sites with high PV potential suitability along with deploying medium-to-high-efficiency PV technologies could generate sufficient energy while occupying only around 0.9% of Germany's area under an intermediate restricted scenario (Fig. 6). Moreover, combining high and moderately suitable lands for PV deployment while conserving protected areas and adopting advanced PV technologies should go hand in hand in achieving renewable energy targets. This study provides a direct comparison between energy-target based and land-area based deployment approaches. The results show that energy-target based strategies, which prioritise high-yield locations, can achieve national energy targets using substantially less land compared to conventional area-target based approaches that are constrained by land restrictions. This also opens ways for integrating complementary land-use strategies, such as land restoration [51]. In addition to large-scale ground-mounted PV systems, future land-energy planning should also consider alternative PV applications or dual use systems such as agri-voltaics – which combine solar energy generation with agriculture, solar-biomass, floating PV, or PV over parking lots [52]. Such multifunctional approaches could ensure sustainable, efficient, and equitable use of land – addressing energy needs without displacing food or ecological services while also contributing to the broader goals of a just energy transition [14,11].

This study provided a comprehensive assessment of land-efficient PV deployment, however, several limitations could be addressed in future work. Future climate variability and extreme weather events were not accounted for in the assessment that may influence PV performance. The study is based on current policy conditions which may evolve over time and affect PV outputs. Economic factors such as material and installation costs as well as market dynamics were not included in the modelling framework. In addition, material availability and the adoption rate of newer PV technologies may influence large-scale implementation. These limitations introduce uncertainties in the estimation of PV potential and deployment feasibility which could be addressed in future studies. Our findings align with multiple Sustainable Development Goals (SDGs) – specifically SDG7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 15 (Life on Land). By integrating spatial land suitability and technology advancement into national planning, this study offers a replicable framework for land-smart PV deployment. Countries with land constraints and ambitious energy goals can adopt similar strategies, tailoring land prioritisation to local contexts. By integrating land suitability and advanced PV technologies, countries like Germany could effectively balance ecological preservation with ambitious renewable energy targets, ensuring a sustainable energy future. A well-planned PV deployment strategy presented here, not only enables a nation to meet its renewable energy goals but also aligns with broader environmental and biodiversity conservation efforts, thereby offering a scalable model for fostering a sustainable and climate-resilient energy transitions globally. From a policy perspective, the results suggest that current land-area based deployment strategies should be complemented with or even replaced by energy-target based planning strategies where high yield locations are prioritised for PV deployment. Integrating the national planning framework (EEG) with a spatial PV efficiency assessment framework could improve PV deployment effectiveness and avoid land-scarcity issues. In addition, dual-use systems, such as agri-voltaics and infrastructure-based PV deployment could offer production of multiple services including energy from the same land.

5. Conclusion

This study presents a spatially explicit assessment of PV energy potential across Germany, considering multiple land-use restriction scenarios and technology pathways. The integration of high-resolution climate data with land suitability and policy-relevant constraints offers a novel framework for energy-land planning. Results show that prioritising highly suitable land areas and adopting high-efficiency PV technologies substantially reduce land requirements while increasing energy yield. Compared to traditional area-based deployment strategies, an energy-targeted approach can deliver more effective outcomes, supporting national energy goals with reduced land-use impact. This modelling approach provides a transferable methodology for other countries seeking to optimise land use in their renewable energy transition goals. Furthermore, prioritising energy-target based PV deployment, integrating advanced PV technologies, and promoting dual-use PV systems, such as agri-voltaics and infrastructure-based installations could further help minimise land scarcity and reduce conflicts between energy, environment, and land-use while supporting sustainable development.

CRediT authorship contribution statement

Ankita Saxena: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Elham Fakharizadehshirazi:** Writing – review & editing, Data curation. **Almut Arneth:** Writing – review & editing, Conceptualization. **David Martín Belda:** Data curation. **Calum Brown:** Writing – review & editing, Methodology. **Dmitry Otryakhin:** Writing – review & editing, Data curation. **Christine Rösch:** Writing – review & editing, Data curation. **Mark Rounsevell:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare no competing financial interests.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2026.101930.

Data availability

We provide PV potential data and outputs that can be accessed and downloaded from https://doi.org/10.17605/OSF.IO/X28EG or https://ee-ankitasaxena03as.projects.earthengine.app/view/pvde.

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