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GIS-based technical analysis of the local renewable energy production potentials of farms in Germany

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ABSTRACT

This study evaluates the potential for integrating renewable energy on farms in Germany. Using Geographic Information Systems, the research assesses the spatial distribution of potential locations for renewable power plants, considering various datasets associated with animal husbandry, existing power plants, farm locations, and meteorological conditions. The analysis reveals potential for small-scale wind and photovoltaic power plants. In particular, the potential for small-scale wind power plants is approximately 4 TWh/a, concentrated mainly in the northern regions of Germany. For photovoltaic power plants, the total potential is estimated at around 637 TWh/a, with a distribution of 56 % for ground-mounted systems, 37 % for agrivoltaic systems, and 7 % for rooftop photovoltaics. The distribution of photovoltaic systems indicates, that ground-mounted systems are predominantly located in the eastern part, rooftop systems in the northwest, and agrivoltaics in Rhineland-Palatine and Baden-Württemberg. The study also identifies near surface geothermal potential in the northwest, Molasse, and Rhine basins. The overview provides valuable insights into optimal locations for sustainable energy production for farmers.

Abbreviations:

a	annum
BE	Berlin
BB	Brandenburg
BW	Baden-Württemberg
BY	Bavaria
DGE	Deep geothermal energy
DWD	Deutscher Wetterdienst – Official German weather forecast service
ED	Energy Demand
GE	Geothermal Energy
GHG	Greenhouse Gas
GIS	Geographic Information System
GMPV	Ground-mounted Photovoltaic
GWp	Gigawatt peak
HB	Bremen
HE	Hesse
HH	Hamburg
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft – Registered agricultural association for technics and engineering
LIAG	Leibniz-Institut für Angewandte Geophysik– Institute for Applied Geophysics
MaStR	Marktstammdatenregister - Central electronic directory of energy industry data in Germany
Mha	Mega hectare – 10^{11} m^2
MV	Mecklenburg-West Pomerania
NI	Lower Saxony
NSGE	Near-surface geothermal energy
NW	North Rhine-Westphalia
OSM	Open Street Map
PV	Photovoltaics
RE	Renewable Energy
RP	Rhineland-Palatinate
SA	Saxony
SH	Schleswig-Holstein
SL	Saarland
ST	Saxony-Anhalt
TH	Thuringia
TI	Thünen Institut
TWh	Terawatt hours – 10^{12} Wh
Wh	Watt hours

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1. Introduction

The German "Federal Climate Change Act" mandates a reduction of greenhouse gas (GHG) emissions to net zero until the year 2045 [1]. To achieve this goal, various sectors find themselves at different stages. In 2022, 46 % of the electricity, 18.2 % of the heating, and 6.9 % of the mobility were already covered through renewable energies (RE) [2]. Transitioning to RE is crucial for a sustainable future. This is particularly true for the heating and mobility sectors, which must be electrified directly or indirectly. Since most of Germany's land is already utilized – for residential purposes, transport infrastructure, industrial activities, or agriculture – identifying suitable space for additional RE installations becomes challenging. Agricultural activities account for 50.4 % of Germany's total land area [3]. This highlights the crucial role that agriculture can play in expanding RE sources. In Germany, the expression 'energy farming' has emerged, reflecting the shift from traditional agriculture towards simultaneously conducted RE production. As this trend proceeds, discussions persist regarding the balance between maintaining land for food production and repurposing it for RE generation [4]. Using a Geographic Information System (GIS) based analysis, this study aims to determine how much agricultural land is available in Germany for RE production while minimizing interference with agricultural operations.

Until now Böhm et al. (2022) indicated that 0.1 % of the agricultural land in Germany has been affected by photovoltaic (PV) installations [5]. However, as the demand for RE increases so does the requirement for land to accommodate such installations and it would be inefficient to cover the large space requirements only on non-agricultural land. In particular, to reach the PV development goal for 2030, the hitherto installed capacity needs to be tripled [6,7]. The following section is a short literature review, depicting studies using partially GIS as a tool for the analysis of RE potentials mostly in the agricultural sector especially in a German, but also in a European and international context.

1.1. Literature overview

A variety of RE options exist to facilitate the energy transition within German agriculture. Biogas is the initial focus when discussing RE in agriculture. Particularly in Germany over 9000 biogas power plants are currently in operation [8]. Numerous studies have previously explored the potential for biomass utilization in Europe, including Germany. Based on a GIS optimization approach, European farm locations, and manure production data, Scarlat et al. [9] identified a theoretical potential of 22.7 billion m^3 CH_4 in Europe, building manure-based biogas plants. In Germany, the potential amount of manure biogas could cover 2.5 % of the natural gas demand. Bidart et al. (2014) investigated the potential of livestock manure for usage in biogas power plants in Chile via a geospatial analysis considering the economic constraints [10]. In addition to manure, crop waste materials can also serve as feedstocks for biogas production. In a GIS analysis, Monforti et al. (2013) displayed an availability of 416.6 TWh/a when utilizing 83–86 % of the EU's crop waste potential [11]. Van Duren et al. (2015) used GIS to evaluate the best locations for rapeseed biodiesel production in Europe, building upon different classes of productivity and conditions of the soil [12]. Bao et al. (2021) carried out a study on a German scale [13]. They considered the future developments in the food-water-energy nexus to evaluate the hazard of bioenergy production for food production, suggesting that limiting energy crop cultivation is the most efficient agricultural method to safeguard food production.

Apart from biogas, farmers possess additional possibilities to generate RE. In Germany around 25 % of farmers already produce electricity via PV power plants [14]. Mehdaoui et al. (2022) employed GIS for a multi-criteria assessment, determining the optimal location for an on-farm desalination system powered by a PV power plant in Tunisia [15]. Looking only on Germany, for instance, one study evaluated the unused rooftop PV potential disregarding usage of the buildings in question [16]. Lödl et al. (2010) gauged rooftop areas within a Bavarian district, then extrapolated these results to the national level to approximate Germany's total PV potential at 161 GWp. Klabunde et al. (2023) computed a more targeted potential specifically for agricultural rooftops [17]. They determined the potential using the "Kuratorium für Technik und Bauwesen in der Landwirtschaft" building model, agricultural structure data and the administrative boundaries, calculating a potential of 102.8 GWp. Another study focused on barns in Lower Saxony by estimating potentials for cow sheds and pigsties using exemplary barn designs and farm statistics, leading to a potential of 1.23 GWp for cowsheds and 0.561 GWp for pigsties [18]. Bao et al. (2022) put forth a bottom-up, GIS-based approach to quantify regional-scale ground-mounted PV (GMPV) potential [19]. They considered the availability of the land and the landscape to calculate the capacity and yield potentials. Other studies did not give a number for the yield [20–22]. Research concerning agrivoltaics appears to be comparatively limited. The Fraunhofer ISE estimated in their guidelines a potential of 1700 GWp for agrivoltaic installations over shade-tolerant plants in Germany, along with an additional 1200 GWp when including grasslands [23]. However, these considerations lack the spatial component.

A lot of research has been conducted on wind energy potential but not specifically located on German farms. The "Statistische Bundesamt" (Destatis) counted 3600 wind power plants on German farms, which is equal to 5 % of the farms [14]. Fliegner and Möst (2023) explored, utilizing GIS, the possibilities to connect offshore wind farms to the power grid [24]. Grieser et al. (2015) employed case studies on building small wind turbines on sample sites to gauge the economic feasibility of small-scale wind turbine deployment [25]. They concluded, that areas with an average wind speed of 4–4.5 m/s as a minimum are economically viable and that an implementation outside of an urban centre is crucial for an economic operation. Furthermore, Lütkehus et al. (2013) evaluated the potential for wind power plants in Germany, considering noise constraints but not only limited to the agricultural sector [26].

Various investigations have examined the potential of geothermal energy (GE) to meet heating demands within Germany. Moeck et al. (2022) provided a review of previously performed studies on a German scale evaluating the GE potential [27]. Most research concentrated on one specific geothermal heat source, either deep [28] or near-surface geothermal energy (NSGE) [29]. None of the existing research considered agricultural aspects.

1.2. Definition of the research questions

The studies mentioned above have assessed different RE potentials, mostly considering one type of RE. Consequently, they calculated more distinct potentials but neglected one or more of the following aspects: (1) The important role that farmers play in the implementation of RE. (2) The reduction of agricultural land losses. (3) The comprehensive assessment of multiple RE sources in Germany.

To fill this gap, the present study focuses on the possibilities, that wind, sun, and GE open up for the transformation of the German agricultural and energy sector. The research questions of the present paper are the following:

1. How much potential for the installation of RE power plants is available on farms spatially distributed over Germany by considering already existing renewable power plants and where are the potentials located in Germany?
2. Could German farms theoretically meet their own energy demand (ED) considering their total RE potential (neglecting the time discrepancy between production and demand)? Or could they even be energy providers if the potential would exceed their ED?

In this study, the energy autonomy as implied in research question 2, is seen as a comparison of energy sums (for demand and potential) by neglecting the time resolution and the need for energy storage. Other studies already investigated regional energy autonomy without the agricultural context, like Müller et al. (2011) [30] or Rae and Bradley (2012) [31]. Mainzer et al. (2014) [32], for example, analysed the concurrence of PV rooftop potential and the local demand. In the present paper, the comparison between demand and potential is not addressed, as the diversity of different farm types is too large.

Biomass is excluded in the present study, as there are already many studies that evaluate the different possibilities to use a variety of biomass sources (manure, crop residues, etc.) on a European or specifically German scale. The studies were already presented in the course of the introduction and are additionally listed in more detail in the table of Appendix 1. Furthermore, the paper provides an overview of potentials for RE production with only a small impact on land use competing with food production. Therefore, biogas production from corn or other crops that need to be cultivated is out of scope. As the usage of deep geothermal energy (DGE) is only worthwhile for farms with a high heat ED, not all farm types are considered in this study for the usage of DGE. Thus, only farms with piglets or poultry as well as with greenhouses were investigated [33–37].

The present study was carried out for Germany but the methodology can be also adapted for other European countries. Additionally, the present investigation refrains from examining the possibility of RE integration into the farms' energy systems or power grids as researched in Refs. [36,38–40].

The results of this study can be used by grid operators to get an indication of where an extension of the grid would support the energy transition, by politics to get an insight, into how a subsidy could be helpful to fasten the energy transition, and by farmers to see the possibilities to diversify their income and become more independent from the electricity price. Furthermore, the CO_2 reduction itself is a viable aim considering the upcoming climate crisis.

1.3. Structure of the paper

The paper is structured as follows: Chapter 2 outlines the data sources and methods used. Chapter 3 presents the results and thereby shows the spatial distribution of the RE potentials in German agriculture on maps but also separated by the federal state. Chapter 4 discusses the findings and methodologies concerning prior studies and describes the uncertainties of this study regarding the methodology and also the database. Chapter 5 summarizes the results and suggests future research directions.

2. Materials and methods

This study concentrates on evaluating the spatial distribution of RE potential across German farms, employing an integrated approach that combines statistical and geospatial data – similar to Scarlat et al.'s (2018) [9] examination of biogas potential in Europe.

The applied methodology is based on a stepwise approach:

1. collection of geospatial and statistical data
2. the evaluation and assessment of the local potential for energy production using solar, wind, and geothermal resources
3. partial evaluation and assessment of the distribution of existing power plants,
4. mapping of the RE potentials at the German scale.

The used datasets were retrieved from different resources: national statistics [41–44], specialized institutes [45–48] as well as community projects like Open Street Map (OSM) [49]. Challenges arose due to inconsistencies among the different data sources; for instance, discrepancies exist in locational variations, with some datasets organized by district, others by postal codes, and still others by geographic coordinates. Moreover, disparities appeared e.g. between geocoordinate systems that required conversions.

2.1. Data sources and software tools

2.1.1. German farms – national data

Various entities supply data related to German farms, each emphasizing distinct aspects. Data on farm sizes and livestock management were obtained from the German Agricultural Statistics, providing absolute figures, yet lacking spatial distribution information [42]. Spatially distributed agricultural data was retrieved from the "Agraratlas" [43,45] provided by the Thünen Institute (TI). Additionally, the "Regionaldatenbank Deutschland", a joint initiative from the federal and state statistical offices [44] was used. They offer data on farms on a district level. Fig. 1 shows the distribution of the number of farms in Germany regardless of their size, depicting, that there are many farms in the north-western part and the south-eastern part of Germany. For the districts in grey, primarily in Mecklenburg West-Pomerania (MV), the data remains unavailable.

Additionally, these data sources provide insights into livestock populations for pigs, cattle, and poultry which are important indicators of heat ED within German agriculture as well as data on the distribution of fallow land, on a district level. These datasets are used for the evaluation of geothermal and PV potentials, respectively.

For calculations of rooftop PV potentials and greenhouse locations, geospatially more explicit data is available. The installation of rooftop PV on farm buildings (stables, barns, etc.) is very promising, as they are usually very large and therefore offer great potential. Greenhouses have, especially during winter time, a high heat demand. Therefore, the usage of geothermal sources could support the energy transition of greenhouses. Data concerning the farm building areas and greenhouses was retrieved via Open Street Map (OSM) [49]. OSM is a community project, where everybody can contribute to maintaining a map of the world. The contributors depict geometries and pin information to e.g. buildings. To obtain all German farm buildings, firstly the land geometries with the land use "farmyard" in Germany were downloaded from OSM via the online application "Overpass" [50]. A farmyard is defined as "land with farm buildings" [51]. Secondly, the geometries of all buildings in Germany were downloaded from OSM. "Overpass" encounters limitations when handling substantial datasets. Downloading farmyard data using "Overpass" proved feasible when dividing Germany into its federal states and acquiring data separately; however, another approach became necessary for greenhouses and buildings across Germany due to the huge amount of data. The Python package "OSMnx" was used [52]. Germany was divided into a grid, each pixel was downloaded

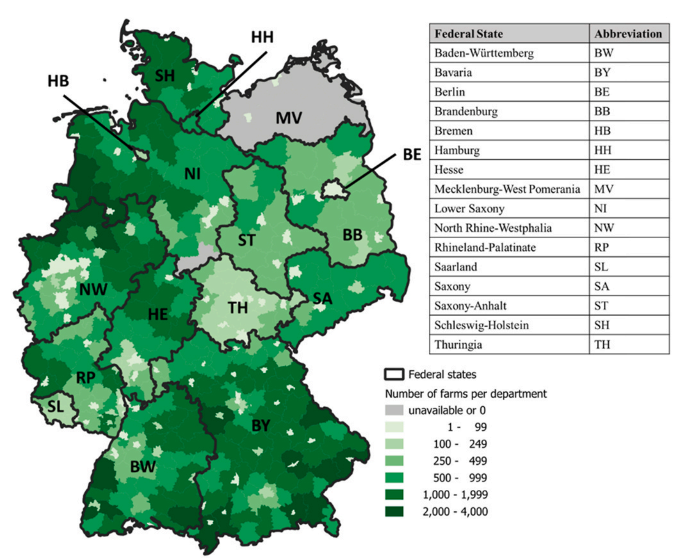

Fig. 1. Number of farms in Germany per department based on the data from the "Regionaldatenbank" [44].

individually to avoid reaching the capacity constraints of the computer and the tool. In the same manner the geometries of the greenhouses, arable land, and meadows/grasslands were retrieved. To isolate the buildings situated on farms, the building dataset was intersected – using QGIS – with the farmyard dataset, retaining only overlapping structures [53].

2.1.2. Meteorological data

To evaluate the amount of RE that German farms could theoretically produce, the locations of the farms and the prevailing weather conditions are important, as the production of RE is highly dependent on irradiance and windspeed. Weather data was obtained from the Deutscher Wetterdienst (DWD). They offer weather data collected on 83 weather stations throughout Germany in a 10-min resolution. Data regarding wind speeds and solar radiation [54,55] were harnessed for this investigation, undergoing pre-processing via pandas [56] in Python prior to interpolation within QGIS. The data for 2020 was utilized, as the data on the livestock and agricultural land were also gathered in 2020.

2.1.3. Geothermal data

GE data was retrieved from the “Leibniz-Institut für Angewandte Geophysik” (LIAG). They provide shape files for DGE resources [47,48]. The shape files can be downloaded and directly used in QGIS. Furthermore, there are datasets for geothermal temperatures every 100 m in depth until 5 km below ground [46]. These datasets were used for the analysis of the NSGE.

2.1.4. Renewable energy power plants data

To identify potential locations for further RE installations, determining existing RE plants is crucial. This information is available through the “Marktstammdatenregister” (MaStR) - a German database encompassing all power plants built in Germany – regardless of their stage (planning, operational or, decommissioned) [41]. An open access download of the whole database was conducted. The publicly available data contains only the locations in geocoordinates of power plants larger than 30 MW. The highest resolution of the location for smaller power plants (e.g. rooftop PV), is the postal code.

2.1.5. Large-scale wind power plant potential

There is a need for all federal states in Germany to assign a certain percentage of the area as potential sites for wind power plants [57]. Only Lower Saxony offers a useable map specifying areas earmarked for wind turbine installations [58]. Therefore, only a wind energy potential analysis of NI can be conducted in the present study.

2.1.6. Software tools

To analyse the collected data, different software tools were utilized. Pre-processing operations were conducted with both the Python package pandas [56] and Microsoft Excel [59]. The data retrieved for example from the MaStR were sorted and filtered depending on the connection to farms utilizing pandas. Regarding weather information, pandas was employed to associate the data with the specific collection location. The calculations shown in 2.2 were performed with Microsoft Excel. QGIS was used for geospatial computations and visualizations. For example, the station-wise weather data was interpolated to gain a nationwide weather data grid. To get district-explicit weather information the statistical analysis functions of QGIS [53] were adopted and thereby the average for each district was calculated. Furthermore, data was merged to be displayed in the same districts. Additionally, areas of buildings and districts were calculated with the usage of QGIS. Considering the geothermal resources, QGIS was used to find overlaps and merge data linked to the same location (e.g. greenhouses and geothermal potential).

2.1.7. Boundary conditions

The current study operates under the assumption that adequate electrical infrastructure exists or can be extended if needed. Different types of potentials are addressed in this study. Was et al. (2022) [60] distinguished between three different types, the theoretical potential, which includes the total potential without any boundaries, the technical potential, taking into account technical constraints, and the economic potential, which also considers minimum profitability [61,62]. The present study examines the technical potential, which is based on the theoretical potential. The analysis of the economic potential is omitted, as it is very dependent on the local circumstances of the farms.

2.2. Calculation of renewable energy potential

A GIS-based methodology was used to assess the RE potentials on German farms. For each RE source, a different approach was chosen, depending on the data available and information needed.

2.2.1. Photovoltaic power plants

To estimate the theoretical solar power generation potential using available rooftop space, the following calculations must be performed. The theoretical potential was calculated from the global irradiation and the size of the PV system with the following formula (1) [63].

$$E_t = \frac{P_{STC} * E_a}{E_{STC}} \left[\frac{kWh}{a}\right] \tag{1}$$

Where $E_t \left[\frac{kWh}{a}\right]$ is the theoretically available energy on a PV site, P_{STC} $[kWh]$ is the rated electrical power of the PV system, $E_a \left[\frac{kW}{m^2\ a}\right]$ is the annual solar irradiation and $E_{STC} \left[\frac{kW}{m^2}\right]$ is the irradiation under standard test conditions. The technical viable PV production, however, is less than the theoretical potential due to the losses of the PV system e. g. from cables or the reduced yield as a result of higher temperatures of the modules. It is calculated with formula (2) [63].

$$E_r = E_t * PR \left[\frac{kWh}{a}\right] \tag{2}$$

Where $E_r \left[\frac{kWh}{a}\right]$ is the technical potential and PR is the assumed performance ratio. The performance ratio of solar power plants was assumed to be 0.85 [64].

The installation density of solar power plants on a surface was assumed with 0.67–1.43 MWp/ha for GMPV systems (for the calculations both the minimum and the maximum were used, the map shows the minimum calculation) [65] and 0.7 MWp/ha for agrivoltaic systems over orchards or vineyards [66]. The irradiation data was retrieved geographically explicitly from the DWD [55].

2.2.2. Wind turbines

The construction of wind turbines is only economically reasonable in areas with enough wind. According to Peters et al. (2013), a minimum wind speed threshold of 4.2 m/s is needed for an economic wind turbine operation [67]. The data retrieved from the DWD was measured at 10 m above ground [54]. Under the assumption, that small-scale wind turbines are mounted at 15 m hub height, the corresponding wind speed was calculated with formula (3) [68].

$$v_h = v_{10} \left(\frac{h}{h_{10}}\right)^g \left[\frac{m}{s}\right] \tag{3}$$

Where $v_h \left[\frac{m}{s}\right]$ is the velocity of the wind in the height of the wind turbine, $v_{10} \left[\frac{m}{s}\right]$ is the velocity of the wind in 10 m height, h_{10} $[m]$ is the reference height (here 10 m), h $[m]$ is the height of the wind turbines (assumed with 15 m like proposed by Tummala et al. (2016) [69]) and g is the roughness, here assumed with 0.28 as a surface with obstacles in walking distance like buildings or forests [70,71]. This surface roughness was chosen, as farms are typically located in rural areas with fewer obstacles compared to cities. However, since wind power plants are assumed to be situated near the farm, the farm itself becomes an obstacle.

2.2.3. Calculation of the deep geothermal energy for piglets and poultry

Livestock population statistics are reported only at the district level instead of individual farm sites [45]. Thus, the calculation of potentials was performed at the district level. An abstraction encompassing both animal counts (for poultry and piglets) and the proportionate district area exhibiting geothermal potential serves as the basis for these calculations (4).

$$a_{den} = \frac{n_a}{a_d} * \frac{a_g}{a_d} \left[\frac{animals}{km^2}\right] \quad (4)$$

Where a_{den} $\left[\frac{animals}{km^2}\right]$ is the number of animals per km^2 of the area over DGE potential within each district, n_a [animals] is the total number of animals in the district, a_d $\left[km^2\right]$ is the area of the district and a_g $\left[km^2\right]$ is the area with DGE potential in that district. The minimum underground temperature considered for DGE potential is 40 °C. Piglets and chickens have a high demand for heat. The maximum temperature needed (32 °C for piglets), should be easily met [72,73].

3. Results

3.1. PV potential

The possible amount of energy generated by PV power plants depends on the irradiation and the area available. The potentially useable space on farms was divided into three categories. Firstly, the rooftop surface of buildings can be used. Fig. 2 shows the status quo of the nominal installed power of PV power plants (from MaStR [41]) by farmers per farming building area (from OSM [49]) spatially distributed by district. The power plants from the MaStR can be connected to farming activities. However, the database is limited, since it gives no evidence, of whether the PV panels are ground-mounted or on a rooftop. Thus, for the potential analysis all existing PV power plants were considered to be mounted on rooftops. Fig. 2 shows in dark bluish colours, where the ratio between installed PV systems and available rooftop area is small and in brighter yellowish colours, where the ratio is high. The higher potential in the western part of Germany is due to the high amount of farm buildings in this area. In the eastern and especially the south-eastern part much more PV modules have been proportionally mounted on the available rooftop area. For the calculations, it must be considered, that not all roofs offer suitable conditions for the installation of PV systems. Restrictions may arise from unsuitable orientations, shadings, installations on top of the roof, etc. Therefore, only 50 % of the ground surface of the agricultural buildings is considered in this study. This neglects the tilt of the roof which leads to a larger roof area than the ground area. The overall PV potential on rooftops was calculated based on formulas (1) and (2), by using data from OSM [49], the MaStR [41], and weather data from the DWD [55]. To calculate the remaining potential, the amount of existing PV power plants on farms was subtracted from the potential rooftop surface area. Due to the fact, that the MaStR does not differentiate between rooftop and GMPV plants, also negative values can occur which were defined as "0" here. This leads to 46 GWp or 43 TWh/a assuming, that 1 kWp requires 6 m^2 of space [74]. The distribution of PV potential is depicted in Fig. 3, demonstrating the large availability of rooftop areas especially in the federal states of Lower Saxony (NI) and North Rhine-Westphalia (NW). They account for 33.1 % and 18.0 %, respectively (Fig. 4).

A second possible option for farmers is to deploy PV systems on fallow plots without losing arable lands or pasture. Data on fallow lands per district originate from the TI [45]. For Germany, fallow lands sum up to around 357,000 ha [43]. The definition of fallow land includes permanent as well as shortly unused land, with or without paid subsidies [42]. When repurposing such fallow areas for solar installations, these sites cease to qualify as fallow lands, resulting in both noncompliance with mandatory fallow requirements and potential revenue losses from associated grant programs. The fallow land is obligatory to support biodiversity. While multiple investigations highlight the benefits of photovoltaic systems for fostering biodiversity, concerns remain about fence impacts on large wildlife species and reflective glare affecting bats and birds. However, in this study, it is assumed that PV power plants provide ecological advantages comparable to fallow spaces as shown by Schlegel (2021) [75]. Furthermore, it is assumed, that a rotation of the fallow land is not necessary and the land can be permanently decommissioned. For the system parameter of the PV power plant, it is assumed, that 0.67–1.43 MWp can be installed on 1 ha [65]. This corresponds to a potential of approximately 240–510 GWp for Germany.

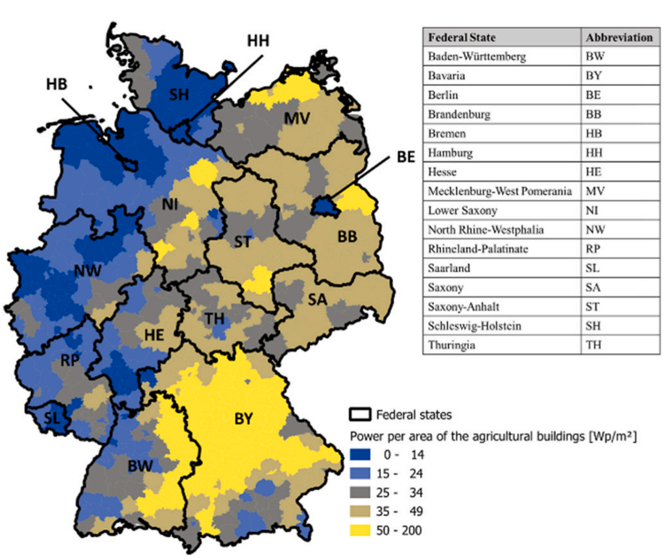

Fig. 2. Already installed nominal power of PV power plants per building area on farms in the resolution of districts, based on data from OSM [49], the MaStR [41] and the DWD [55].

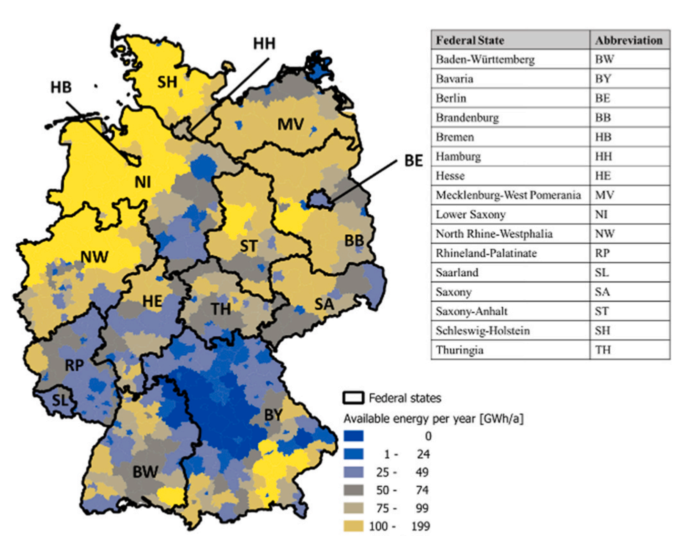

Fig. 3. PV energy potential per year based on the mean irradiation on unused farm rooftops per districts, based on data from OSM [41], the MaStR [41] and the DWD [55].

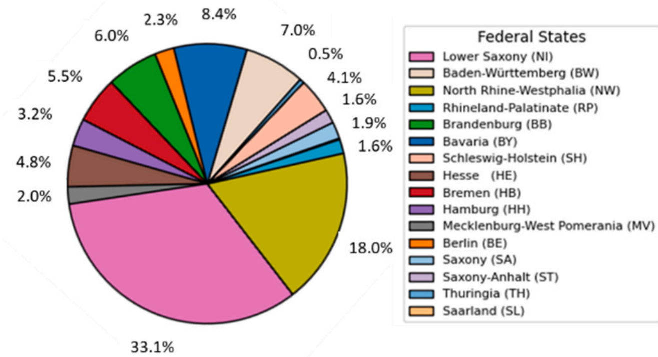

Fig. 4. Distribution of the PV rooftop potential per federal state.

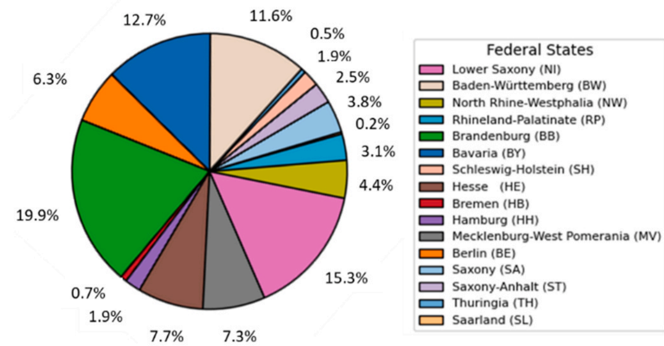

Fig. 6. Distribution of the potential of ground-mounted PV per federal state.

With the calculations of (1) and (2) and an assumed performance ratio of 0.85 [64] this leads to a potential of 230–490 TWh/a. Fig. 5 shows the spatial potential distribution of PV power plants on fallow land per district. The highest potential with the largest fallow land area is located in the eastern part of Germany. A lower population density and larger farms in these districts could explain the higher area appearance of fallow land. Fig. 6 shows the distribution per federal state. The federal states Brandenburg (BB), NI, Baden-Württemberg (BW), and Bavaria (BY) have the highest potentials above 10 %.

The third viable approach for integrating PV into farming operations is the construction of agrivoltaic systems. These are configurations where crops and/or fruit trees coexist alongside or beneath solar panels, mutually benefiting one another [76]. Figs. 7 and 8 show the district-wise divided potential for agrivoltaics over orchards and vineyards, respectively.

They depict that there is more potential to construct agrivoltaic systems over vineyards than over orchards. Figs. 7 and 9 reveal that there are particularly high potentials for agrivoltaics near Lake Constance (BW) with 36,5 % and in the west of Hamburg (HH) in the northern part of Germany with 17,5 %, estimated at 10.5 and 12.2 GWp respectively, which leads to 11,200 TWh and 11,000 TWh, respectively. The orchard area in the north of Germany is around 1000 ha larger than in the district Lake Constance in BW, but the irradiation is higher in the south of Germany. Regarding vineyards, Rhineland-Palatinate (RP) exhibits the highest potential for agrivoltaics with almost 50 % of the

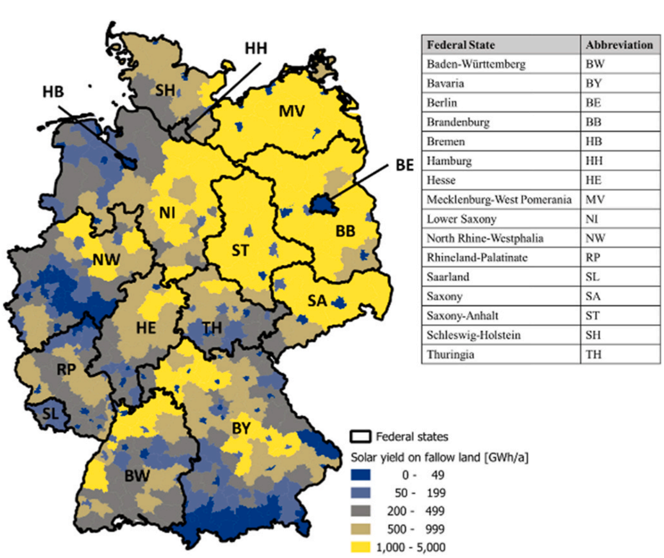

Fig. 5. Potential energy for the installation of PV systems on fallow land spatially distributed per district, with the minimal installation density per ha of 0.67 MWp/ha based on data from the Thünen Institut [45] and the DWD [55].

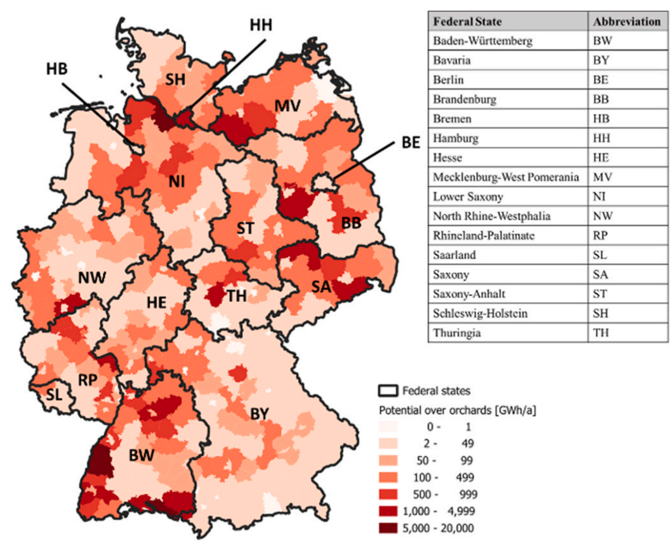

Fig. 7. Energy potential of agrivoltaic systems over orchards based on data from the Agraratlas and the DWD [45,55].

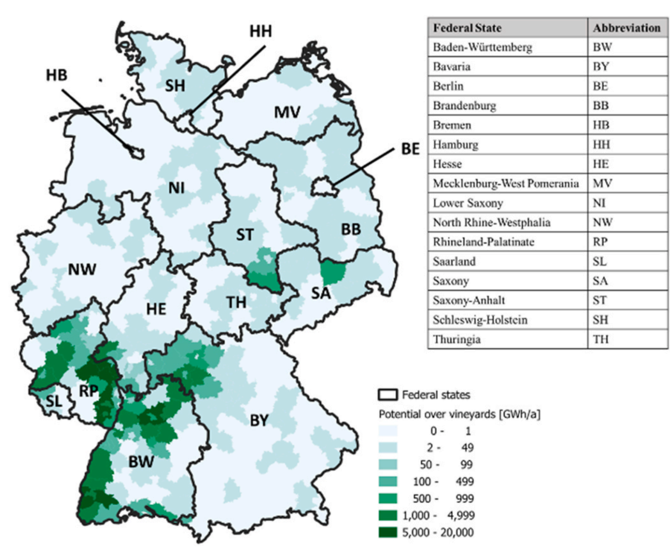

Fig. 8. Energy potential of agrivoltaic systems over vineyards based on data from the Agraratlas and the DWD [45,55].

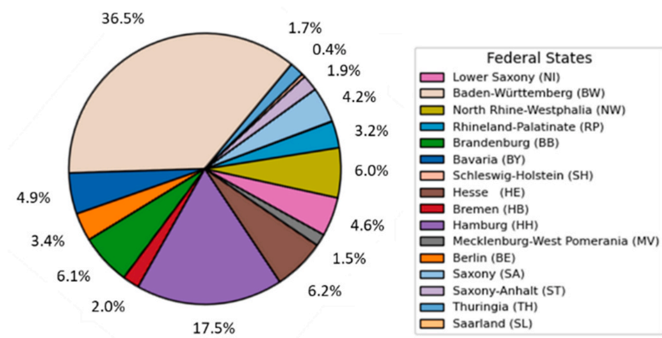

Fig. 9. Distribution of the PV potential over orchards per federal state.

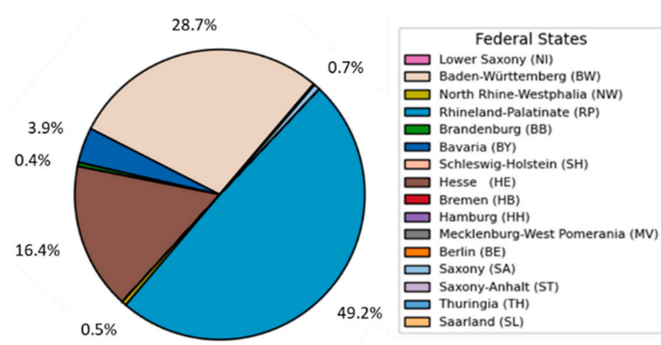

Fig. 10. Distribution of the PV potential over vineyards per federal state.

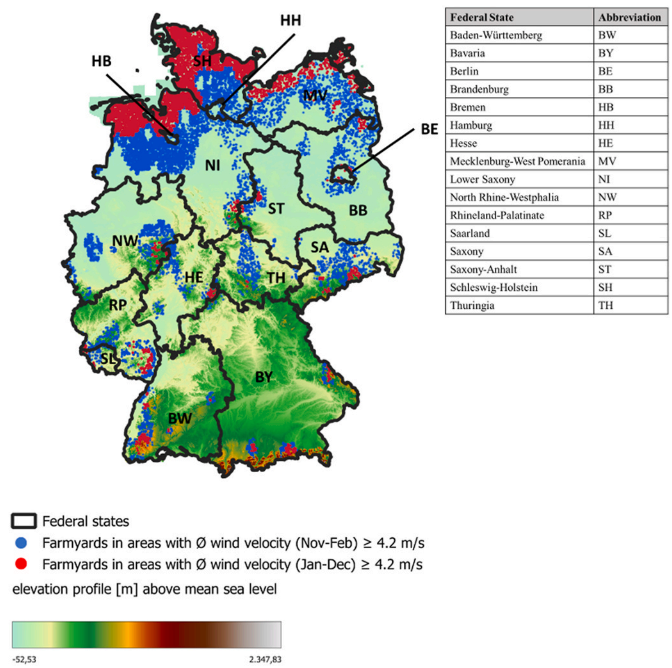

Fig. 11. Distribution of the farms, where sufficient wind velocity is available for wind power plants (wind distribution over the course of one year) based on data from OSM [49] and the DWD [54].

overall potential, as depicted in Figs. 8 and 10. Even though vineyards are not represented in as many districts as orchards, the areas especially in the regions of Worms, the "Southern Wine Route", and near Mainz, (all located in RP) encompass more than 10,000 ha of vineyards. Thereby orchards contribute about 61 % to the agrivoltaic potential which corresponds to roughly 145 TWh/a in contrast to 89 TWh/a for orchards.

3.2. Wind energy potential

Wind energy systems can especially add to energy generation in times differing from PV e.g. during the night or during winter times.

Large-scale turbine installations are mostly built by investors, who rent land and build power plants. Two approaches were used to evaluate the current state of involvement of farmers in building large-scale wind turbines. Firstly, the existing wind turbines in Germany were investigated. A comparison between the locations of the wind turbines from the MaStR with the arable land and meadows retrieved from OSM was conducted. No intersections could be found. One explanation is the possible incorrectness of the geographical data in the MaStR, another is the possible change of land use type in OSM after the installation of the wind energy systems.

In the second approach, the state-designated potential wind energy zones were compared against arable lands and grassland recorded in OSM. Due to lack of data (see 2.1.5.), only NI was considered in this study. 47 % of the designated potential areas were set out on arable land, and 15 % on meadows. Thiele et al. (2022) indicated that substantial portions of these surfaces remain still useable for agriculture after the installation. In the long-term just 0.5 ha become permanently sealed [77]. The total amount of potentially installable large wind power plants on agricultural land shall not be considered in the further calculations the farmers are generally not expected to be the owners of the wind turbines and there is scant information on the areas assigned in all other federal states except NI to draw conclusions for Germany.

Also small-scale wind power plants can be used for electricity production. Fig. 11 shows farms in red that are located in an area with an average wind speed of at least 4.2 m/s throughout the whole year. In blue further farms are labelled when taking into account the average wind velocity of at least 4.2 m/s but only during the winter months (November – February) [67]. It is assumed that small-scale wind turbines are installed close to the farmyards, so the electricity can be used directly. Fig. 11 gives evidence that there is a higher wind velocity during the winter months. As there is less sunshine during winter time compared to the summer months the wind and PV power plants complement each other. Fig. 11 illustrates as well that coastal and mountainous regions generally have favourable conditions for small-scale wind turbine deployment, however, most of the respective farms are rather located in the coastal part instead of the mountainous region. Approximately 61,500 farmyards are situated in areas with suitable wind conditions. Of these farms, 21,400 are located in areas with an average wind speed of 4.2 m/s throughout the year, while the remaining 40,100 farmyards are in areas where the average wind speed exceeds 4.2 m/s during the winter months.

For the wind energy potential calculation, it was defined that a small-scale wind turbine has a power capacity of 20 kW [69]. Assuming every "whole year" - qualifying farm (in red in Fig. 11) constructs one 20 kWp wind turbine, approximately 428.7 MWp capacity could be installed. When considering the farms that reach this average wind velocity during the winter months the summarized potential rises to 1230 MWp. Looking at the wind average over the course of the whole year, Schleswig-Holstein (SH) (10,4 %) and NI (10,3 %) have the highest potential. Taking also the winter average into account, NI has the highest overall potential with 30,8 % (Fig. 12). According to Deutsche WindGuard, for the northern part of Germany, 3299 full load hours per year can be assumed [78]. This leads to a potential of 4 TWh in total for a whole year.

3.3. Geothermal potential

In addition to the possibility to use solar irradiation or wind as RE sources, there is the option to utilize GE. It might be useful to meet the heating demand of farms e.g. for the application in greenhouses and to

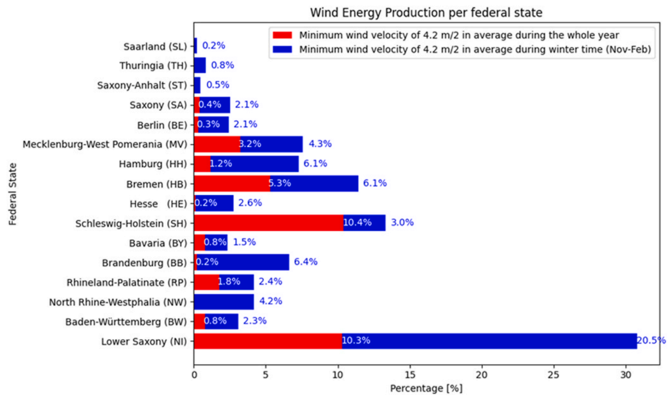

Fig. 12. Distribution of the wind energy potential per federal state.

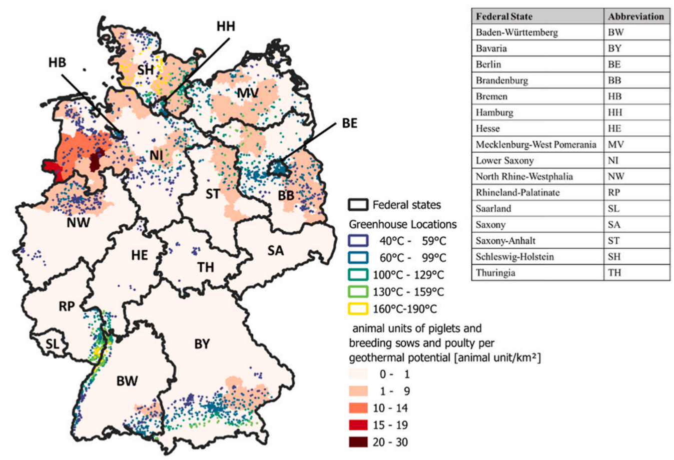

Fig. 13. Distribution of poultry and piglets and breeding sows in animal units per area of the district and share of geothermal potential in the district. The calculation is described in detail in chapter 2.2.3. All deep geothermal resources are equally considered (40 °C–190 °C). White districts either do not contain any poultry farms or have no deep geothermal resources. Greenhouses located above potential hydrothermal areas are shown as coloured points. They are coloured depending on the temperature of the deep geothermic source. The map is based on data from the Agraratlas [45], the Geothermie-Atlas [47] and OSM [49].

maintain warm temperatures of stables, especially for piglets and poultry. Piglets have warmth requirements of approximately 32 °C during their initial week and gradually decrease to roughly 27 °C thereafter [73]. Laying birds produce the greatest number of eggs within the range of 13–24 °C but have the best food conversion in the range of 21–24 °C [72]. Several approaches exist to harness geothermal resources. One such approach is the application of NSGE potential. Numerous studies examined the general potential of NSGE in Germany. Born et al. (2022) studied the potential for NSGE applications in NW [29]. They concluded, that the usage of NSGE is possible everywhere. Restrictions arise from environmental conditions (e.g. nature reserve or a high building density) or the ground for drilling. This means that in rural areas there is a much higher potential than in cities, as the building density is much lower. There are areas in the countryside that allow the coverage of 95 % of the heat demand of residential buildings via geothermal heat pumps [29]. It is assumed, that most farms are located in the countryside and have no or little restrictions concerning the environment. Thus, roughly 95 % of the heat demand on farms could be covered by NSGE heat pumps.

Another approach is geothermal collectors, which are installed 0.8–1.6 m below the surface on approximately twice the area of the heated area. The space required by those collectors strongly depends on the type of soil in the area. Sandy soil requires a larger area, than clay soils, due to the better heat transfer of the wetter clay soil [79]. The soil atlas of the "Bundesanstalt für Geowissenschaften und Rohstoffe" (BGR) shows, that there is sandy soil mostly in the northern part of Germany and clay can be found in the northeastern and southern parts of Germany [80]. It is assumed, that farms especially in the northeastern and southern parts of Germany have the opportunity to use this technology. However, it needs to be considered, that the installation of those large collector areas hinders the cultivation of the fields, mainly when the farmers work with ploughing and do not use direct seeding methods. Nonetheless, there are research approaches that examine the possibilities of installing such collectors under cultivated fields [81,82].

Besides NSGE and geothermal collectors, there is the possibility to use DGE in the form of hydrothermal resources. Those resources are not available everywhere in Germany, but only in specific areas [47]. Fig. 13 depicts an overview of how many farms could use this type of geothermal resource distinguishing between animal husbandry and greenhouse locations. It shows the distribution of farms with animal husbandry in connection with the hydrothermal potential and displays the location of greenhouses that are located above a geothermal potential area. The different colours emphasize greenhouse sites proximate to distinct geothermal temperature levels.

Fig. 13 presents the districts in Germany that have a high number of piglets and poultry, respectively, in areas with DGE heat available. For this investigation's purposes, it is assumed that varying underground temperature levels hold little relevance since geothermal heat pumps can operate efficiently even at temperatures as low as 40 °C. The white districts in the middle of Germany have no DGE potential, so the respective animal farms cannot profit from this RE source (approximately 47 %). In the light-cream-coloured districts either only comparatively few animals are raised or only a small ratio of DGE potential is available in that area (approximately 30 %). The districts in darker orange or darker red contain a high density of piglets and poultry. They are mainly located in the north-west of Germany for piglets and poultry. An analysis per federal state is depicted in Fig. 14 and shows that the geothermal potential for piglets and poultry is especially high in NI, while greenhouses can mostly profit in NW and BY.

Table 1 shows DGE sources for Germany as total numbers, on the one hand for the number of greenhouses and on the other hand dependent on the greenhouse area. However, it must be considered, that it was not possible to distinguish the greenhouses in types of usage. Therefore, not only agricultural-related greenhouses are included.

3.4. Sensitivity analysis

The previously described and applied methodologies rely on several assumptions. These include assumptions concerning the wind velocity, e.g. the roughness factor, the hub height, as well as the assumed operation time of the wind power plants. Regarding the PV potential factors related to PV yield, such as PR, yield per area, and others are assumed. The sensitivity of these factors is depicted in Fig. 15. The 0 % accounts for the assumptions taken in this study (e.g. 15 m hub height and a roughness factor of 0.28). All mentioned PV factors, as well as the operational time of the wind power plants, exhibit a linear correlation. In contrast, the wind factors do not display a linear correlation. For example, a 50 % increase in hub height leads to a 150 % increase in yield, whereas a change in the roughness factor has a significantly smaller impact. An increase in these factors would lead to a change in wind velocity and thereby more farms could qualify for a small wind power plant.

4. Discussion

The previous chapter presented detailed results, which were validated and subsequently used to address the research questions outlined in the introduction chapter.

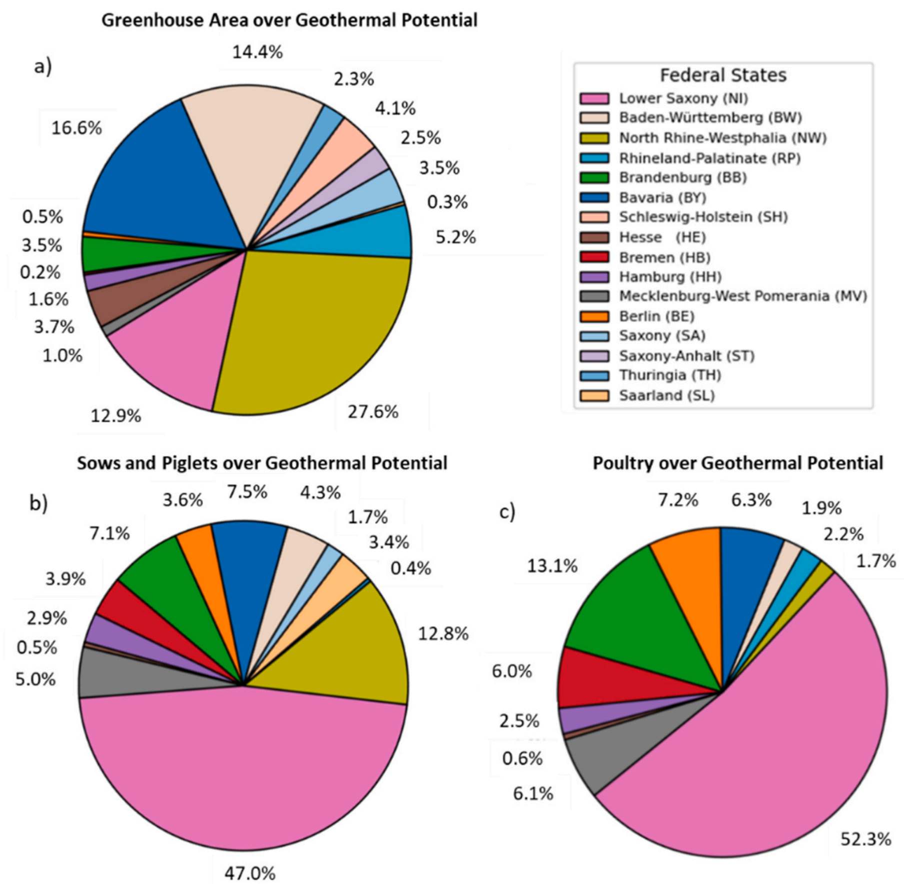

Fig. 14. Distribution of the geothermal potential per federal state for a) greenhouse area, b) amount of sows and piglets and c) amount of poultry.

Table 1
Distribution of greenhouses over the different levels of heat from deep geothermal sources based on data from OSM [49] and the LIAG [46].

Level of underground temperature [°C]	Number of greenhouses	Share of the total amount of greenhouses [%]	Area of greenhouses [m^2]	Share of the total area of greenhouses [%]
40–59	3,773	9.3	3,521,549	9.9
60–99	4,147	10.2	3,703,226	10.4
100–129	2,302	5.7	2,304,652	6.5
130–159	977	2.5	1,279,441	3.6
160–189	534	1.3	824,590	2.3

The first research question in the introduction addresses the still available potential to install additional RE power plants on German farms and their spatial distribution. The calculations were done under the requirement to use available areas for the RE plants without leading to major reductions in the size of the useable agricultural land. In summary, the options of farmers to produce electricity by wind and PV are 4 TWh/a from small-scale wind power plants, 43 TWh/a from rooftop PV plants, 360 TWh from GMPV plants, 145 TWh/a from vineyard agrivoltaic and 89 TWh/a from orchard agrivoltaic installations (in total approx. 641 TWh). Further possibilities are the installation of large-scale wind power plants on agricultural land, however, they are also financed by external investors and not only by farmers. For NI e.g. more than 50 % of the area with large scale wind power plants is located on agricultural land. Depending on the regional properties of the farm's location in Germany and the characteristics of the farm type, the selection of the variety of RE options needs to be considered carefully. In the north region, there is a huge potential for small-scale wind turbines. Solar PV installations are generally feasible all over Germany. However, their precise allocation depends on the chosen system type (rooftop, ground-mounted, or agrivoltaics. Potential disparities stem less from varying irradiance intensities, but rather result predominantly from differing land availability – specifically by accessible roof surfaces, fallow lands, or orchards/vineyards. Orchards can mostly be found near Lake Constance (BW) and in the west of HH and vineyards near the Rhine rift (RP and BW). Fallow land is mostly available in the eastern part of Germany and yet unused rooftops are mainly allocated in the north-eastern part of Germany. Here the lesser PV power production caused by the comparatively lower irradiance can be compensated by more available area compared to the south of

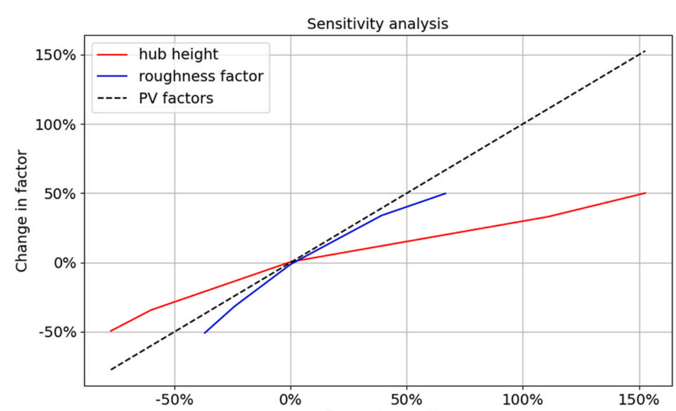

Fig. 15. Results of the sensitivity analysis: Relative changes of the German wind and PV production by relative changes of input parameters.

Germany with higher PV yields. The possibilities of using geothermal potential strongly depends on the form of the GE source. NSGE applications are useable nationwide, while deeper geothermic resource exploitation remains feasible upon specific subterranean reservoirs primarily located within northern regions, yet additionally encompassing the Rhine (BW, HE, and RP) and Molasse Basins (BW and BY). More than 50 % of the animal farmers with poultry and piglets and more than 28 % of the greenhouse operators could profit from DGE. In general, the federal state with the highest total potential for RE generated on farms is thereby NI with the highest rooftop PV potential and geothermal potential for poultry and piglets, with the second highest wind energy potential and GMPV potential as well as the eighth and ninth highest potential on orchards and vineyards, respectively. NI is followed by BW as the federal state with the second highest total potential for RE, with high potential, especially in the agrivoltaics sector, but rather low wind energy potential.

The second research question comprised whether the farms could meet their own ED, by using all their RE potential and whether they could be energy providers if the potential exceeded their own ED. The primary energy needs in German agriculture, forestry, and fishery accounted for approximately 65 TWh/a in the year 2020, which is approximately 2 % of the total primary energy need of Germany [83]. Comparing the energy demand of 65 TWh/a with the RE potential in the German agricultural sector, farmers could produce ten times more energy than needed by themselves, thus, covering their own ED and eventually supplying exceeding energy to the grid. If the RE potential on German farms were exhausted, they could cover up to 20 % of the total primary ED of the country.

To evaluate the findings, additional data sources were incorporated. Regarding PV installations, a comparative analysis between the calculated yields per rated capacity of rooftop PV power plants against those reported in the “Solarertragsdatenbank” was done [84]. In the “Solarertragsdatenbank” operators of PV power plants can insert their annual yield and their rated power. Fig. 16 depicts the discrepancy in percent between the yield values in kWh/kWp listed in the “Solarertragsdatenbank” and the calculated expected yields for rooftop PV on farms. It can be seen, that there is a variation between - 15 % and +15 %. 44 % of the PV power plants are in the range of – 1 %–1 % and 12 % are in the extremes of – 15 % to – 6 % and 6 %–15 %. The yield depends on many factors (e.g. clouding, orientation of the modules, or soiling).

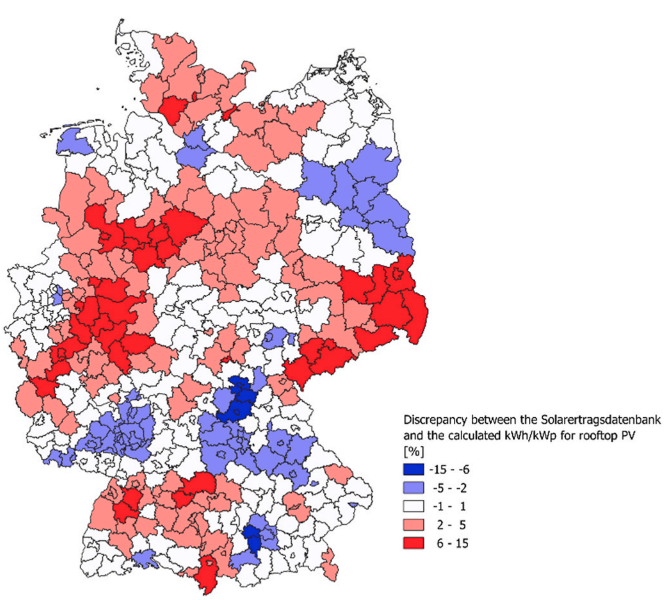

Fig. 16. Discrepancy between the Solarertragsdatenbank and the calculated kWh/kWp for rooftop PV based on data from the Solardatenbank [83], the MaStR [41], OSM [49], and the DWD [55].

Another option to evaluate the calculated potential for PV power plants of the present study is the comparison with other studies. Only Klabunde et al. (2023) [17] and the final report of the project H2@AgTech [18] defined potentials specifically for PV on agricultural rooftops. The current study concludes that there is a potential on agricultural roofs of 46 GWp in Germany whereas Klabunde et al. (2023) [17] identified a potential of 102 GWp, which is more than twice the amount. They chose a different approach in identifying rooftop size in German agriculture by evaluating animal counts and average stable sizes. However, in the present study only 50 % of the agricultural building area was considered. When taking all the roofs into account the numbers show only a difference of 8 %. Comparing the results of the present study to the results of H2@AgTech [18], they identified a potential of 1.79 GWp in NI, whereas the current study identified a potential of around 15 GWp. The approach in the project H2@AgTech was comparable to Klabunde et al. (2023) and therefore very different from the approach used in the current study, as they counted the animals and the adjoining stables for dairy and pig farms [18]. Considering the agrivoltaic potential in Germany, Trommsdorff et al. (2022) found a potential of 1700 GWp in Germany [23]. The present study concluded, that there is an agrivoltaic potential of approx. 233 GWp for vineyards and orchards. It differs a lot from the previously calculated potential, but it neglects arable land and meadows.

The evaluation of wind energy potential is conducted by comparing already existing sites of wind power plants in Germany (not only on farms) to the wind energy potential on farms identified in the present study. Thus, it can be observed that both, the computational model and the current state indicate potential for wind turbine installations in Germany’s northern regions. The largest deviation is observed for Brandenburg (BB), where the model suggests 7 % less build-up of small wind power plants and for Bremen (HB), where it implies a 7 % higher plant installation compared to the current state. Closest to reality are BY, Saxony (SA), Saarland (SL), and Thuringia (TH) with a difference of less than 1 % (Table 2). Thus, the available data for the computational model and the calculation approach led to realistic values. However, it also needs to be considered that the build-up of wind power plants - especially of large wind power plants – can strongly depend on the political circumstances and does not necessarily cohere with wind velocities. For example, the BY federal state law enforces a minimum distance of wind

Table 2
Comparison of the share of large-scale wind power plants that are already installed in Germany with the potential installation of small-scale wind power plants on farms as calculated in Section 3.2.

Federal State	Already installed wind power plants [%]	Potential of small wind power plants on farms [%]	Difference [%]
Brandenburg (BB)	14.0	6.6	7.4
North Rhine-Westphalia (NW)	9.0	4.2	4.8
Hesse (HE)	7.6	2.8	4.8
Berlin (BE)	6.3	2.4	3.8
Saxony-Anhalt (ST)	3.1	0.5	2.6
Baden-Württemberg (BW)	4.7	3.1	1.6
Bavaria (BY)	3.8	2.3	1.5
Saxony (SA)	3.1	2.5	0.6
Rhineland-Palatinate (RP)	4.6	4.2	0.5
Saarland (SL)	0.1	0.2	−0.1
Thuringia (TH)	0.5	0.8	−0.4
Mecklenburg-West Pomerania (MV)	4.3	7.6	−3.2
Schleswig-Holstein (SH)	8.4	13.3	−5.0
Hamburg (HH)	2.1	7.3	−5.2
Lower Saxony (NI)	24.4	30.8	−6.4
Bremen (HB)	4.1	11.4	−7.4

power plants from residential areas of at least 1000 m [85], which does not apply for the other federal states.

Furthermore, it is necessary to generally assess the available data for the calculations within the present study. Data uncertainties may arise due to the community-generated nature of OSM input; for instance, precise differentiation between farmyard and non-farmyard buildings is challenging. In addition, there are no labels in OSM that could distinguish between greenhouses located on a farm or e.g. a botanical garden. Nonetheless, all of them were considered as farm-related. Demetriou (2016) [86] investigated the uncertainties of the usage of OSM for the Cyprian road network. This study concluded that there is especially a lack of positional accuracy. This could lead to incorrect conclusions related to e.g. the intersection of wind power plants and arable land in Section 3.2. Additionally, local variations in wind patterns, including phenomena like wind channels, can impede correct wind velocity prediction using data gathered exclusively from a limited number of DWD meteorological stations. The data collected by the MaStR does not differentiate between already existing rooftop PV or GMPV systems. Hence, there are districts where presumably GMPV systems are installed but, in this analysis, counted as rooftop systems. Since these installed PV power plants were subtracted from the overall potential rooftop area on farms, this calculation leads to negative energy potential values in some districts. Moreover, the investigation of agrivoltaics focuses primarily on the implementation above orchards and vineyards. However, numerous alternative configurations exist for integrating solar arrays with arable lands or even employing vertical installations over pasturelands which are not considered in this paper. Furthermore, data from the TI was used for the present paper [87]. The TI used Bayesian estimation procedures to combine different data sets. This leads to data inaccuracies. Also, the data shown in the geothermal atlas by the LIAG is not free of errors as can be read in their description [88].

The geothermal resources are usually used in combination with a heat pump. This means the heating demand could be covered either by using an NSGE or a DGE heat pump or just by air heat pumps. The usage of geothermal resources can increase the coefficient of performance in comparison to simple air heat pumps, especially on cold days. This could be an advantage considering the high demand for heat on some types of farms. However, an economic analysis for every individual case would be necessary, as the investment costs for NSGE heat pumps, DGE heat pumps, and air heat pumps vary a lot, depending on the sizing, etc. Especially the depth drilling increases the cost of geothermal solutions [89–91]. However, the higher the temperature level of DGE, the lower the need for the required electricity used by the heat pump. In this study, though, the electricity demand of the heat pump was not considered, as well as economic investigations were out of the scope of this paper.

Looking at the methods used in this paper, the limitations result from the availability of data and the definition of assumptions. The variation of some assumptions was examined for wind energy and PV potentials in a sensitivity analysis in section 3.4 which gave evidence that the results are more or less dependent on the adjustment of single factors.

Despite the constraints of the present study mentioned above, the collected data shows the large number of options that farmers have to invest in RE power plants. Especially by considering new concepts of hybrid farms, which engage in a more technological way of farming, the energy demand rises and the local production becomes more crucial. This could be advantageous when electricity prices rise, when the CO_2 taxes increase, when customers of agricultural products become more aware of their CO_2 footprint, or as an alternative income source when there is only little harvest due to droughts or other extreme weather events. Furthermore, other than the production of energy by biomass or fossil resources, for wind, PV as well as GE there are only the investment and maintenance costs and no ongoing costs e.g. for fuel. The presented RE systems account only for the electricity and heat demand on farms, as the produced electricity can be converted into heat for example with a heat pump.

5. Conclusion, summary, and Outlook

This study explored the potential for integrating RE on agricultural lands to support a net-zero-emission energy system. Using GIS, the research evaluated the spatial distribution of suitable locations for renewable power plants on German farms. The results indicate substantial potential for small-scale wind and PV power plants. Specifically, the study identifies a potential of approximately 4 TWh/a for small-scale wind power plants, primarily concentrated in the northern regions of Germany. For PV power plants, the total estimated potential is around 637 TWh/a, with the following distribution: 56 % for GMPV systems, 37 % for agrivoltaic systems, and 7 % for rooftop PV. Furthermore, the study highlights geothermal potential in the northwest, Molasse (BW and BY), and Rhine basins (BW, HE, RP). The analysis also shows that GMPV systems are mostly located in the eastern part, rooftop systems in the northwest, and agrivoltaic systems in RP and BW.

In subsequent studies, it is planned to explore the integration of RE generation into individual farm operations based on case studies considering the presented RE potentials and measured EDs. The findings of the present study only consider annual RE generation and they do not provide insight into the temporal overlaps between ED on farms and the possible RE supply. To increase the locally useable amount of fluctuating RE, different storage technologies might be necessary. Additionally, a deeper analysis of sector integration on farms, based on their regional properties and farm type, would be worthwhile. Further studies should also consider the potential for farms to produce their own fuels for mobility, including hydrogen through electrolysis, biogas, and plant oil. By exploring these possibilities, a more comprehensive understanding of the opportunities for integrating RE generation into farm operations can be gained, thereby enhancing the sustainability and profitability of farms in Germany.

Usage of generative AI

The authors utilized Generative AI technologies for language optimization during the preparation of this work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Lea von Rüden: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Barbara Satola:** Conceptualization, Writing – review & editing, Project administration. **Nies Reininghaus:** Conceptualization, Writing – review & editing. **Michael Kröner:** Conceptualization, Writing – review & editing, Project administration, Supervision. **Martin Vehse:** Conceptualization, Writing – review & editing, Supervision. **Alexander Dyck:** Supervision. **Carsten Agert:** Supervision.

Declaration of competing interest

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

Appendix

Appendix 1Table with an overview on the cited literature in the literature review part

Study	Energy considered	Location	results	Agricultural context
Scarlat et al. (2018) [9]	Biomass – from manure	Europe	Theoretical potential: 22.7 billion m^3 in Europe 2907 million m^3 CH_4 in Germany	yes
Bidart et al. (2014) [10]	Biomass – from manure and crop residue	Chile	From manure economic potential of 0.8 TWh_e/y From mono-digestion of agricultural residue economic potential of 1.1 TWh_e/y	yes
Monforti et al. (2013) [11]	Biomass from crop residue	Europe	Theoretical potential of 416.6 TWh/a	yes
Van Duren et al. (2015) [12]	Biodiesel production - rapeseed	Europe	Only a limited number of areas with an energy return on energy investment >1	yes
Bao et al. (2021) [13]	Bioenergy	Germany	Study suggests that limiting the bioenergy production is the best way to secure food production.	yes
Mehdaoui et al. (2022) [15]	PV	Tunisia	Methodology for optimal location of desalination plants	no
Lödl et al. (2010) [16]	PV – rooftop	Germany	Technical potential of 161 GWp on rooftops	no
Klabunde et al. (2023) [17]	PV – rooftop in agriculture	Germany	Technical potential 102.8 GWp	yes
Hüer et al. (2022) [18]	PV – rooftop in agriculture	Lower – Saxony (Germany)	Technical potential of 1.23 GWp for cowsheds and 0.561 GWp for pigsties	yes
Bao et al. (2022) [19]	PV – ground mounted	Two specific regions in Germany	Development of a methodology	no
Kelm et al. (2019) [21]	PV – ground mounted	Germany	Analysis with focus on restrictions of the law	no
Perpina et al. (2016) [20]	PV	Europe	GIS analysis on where PV is most suitable	no
Trommsdorff et al. (2022) [23]	Agrivoltaics	Germany	Theoretical potential: 1700 GWp for agrivoltaic installations over shade-tolerant plants in Germany, and additional 1200 GWp over grassland	yes
Fliegner and Möst (2023) [24]	Offshore Wind energy potential	Germany	Connection of offshore wind to the grid	no
Grieser et al. (2015) [25]	Small wind turbines	Germany	Economic analysis	no
Moeck et al. (2022) [27]	Geothermal	Germany	Review study on geothermal potential in Germany	no
Sandrock et al. (2023) [28]	Deep geothermal potential	Germany	Study on the deep geothermal potential in Germany	no
Born et al. (2022) [29]	Near surface geothermal potential	Germany	Study on the near surface geothermal potential in Germany	no

Data availability

There are various data sources used to conduct the study. Those are all publicly available and cited at the relevant position in the text. They can be accessed via the links given in the reference list. The metadata shown in this study is available upon request.

References

[1] Deutscher bundestag. Bundes-klimaschutzgesetz: KSG 2021;24.06.
[2] Umweltbundesamt. Erneuerbare energien in Zahlen. Available from: https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick; February 08, 2024.
[3] Bundesamt Statistisches. Flächennutzung: Bodenfläche insgesamt nach Nutzungsarten in Deutschland. Available from: https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Landwirtschaft-Forstwirtschaft-Fischerei/Flaechennutzung/Tabellen/bodenflaeche-insgesamt.html; February 08, 2024.
[4] Südwestrundfunk. Bauern in RLP regen sich über Diskussion um Biosprit auf. Available from: https://www.swr.de/swraktuell/rheinland-pfalz/debatte-um-energie-vom-acker-100.html; February 26, 2024.
[5] Böhm J, Witte T de, Michaud C. Land use prior to installation of ground-mounted photovoltaic in Germany—GIS-analysis based on MaStR and basis-DLM. Z Energiewirtschaft 2022;46(2):147–56. https://doi.org/10.1007/s12398-022-00325-4.
[6] Bundestag. Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare- Energien-Gesetz - EEG 2023). EEG; 2024. §4.
[7] Pfaffinger A. Photovoltaikausbau in Deutschland: Ein Blick auf die Fortschritte und Zukunftsaussichten. Available from: https://www.power2nature.de/artikel/photovoltaikausbau-in-deutschland-ein-blick-auf-die-fortschritte-und-zukunftsaussichten; December 17, 2024.
[8] Umweltbundesamt. Biogasanlagen. Available from: https://www.umweltbundesamt.de/themen/wirtschaft-konsum/industriebranchen/biogasanlagen#einfuhrung; February 09, 2024.
[9] Scarlat N, Fahl F, Dallemand J-F, Monforti F, Motola V. A spatial analysis of biogas potential from manure in Europe. Renew Sustain Energy Rev 2018;94:915–30. https://doi.org/10.1016/j.rser.2018.06.035.
[10] Bidart C, Fröhling M, Schultmann F. Livestock manure and crop residue for energy generation: macro-assessment at a national scale. Renew Sustain Energy Rev 2014;38:537–50. https://doi.org/10.1016/j.rser.2014.06.005.
[11] Monforti F, Bódis K, Scarlat N, Dallemand J-F. The possible contribution of agricultural crop residues to renewable energy targets in Europe: a spatially explicit study. Renew Sustain Energy Rev 2013;19:666–77. https://doi.org/10.1016/j.rser.2012.11.060.
[12] van Duren I, Voinov A, Arodudu O, Firrisa MT. Where to produce rapeseed biodiesel and why? Mapping European rapeseed energy efficiency. Renew Energy 2015;74:49–59. https://doi.org/10.1016/j.renene.2014.07.016.
[13] Bao K, Padsala R, Coors V, Thrän D, Schröter B. A GIS-based simulation method for regional food potential and demand. Land 2021;10(8):880. https://doi.org/10.3390/land10080880.
[14] Statistisches Bundesamt. Landwirtschaftliche Betriebe: Anlagen zur Erzeugung erneuerbarerer41 Energien - 2023. 2024.
[15] Mehdaoui R, Anane M, Cañas Kurz EE, Hellriegel U, Hoinkis J. Geospatial multi-criteria approach for ranking suitable shallow aquifers for the implementation of an on-farm solar-PV desalination system for sustainable agriculture. Sustainability 2022;14(13):8113. https://doi.org/10.3390/su14138113.
[16] Lödl M, Kerber G, Witzmann R, Hoffmann C, Metzger M. Abschätzung des Photovoltaik-Potentials auf Dachflächen in Deutschland. In: 11. Symposium Energieinnovation "Alte Ziele – Neue Wege".
[17] Klabunde F, Engel B. Rooftop photovoltaic systems in German agriculture – an analysis of the status quo and potential for the future. In: VDE ETG kongress; 2023.

[18] Agravis DLR. Cloppenburg Landkreis, Grimme, Osnabrück-Emsland-Grafschaft Bentheim Handwerkskammer, Krone Strautmann, Vogelsang Wigos H2BX. H2@ AgTech – Ein Projekt der Metropolregion Nordwest: Wasserstoff in der Landwirtschaft und Landtechnik. Abschlussbericht; 2023. p. 18–20.
[19] Bao K, Kalisch L, Santhanavanich T, Thrän D, Schröter B. A bottom-up GIS-based method for simulation of ground-mounted PV potentials at regional scale. Energy Rep 2022;8:5053–66. https://doi.org/10.1016/j.egyr.2022.03.187.
[20] Perpiña Castillo C, Batista e Silva F, Lavalle C. An assessment of the regional potential for solar power generation in EU-28. Energy Pol 2016;88:86–99. https://doi.org/10.1016/j.enpol.2015.10.004.
[21] Kelm T, Metzger J, Fuchs A-L, Schicketanz S, Günnewig D, Thylmann M. Untersuchung zur Wirkung veränderter Flächenrestriktionen für PV-Freiflächenanlagen: Kurzstudie im Auftrag der innogy SE. 2019. p. 81–2.
[22] Charabi Y, Rhouma MBH, Gastli A. Siting of PV power plants on inclined terrains. Int J Sustain Energy 2016;35(9):834–43. https://doi.org/10.1080/14786451.2014.952298.
[23] Trommsdorff M, Gruber S, Keinath T, Hopf M, Hermann C, Schönberger F, et al. Agri-Photovoltaik: Eine Chance für Landwirtschaft und Energiewende: Ein Leitfaden für Deutschland. Freiburg; 2022.
[24] Fliegner FJ, Möst D. High-resolution scenario building support for offshore grid development studies in a geographical information system. Energy Strategy Rev 2023;48:101110. https://doi.org/10.1016/j.esr.2023.101110.
[25] Grieser B, Sunak Y, Madlener R. Economics of small wind turbines in urban settings: an empirical investigation for Germany. Renew Energy 2015;78:334–50. https://doi.org/10.1016/j.renene.2015.01.008.
[26] Lütkehus I, Salecker H, Adlunger K. Potential der Windenergie an Land: Studie zur Ermittlung des bundesweiten Flächen und Leistungspotentials der Windenergienutzung an Land. Dessau-Roßlau; 2013.
[27] Moeck I. Metastudie zur nationalen Erdwärmestrategie: Ersatz fossiler Brennstoffe im Bereich Raumwärme und Warmwasser durch Geothermie als unverzichtbarer Bestandteil im Energiesektor Ökowärme bis 2045. In: Entwicklung des Energiebedarfs für Raumwärme und Warmwasser gespiegelt mit Ausbaupfaden der Geothermie; 2022. Hannover.
[28] Sandrock M, Maaß C, Weisleder S, Westholm H, Schulz W, Löschan G et al. Kommunaler Klimaschutz durch Verbesserung der Effizienz in der Fernwärmeversorgung mittels Nutzung von Niedertemperaturwärmequellen am Beispiel tiefengeothermischer Ressourcen: Abschlussbericht.
[29] Born H, Bracke R, Eicker T, Rath M. Roadmap oberflächennahe Geothermie. Fraunhofer IEG; 2022.
[30] Müller MO, Stämpfli A, Dold U, Hammer T. Energy autarky: a conceptual framework for sustainable regional development. Energy Pol 2011;39(10):5800–10. https://doi.org/10.1016/j.enpol.2011.04.019.
[31] Rae C, Bradley F. Energy autonomy in sustainable communities—a review of key issues. Renew Sustain Energy Rev 2012;16(9):6497–506. https://doi.org/10.1016/j.rser.2012.08.002.
[32] Mainzer K, Fath K, McKenna R, Stengel J, Fichtner W, Schultmann F. A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany. Sol Energy 2014;105:715–31. https://doi.org/10.1016/j.solener.2014.04.015.
[33] Benli H, Durmuş A. Evaluation of ground-source heat pump combined latent heat storage system performance in greenhouse heating. Energy Build 2009;41(2):220–8. https://doi.org/10.1016/j.enbuild.2008.09.004.
[34] Blanco I, Anifantis AS, Pascuzzi S, Scarascia Mugnozza G. Hydrogen and renewable energy sources integrated system for greenhouse heating. J Agricult Engineer 2013;44(2s). https://doi.org/10.4081/jae.2013.287.
[35] Ganguly A, Misra D, Ghosh S. Modeling and analysis of solar photovoltaic-electrolyzer-fuel cell hybrid power system integrated with a floriculture greenhouse. Energy Build 2010;42(11):2036–43. https://doi.org/10.1016/j.enbuild.2010.06.012.
[36] Islam MM, Mun H-S, Bostami ABMR, Park K-J, Yang C-J. Combined active solar and geothermal heating: a renewable and environmentally friendly energy source in pig houses. Environ Prog Sustain Energy 2016;35(4):1156–65. https://doi.org/10.1002/ep.12295.
[37] Amid S, Mesri Gundoshmian T, Rafiee S, Shahgoli G. Energy and economic analysis of broiler production under different farm sizes. Elixir Agriculture 2015;78:29688–93.
[38] Bey M, Hamidat A, Benyoucef B, Nacer T. Viability study of the use of grid connected photovoltaic system in agriculture: case of Algerian dairy farms. Renew Sustain Energy Rev 2016;63:333–45. https://doi.org/10.1016/j.rser.2016.05.066.
[39] Fuchs C, Poehls A, Skau K, Kasten J. Economics of battery use in agriculture: economic viability of renewable energy complemented with batteries in agriculture. Energies 2021;14(9):2430. https://doi.org/10.3390/en14092430.
[40] Aschilean I, Rasoi G, Raboaca M, Filote C, Culcer M. Design and concept of an energy system based on renewable sources for greenhouse sustainable agriculture. Energies 2018;11(5):1201. https://doi.org/10.3390/en11051201.
[41] Bundesnetzagentur. Marktstammdatenregister. Available from: https://www.marktstammdatenregister.de/MaStR/Datendownload; February 28, 2023.
[42] Bundesministerium für Ernährung und Landwirtschaft. Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten 2022. Frankfurt am Main. 2023.
[43] Forschungsdatenzentren der Statistischen Ämter des Bundes und der Länder. Landwirtschaftszählung - Haupterhebung 2020, On-Site, Version 0. RDC of the Federal Statistical Office and the statistical offices of the Länder (RDC); 2021. p. 23–39.
[44] Landesbetrieb Information und Technik Nordrhein-Westfalen. Regionaldatenbank Deutschland February 09, 2024. Available from: https://www.regionalstatistik.de.
[45] Johann Heinrich von Thünen-Institut. Thünen agraratlas: landwirtschaftliche nutzung. Version 2022. 2022. Braunschweig.
[46] Agemar T, Schellschmidt R, Schulz R. Subsurface temperature distribution in Germany. Geothermics 2012;44:65–77. https://doi.org/10.1016/j.geothermics.2012.07.002.
[47] Schulz R, Knpf S, Suchi E, Ölschläger D, Dittmann J, Müller C. Geothermie-Atlas zur Darstellung möglicher Nutzungskonkurrenzen zwischen CCS und Tiefer Geothermie. 2013. Hannover.
[48] Agemar T, Alten J-A, Ganz B, Kuder J, Kühne K, Schumacher S, et al. The geothermal information system for Germany: GeotIS. Z Dtsch Ges Geowiss 2014;165(2):129–44. https://doi.org/10.1127/1860-1804/2014/0060.
[49] OpenStreetMap contributors. Planet dumpretrieved from: https://planet.openstreetmap.org; Available from:: https://www.openstreetmap.org.
[50] Martin Raifer. overpass turbo. Available from: https://overpass-turbo.eu/. [Accessed 19 February 2024].
[51] Xylome. Proposal:Farmyard. Available from: https://wiki.openstreetmap.org/wiki/Proposal:Farmyard. [Accessed 19 February 2024].
[52] Boeing G. OSMnx: new methods for acquiring, constructing, analyzing, and visualizing complex street networks. Comput Environ Urban Syst 2017;65:126–39. https://doi.org/10.1016/j.compenvurbsys.2017.05.004.
[53] QGIS Development Team. QGIS geographic information system. 2024. Available from: https://www.qgis.org.
[54] Wetterdienst Deutscher. Climate Data Center. 10-minütige Stationsmessungen des Windes für Deutschland. Available from: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/10_minutes/wind/. [Accessed 19 February 2024].
[55] Wetterdienst Deutscher, Climate Data Center. 10-minütige Stationsmessungen der Strahlung und Sonnenscheindauer für Deutschland. Available from: https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/10_minutes/solar/. [Accessed 19 February 2024].
[56] The pandas development team. pandas-dev/pandas: pandas. Zenodo; 2024. https://doi.org/10.5281/zenodo.10957263.
[57] Bundestag. WindBG; 2022. §3.
[58] Peters W, Herbeck T, Hildebrand S, Pape C, Geiger D, Zink C, et al. FLÄCHENPOTENZIALANALYSE FÜR WINDENERGIE AN LAND IN NIEDERSACHSEN: (WINNIEPOT). February 19, 2024. Available from: https://www.umwelt.niedersachsen.de/startseite/aktuelles/ergebniskarten-derwindflachenpotenzialanalyse-downloadmoglichkeit-220485.html.
[59] Microsoft Corporation. Microsoft Excel. Microsoft Office Professional Plus; 2019.
[60] Wąs A, Sulewski P, Gerasymchuk N, Stepasyuk L, Krupin V, Titenko Z, et al. The potential of Ukrainian agriculture's biomass to generate renewable energy in the context of climate and political challenges—the case of the kyiv region. Energies 2022;15(18):6547. https://doi.org/10.3390/en15186547.
[61] Ghasemi G, Noorollahi Y, Alavi H, Marzband M, Shahbazi M. Theoretical and technical potential evaluation of solar power generation in Iran. Renew Energy 2019;138:1250–61. https://doi.org/10.1016/j.renene.2019.02.068.
[62] Grassi S, Veronesi F, Schenkel R, Peier C, Neukom J, Volkwein S, et al. In: Mapping of the global wind energy potential using open source GIS data; 2015.
[63] Doelling RJ. Photovoltaik: Ertrag verstehen, einfach berechnen & mit Kennzahlen vergleichen. Available from: https://www.energie-experten.org/erneuerbare-energien/photovoltaik/planung/ertrag; April 29, 2024.
[64] Finke Hanns-Stefan. Die Performance Ratio in der Photovoltaik. Available from: https://photovoltaiksolarstrom.com/photovoltaiklexikon/performance-ratio-photovoltaik/; March 25, 2024.
[65] Leumann T. Wie viel Strom produziert 1 ha Photovoltaik? Erfahre jetzt, wie viel Energie du mit Solaranlagen erzeugen kannst. Available from: https://pv-held.de/wie-viel-strom-produziert-1-ha-photovoltaik/; March 25, 2024.
[66] Trommsdorff M, Hopf M, Hörnle O, Berwind M, Schindele S, Wydra K. Can synergies in agriculture through an integration of solar energy reduce the cost of agrivoltaics? An economic analysis in apple farming. Appl Energy 2023;350:121619. https://doi.org/10.1016/j.apenergy.2023.121619.
[67] Peters W, Rosenthal S, Volmer M, Hanusch M, Bovet J, Kindler L, et al. Untersuchung von speziellen Hemmnissen im Zusammenhang mit der Umweltbewertung in der Planung und Genehmigung der Windenergienutzung an Land und Erarbeitung von Lösungsansätzen: -Schlussbericht-. Dessau-Roßlau; 2013.
[68] Schmidt B, Schmidt D. Grundkurs Windenergie 2015:9–13.
[69] Tummala A, Velamati RK, Sinha DK, Indraja V, Krishna VH. A review on small scale wind turbines. Renew Sustain Energy Rev 2016;56:1351–71. https://doi.org/10.1016/j.rser.2015.12.027.
[70] Reinboth C. Wie berechnet man die Windgeschwindigkeit auf Höhe der Rotornabe eines Windrads?. Available from: https://scienceblogs.de/frischer-wind/2009/10/12/wie-berechnet-man-die-hohenabhangige-windgeschwindigkeit/; April 05, 2024.
[71] Strzelczyk P, Szczerba Z, Woźniak A. Modelowanie pionowego profilu prędkości wiatru w tunelu aerodynamicznym. ZNPRzBiS 2015;XXXII(3/I/2015)413–427. https://doi.org/10.7862/rb.2015.125.
[72] FAO. Rural structures in the tropicsDesign and development. 2011. p. 229.
[73] Licharz H, Rösmann P, Krommweh MS, Mostafa E, Büscher W. Energy efficiency of a heat pump system: case study in two pig houses. Energies 2020;13(3):662. https://doi.org/10.3390/en13030662.
[74] Leumann T. Wie viel qm Dachfläche braucht man für 1 kWp Photovoltaik? Erfahre die Antwort und warum es wichtig ist. Available from: https://pv-held.de/wie-viel-qm-dachflaeche-fuer-1-kwp-photovoltaik/; April 04, 2024.
[75] Schlegel J. Auswirkungen von Freiflächen-Photovoltaikanlagen auf Biodiversität und Umwelt Literaturstudie. Bundesamt für Energie BFE; 2021.

[76] Goetzberger A, Zastrow A. On the coexistence of solar-energy conversion and plant cultivation. Int. J. Solar Energy 1982;1(1):55–69. https://doi.org/10.1080/01425918208909875.
[77] Thiele E. Zum Flächenbedarf der Windenergie. Available from: https://www.naturschutz-energiewende.de/kompetenzzentrum/presse/pressemitteilungen/zum-flaechenbedarf-der-windenergie/; January 30, 2024.
[78] Windguard Deutsche Volllaststunden von Windenergieanlagen an Land. Auswirkungen. Varel. 2020. p. 16–8.
[79] Bundesverband Geothermie e.V. Erdwärmekollektor. Available from: https://www.geothermie.de/bibliothek/lexikon-der-geothermie/e/erdwaermekollektor; May 31, 2024.
[80] Bundesanstalt für Geowissenschaften und Rohstoffe. Bodenarten der Oberböden; May 31, 2024. Available from: https://geoportal.bgr.de/mapapps/resources/apps/geoportal/index.html?lang=de#/geoviewer?metadataId=0f71e68f-8c83-4371-8842-1a26abed1854.
[81] Grosa A, Henke M, Herlitzius T, Kluge J. In: Technik Land, editor. Agrothermie – Minimal Invasive Einrichtung von Geothermie-Netzen unter landwirtschaftlich genutzten Flächen – Warum eine Sondermaschine für die Agrothermie?. first ed., vol. 2018. Düsseldorf: VDI Verlag; 2018. p. 309–20.
[82] Liu J, Beck B, Münch J, Grosa A, Kahle R, Weber J, et al. Agrothermie - design and testing of a novel hydraulically-actuated, locally vibrating plough. In: Volume 3 - conference. Technische Universität Dresden; 2020. p. 73–82.
[83] Statistisches Bundesamt. Primärenergieverbrauch nach Wirtschaftszweigen. Available from: https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/energiefluesse-emissionen/Tabellen/primaerenergieverbrauch.html; April 29, 2024.
[84] Solarenergie Förderverein e.V. Regionale Ertragsübersichten. Available from: https://ertragsdatenbank.de/auswertung/region.html?j=2020&r=01&a=regionen; March 26, 2024.
[85] Bayerische Bauordnung. BayBO; 2007. §82.
[86] Demetriou D. Uncertainty of OpenStreetMap data for the road network in Cyprus. In: Themistocleous K, Hadjimitsis DG, Michaelides S, Papadavid G, editors. Fourth international conference on remote sensing and geoinformation of the environment (RSCy2016). SPIE; 2016, 968806.
[87] Gocht A. Der thünen-agraratlas. Available from: https://www.thuenen.de/de/institutsuebergreifende-projekte/der-thuenen-agraratlas; January 06, 2025.
[88] Agemar T, Alten J-A, Kunkel C, Kuder J, Skiba P, Suchi E, et al. Charakterisierung geothermischer Ressourcen unter Berücksichtigung von Grenz- und Trennflächen in NW-Deutschland: Teilprojekt A. Endbericht. 2020. Hannover.
[89] Schlagermann P, Reinicke KM. Modeling and economic evaluation of deep geothermal heat supply systems using the example of the Wealden near Hannover, Germany. Geotherm Energy 2023;11(1):1–22. https://doi.org/10.1186/s40517-023-00276-0.
[90] Kutzner S, Heberle F, Brüggemann D. Thermo-economic analysis of near-surface geothermal energy considering heat and cold supply within a low-temperature district heating network. Processes 2022;10(2):421. https://doi.org/10.3390/pr10020421.
[91] Blum P, Campillo G, Kölbel T. Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. Energy 2011;36(5):3002–11. https://doi.org/10.1016/j.energy.2011.02.044.