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Energy, Sustainability and Society (2025) 15:12
https://doi.org/10.1186/s13705-024-00504-w

Energy, Sustainability and Society

RESEARCH

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Evolution of patterns of specific land use by free-field photovoltaic power plants in Europe from 2006 to 2022

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Abstract

Background Land use for the conversion of energy from renewable sources into electrical energy is increasingly competing with cultural landscapes and natural areas. It is anticipated that by 2050, solar energy generation will have increased by a factor of 15, which will result in a considerable expansion of the land area required for photovoltaic (PV) power plants on a global scale. An increase in the efficiency of PV modules and an optimisation of the space usage for PV power plant construction will contribute to a reduction in the expected environmental impact on land use. This study represents an empirical investigation into the European development of specific energy and area-relevant key performance indicators of free-field PV power plants. It employs a comprehensive sample drawn from diverse European geographical locations from different installation years.

Methods This study investigated the evolution of various location-independent and location-dependent system parameters over time, using a sample of 107 free-field PV power plants across diverse European regions from 2006 to 2022 related to the fenced area. The investigations concentrated on the land use per installed power, land use per module area, land use per generated electrical energy, generated electrical energy per PV module area, energy density, capacity factor, and power density. The determined data provide the first European average life cycle inventory data, disaggregated by year and location, for environmental life cycle assessment. To facilitate a comparison of the system parameters of PV power plants with those of other renewable energy technologies, a further database was employed, including 89 power plants from the biomass, wind power, geothermal energy, solar thermal energy, and photovoltaic sectors. The selected samples were compiled from this database to compare the area-specific energy yields of both data sources.

Results The European trends for free-field PV power plants demonstrate a 60% reduction in specific land use per installed power and land use per generated electrical energy over the study period. In 2022, the median values were 14 m^2/kW and 0.011 m^2.a/kWh, respectively. The analysis indicates that three significant technological advances have occurred at approximately 5-year intervals. At the mounting design level, the land use per module area for conventional fixed-tilt row systems decreased by 30%. Overall, the mean land usage of all the considered PV power plants is threefold greater than the module area over the entire study period. Likewise, the results show that the high land usage caused by tracking systems is entirely compensated for by a relatively high energy yield, which presents an opportunity to develop innovative designs for multiple-use systems. A comparison of PV power plants with other

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renewable energy power plants reveals that solar thermal heat is distinctly superior in terms of the energy yield received per unit area.

Conclusions To minimise land use, it is recommended that minimum energy efficiency requirements should be defined for new free-field PV power plants in addition to an optimised mounting design within the fenced area. The high energy yield of tracking systems, which have comparatively large row/pole distances, provides the opportunity for multiple uses of the ground area. Furthermore, the discrepancy in energy yield between northern and southern Europe underscores the need for a more comprehensive European planning strategy with regard to the future location of free-field PV power plants. To realise energy transition in the future, it will also be essential to consider all energy potentials together rather than to focus on isolated and small-scale initiatives. The policy changes require Europe-wide coordination, coupled with tailored national and regional definitions. Integrated spatial and energy planning could be a potential avenue for achieving this challenging aim.

Keywords Photovoltaic PV, Solar park, Land use, Agricultural land occupation ALO, Life cycle assessment LCA, Life cycle inventory LCI, Europe

Background

The renewable energy transition represents a significant challenge to *land use* and *land use change*. The increasing utilisation of renewable energy sources has resulted in long-lasting changes in landscapes, natural habitats and ecosystems and increased competition for land [1]. Photovoltaic power plants, followed by wind power plants, are expected to be the greatest drivers of the energy transition [2, 3]. However, the associated land requirements could meet the limits, particularly for a number of industrial nations [4].

Consequently, a successful renewable energy transition requires the establishment of new interdisciplinary collaboration [5], which should pursue innovative approaches to local integrated spatial and energy planning and multiple-use systems [6, 7], as well as appropriate feedback mechanisms [8].

The technical rollout of renewable energy infrastructure is also embedded in a changing regulatory and sociocultural context [9]. Furthermore, it is essential to integrate environmental psychology and aesthetics into the design of sustainable energy landscapes [10] as well as changes in consumption patterns and lifestyles [11] through a multidisciplinary approach.

Global and European energy statistics

To provide a framework for investigating the topic of land use and energy landscapes, a detailed analysis of global and European energy balances is presented in the following section. The total world energy balance shows that in 2022, the world *final energy* demand was approximately 441 EJ (equal to 122.5 PWh), with an electrical energy share of 24% [2].

In addition to biomass, solar thermal and geothermal energy, the largest share of the utilisation of renewable energy sources is characterised by the direct conversion of solar energy into electrical energy through hydroelectric power plants, wind power plants, and photovoltaic power plants. One pillar of achieving low-emission energy transformation is the future electrification of energy applications, including the mobility sector and domestic heating and cooling [12]. Consequently, the demand for electrical energy in Europe is projected to double by 2050 [13].

Electrical energy

In 2022, the global demand for *electrical energy* was 29.5 PWh [2]. Of this, 2.8 PWh, representing 9.5%, were accounted for by the European Union [14]. In the same year, the proportion of global electrical energy generation based on *solar energy* (photovoltaics and solar and storage) was approximately 1.4 PWh. A forecast for 2030 indicates an increase of a factor of 4, and a forecast for 2050 indicates an increase of a factor of 15 [2].

These predictions entail large-scale new energy infrastructure, the implementation of which will be accompanied by extensive spatial changes in spatial structure and considerable additional land demand.

Share of energy from renewable sources in Europe

In the *European Union* (EU27) in 2020, the overall average share of *energy from renewable sources* (annual balancing) was 22%. However, the single values differ significantly between countries, ranging from 10% (Malta, lower bound) to 60% (Sweden, upper bound). Notably, two non-EU countries have achieved even higher rates: Norway and Iceland (78% and 84%, respectively) [15].

In accordance with Fig. 1, the proportion of renewable energy in total demand has significantly increased since 2005. However, only a limited number of countries, including Sweden, Norway and Iceland, have achieved a level exceeding 50%. The remaining countries

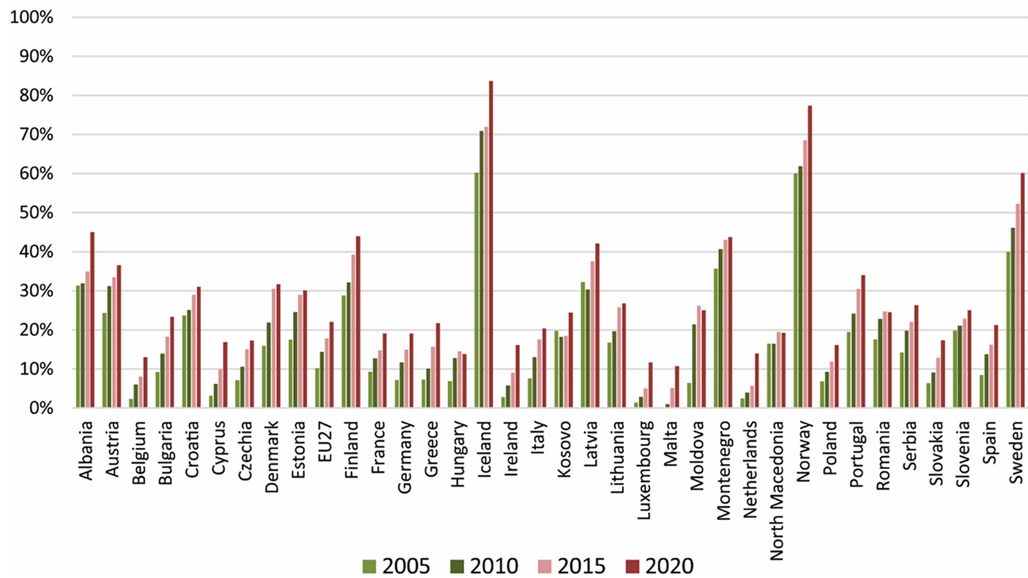

Fig. 1 Development of the overall share of energy from renewable sources by country and year in Europe. (Own graph, data source: [15])

are confronted with considerable challenges in attaining these targets.

Installed power and electrical energy generation of PV power plants in Europe

The European Photovoltaic Barometer [16] provides an annual overview of the photovoltaic expansion of individual countries. Figure 2 illustrates the development of the annually installed power of PV power plants in Europe by country and year. This encompasses both rooftop and free-field photovoltaic power plants. The figure displays only countries with a total installed power of at least 600 MW.

The chart illustrates that around 2010, Germany, Italy, Spain and the Czech Republic were leading in PV expansion, whereas around 2015, the United Kingdom showed a peak in PV installation. Since 2019, the expansion of PV power plants has been distributed across multiple countries, again led by Germany, followed by Poland, the Netherlands, Spain, France and Italy.

Analogous to Fig. 2, Fig. 3 illustrates the annual cumulative PV energy generation in the EU countries (no data were available for the year 2008). It should be noted that

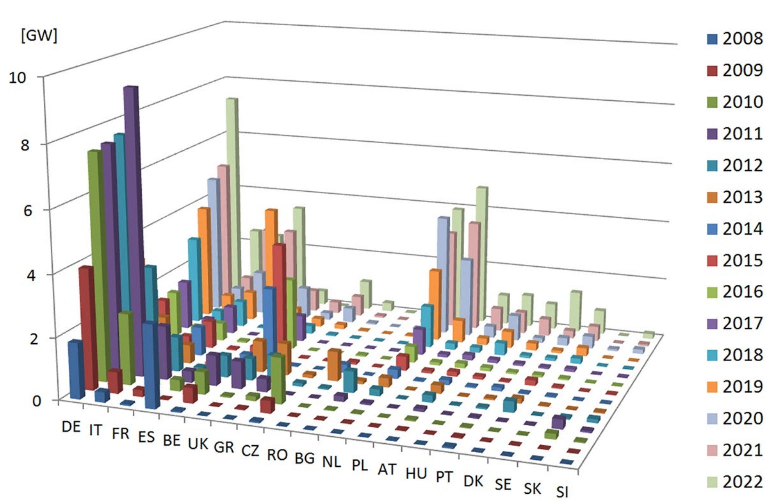

Fig. 2 Development of the annually installed power of PV power plants by country and year in Europe (Own work, data source: [16]).

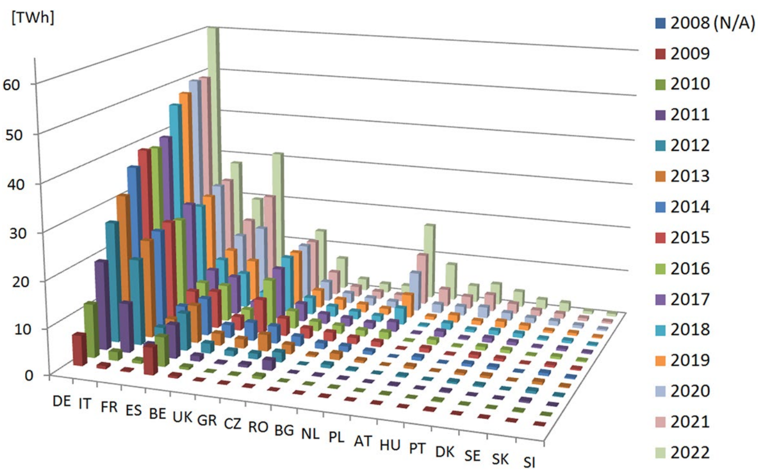

Fig. 3 Development of the annual cumulative photovoltaic (PV) energy generation by country and year in Europe (Own work, data source: [16, 17])

the effects of new installations are first visible in the following year.

Location dependency of electrical energy generation from PV power plants

The aforementioned considerations and study results provide justification for a more detailed analysis of the development of the specific land use of free-field PV power plants over time. This analysis should consider both the technical mounting design and the steady increase in solar cell efficiency, as well as the geographical location of the installation.

The difference in the PV power plant location has a significant influence on the annual electrical energy generation. In Europe, the annual industrial exploitation of global horizontal solar irradiation, connected with the related *photovoltaic power potential*, varies considerably from approximately 950 kWh/kWp in northern UK and Sweden to 1900 kWh/kWp along the southern coastlines of the Mediterranean [18].

Consequently, the electrical energy yield of PV power plants varies by up to 100% depending on the geographical location. Figure 4 illustrates the theoretical dependence of electrical energy generation on the geographical location of the PV power plant over time. In this illustration, it is assumed that technology development is steady and that the same technology is employed in both northern and southern Europe.

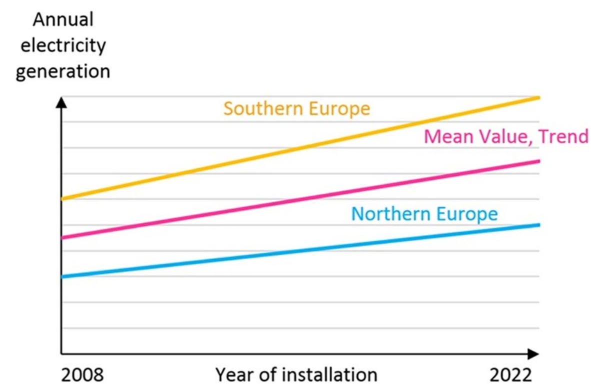

Fig. 4 Principal differences in electrical energy generation depending on the geographical location of the PV power plant (own work)

Land use of PV power plants

To ascertain the potential impact of energy forecasts on land use conflicts, it is necessary to conduct a detailed analysis of the specific land use of PV power plants. The land use for the generation of electrical energy can be determined by considering a range of key performance indicators and boundary conditions, which may not be directly comparable.

It is possible to differentiate between (a) the *cumulative* total land requirements [19–21]; (b) the *power density* [22]; (c) the specific land use on an *annual* basis according to various indicators [7, 22–27]; and (d) the *one-time* land use *change* [25]. The present study concerns the specific land use, which is reassessed annually.

Power density

One potential method for investigation is to determine the areal power density of a power plant. This value is calculated by dividing the product of the nominal power and the annual full load hours by the required land area. The power density of technologies for the generation of electrical energy from renewable energy sources is several orders of magnitude lower than that of technologies based on fossil energy sources [22].

Furthermore, the power density per unit area of PV power plants significantly varies and depends on whether the system is rooftop-mounted or ground-mounted. It further depends on the applied module technology, the solar cell efficiency, and the geographical region in which the system is installed [23, 24].

Land use per kWh generated

An alternative representation of land use is to determine the occupied area of a PV power plant per kWh generated. It is necessary to distinguish between two approaches to calculating land use: the first is to consider a *one-time* land use *change* over the entire lifetime of the PV power plant [25]. The second is to use the land area occupied *annually* by the plant as the reference value [26]. In the context of life cycle assessment, *land use change* represents a discrete impact category that is distinct from the various types of land use, such as *agricultural land occupation* (ALO), and it is considered only once over the life cycle [28]. Furthermore, a distinction is made as to whether the proportional land occupation for the manufacturing phase of the infrastructure is taken into account [27].

A number of databases have been developed that provide data on land use in the energy sector. The Ecoinvent database (version 3.4) [29], for example, only provides land use data for the manufacturing stage of PV modules for the impact category "agricultural land occupation". It does not include data for the use phase. Therefore, the Ecoinvent data are applicable for both rooftop PV plants and free-field PV power plants. However, it is possible that essential land use data for the life cycle of free-field PV power plants may be unintentionally neglected.

Configuration of a free-field PV power plant

In this study, unless otherwise specified, the term "land use" of free-field PV power plants refers to the fenced area surrounding the ground-mounted PV modules, including the associated technical infrastructure and maintenance paths. With respect to temporality, this impact category pertains to the use phase within the life cycle.

Nevertheless, even direct land occupation in the use phase can be measured in a variety of ways. Figure 5 illustrates a typical configuration of a free-field PV power plant with uneven terrain and property lines.

The land areas beneath the module rows, including the corresponding shaded ground (yellow area) and maintenance paths, are considered, which are determined by the so-called *packing factor* [25, 31], or the entire fenced area of the PV power plant is considered [26, 32]. The optimal packing factor represents the theoretical idealised relationship between the required land area and total module area, resulting from the minimum distances between the PV module rows due to shadowing and the minimum maintenance paths [25]. However, satellite images indicate that the fenced areas of free-field PV power plants can be considerably larger than previously assumed. In the case of certain types of utility-scale PV power plants, multiple fenced areas next to each other could be merged together if, for instance, roads, hedges or streams lie in

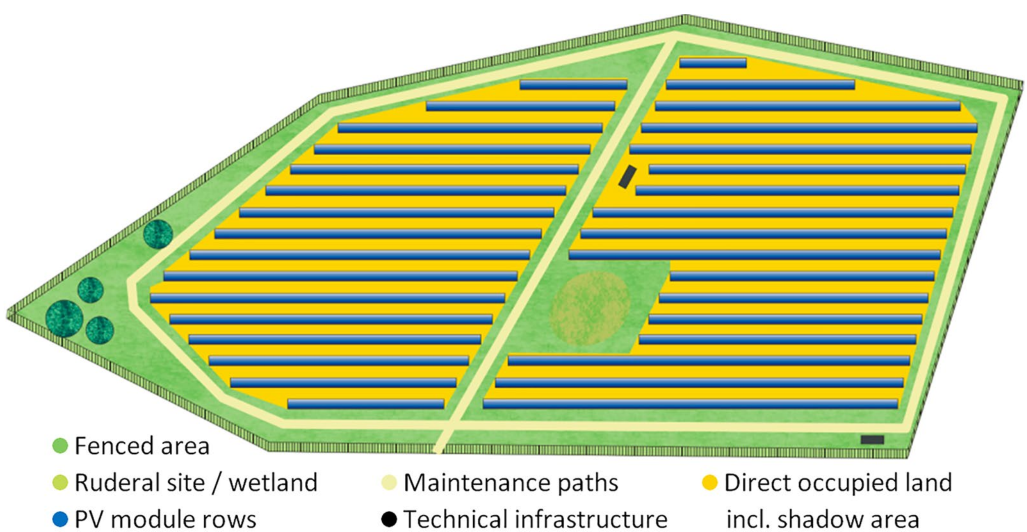

Fig. 5 Configuration of a free-field PV power plant with uneven terrain and property lines (own work) (ruderal areas (lat. rudus = debris) are natural soils that are neither fertilised nor enhanced with garden soil, compost or peat. In most cases, the base consists of gravel, which includes various sizes of stones and may also contain a portion of sand. On this substrate develops a plant community that corresponds to the natural local diversity [30]

between them. In other cases, reserve areas designated for future expansion are already enclosed by fencing.

Study relevance

A multidisciplinary approach to the energy transition requires the acquisition of detailed, diversified data and trends. A systematic review of the specific land use of European free-field PV power plants by technology level, country, and solar irradiation could not be found in the literature. Therefore, owing to the increasing scarcity of land and competition for land, this study was designed to conduct a comprehensive analysis of the direct land demand of free-field PV power plants.

The novel contribution of this study is its comprehensive analysis and presentation of the development of the specific land use of free-field photovoltaic power plants in Europe across the entire epoch of PV expansion, spanning the period from 2006 to 2022. The study is based on empirical data collection for a sample intended to represent the entirety of photovoltaic implementation in Europe. Particular focus is placed on the joint presentation of key performance indicators related to specific land use and siting. In addition to the installed power, the corresponding energy generated on an annual basis and detailed system data are also recorded. All key parameters are presented in a disaggregated format, with an average calculated for each year of installation. This allows for the observation of the technological development implemented over time. The processed data can be employed as life cycle inventory data in the use phase within environmental life cycle assessment studies and other applications. The results are evaluated in comparison with existing literature data and other renewable energy technologies.

Methods

The objective of this study was to conduct a comprehensive analysis of the European trend in the specific land use of free-field PV power plants by investigating the development of installed free-field PV power plants over time. The study is based on a larger sample size than that in the existing literature. The sample selected for analysis should be as representative as possible of Europe as a whole according to Fig. 2 to ensure a sufficiently broad cross-section. However, the data in Fig. 2 include both free-field and rooftop PV power plants, and there is no differentiation of local sites within individual countries.

Ratio of free-field to rooftop PV power plants in Europe

It is challenging to provide a general quantification of the share of free-field PV power plants in the annual total PV installation and energy generation, as this depends on various factors, including location and reporting period. The available data on the share of rooftop PV power plants are partly contradictory or rather inconclusively defined. Solar Power Europe reports a 58% EU total share of newly installed power of rooftop PV power plants and a 42% share of utility-scale PV power plants for 2022 [33]. These values may be driven by Germany and the Netherlands (cf. Figure 2).

The same report indicates that the proportion of newly installed utility-scale PV power plants in Spain ranged from 71% in 2021 to 54% in 2022. In the case of Denmark, the proportion of rooftop-mounted installations is reported to have reached 7.7% by 2022. With respect to the remaining countries and years, no clear data are available. Furthermore, other categories, namely, commercial scale and industrial scale, are not distinguished by mounting type [33]. As a consequence of the incomplete data situation, it was assumed for the purposes of this study that the available data on the installed PV nominal power [16] are representative of the distribution of free-field PV power plants.

Study setting

This study examined the *annual* land use of free-field PV power plants, in contrast to one-time land use *change*, over the entire lifetime. From the perspective of a life cycle assessment, only the use phase was considered, excluding the land use in the manufacturing phase and the end-of-life phase. The study thus contributes to the location-dependent and time-dependent determination of new life cycle inventory data for a life cycle assessment of free-field PV power plants.

The land area under investigation refers to the fenced area, which is allocated to the PV power plant in its entirety, irrespective of whether it is used for other purposes or remains fallow. This methodology was employed in a similar manner as in Sect. "Comparison to the land use of other renewable power plants", where the specific energy yield values from PV power plants were compared to those of other renewable power plants.

The investigation included a total of 107 European free-field PV power plants, which were compared with seven PV power plants in Mexico, South Africa and the USA. The number of investigated European PV power plants represents approximately 0.4% of all installed free-field PV power plants in Europe in 2022. This estimation is based on the results of a previous work [34]. The sample selection criteria were based on regions with a high density of free-field PV power plant installations (ibid.), extended by new installations according to the regions and installation years of Fig. 2. The selection was also dependent on the availability of data.

Figure 6 shows the geographical distribution of the selected free-field PV power plants employed in this

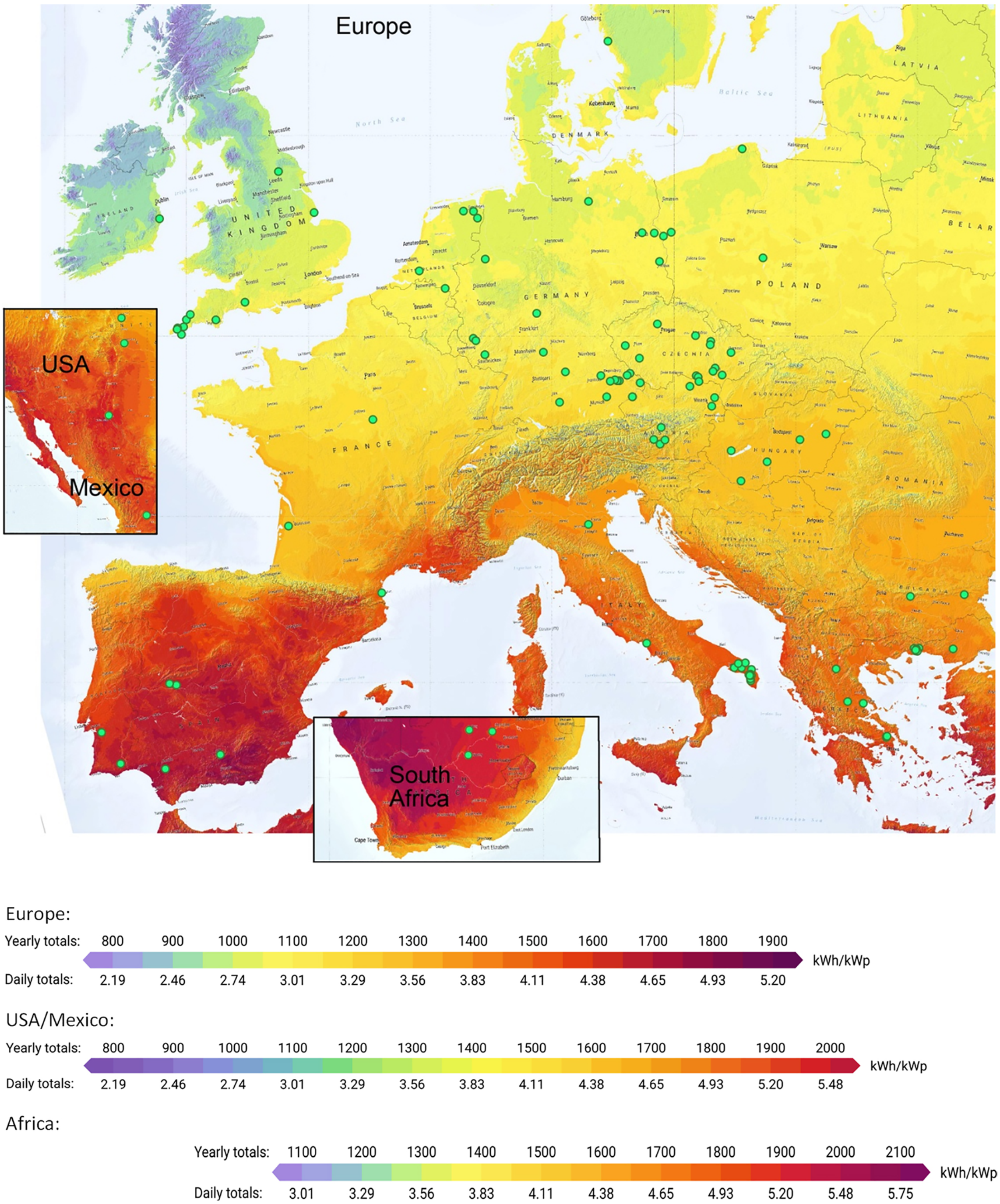

Fig. 6 Locations of the investigated free-field PV power plants (green dots). Background: map sections of the long-term average PV power potential (source: [18]). Note: the associated legends of the different continents are coloured differently

study. The background map depicts the associated PV power potential provided by Solargis [18]. The non-European PV power plant data are included only in the supplementary materials for comparison.

The following data were collected from the investigated PV power plants:

(i) Fenced area
(ii) Installed power
(iii) Number and area of the PV modules
(iv) Annually generated electrical energy
(v) Year of PV power plant installation

(vi) Photovoltaic power potential of the respective site (mean value of the respective colour code of the colour scale according to Fig. 6); data source: regional maps by [18].

Data acquisition

A comprehensive set of GIS data on free-field PV power plants in Europe was generated over the course of an earlier study [34]. The technical data of the selected PV power plants were subsequently obtained through online research by using the Google search engine. The search terms employed included the name of the village or town near which the PV power plant is installed, as well as terms such as the PV power plant, solar power plant, and solar park. The data sources employed included PV databases, manufacturer and operator references, investment companies, media reports, and lobby group information. The primary search was conducted in English and German. In the case of well-documented data provided by a manufacturer, other reference projects were included. Additionally, the locations and surface areas of the PV power plants were mapped in GIS format using Google Earth Pro [35]. Further details and references can be found in the supplementary materials.

The number and surface area of the modules were partly calculated and measured from satellite images provided by Google Earth [35]. For 18 PV power plants, no data on the electrical energy generated could be determined. These power plants were excluded from location-dependent evaluations, but the location-independent parameters of these PV plants were included in the study. Consequently, the results include a different sample size.

A limited number of data records were identified for the years 2016 and 2017. In some instances, the values for these years may not be representative when considered in the context of the surrounding results.

Calculation of the key performance indicators

The data collected were used to calculate the following parameters for each free-field PV power plant:

Location-independent parameters:

(a) Installed power per module area
(b) Land use per m^2 of module area
(c) Land use per kW of installed nominal power[1]

Location-dependent parameters:

(d) Annual generation of electrical energy per m^2 of module area
(e) Land use per kWh of annually generated electrical energy
(f) Energy density
(g) Capacity factor
(h) Power density

The results were represented graphically and analysed in terms of overall European results over time and by country, with a comparison made with data from the relevant literature. The averaged European trends were represented using the equations for linear trendlines provided by Microsoft Excel, which are based on the calculation of the least squares fit for a line [36].

It is important to note that the annual data are not cumulative, which would lead to different results; rather, they refer to the year in which the PV power plant was installed. The aforementioned data remain unaltered for the entirety of the service life of each individual sample unit, with the exception of the age-related reduction in energy output.

A sensitivity analysis was conducted to evaluate the robustness of the data and the employed evaluation method on the basis of a linear trend line. The impact of excluding all PV power plants with special mounting designs was evaluated, given the uncertainty regarding the extent to which these designs are represented in the European PV expansion. Additionally, the significance of the linear trend lines was compared with that of a polynomial trend curve of the 6th degree.

The incomplete assignment of a country code to the data points in the graphs is provided for exemplary purposes only in the main article, with the intention of enhancing clarity. The supplementary materials contain all the detailed data, including a comparison with non-European countries and enlarged representations of the graphics, together with all country codes.

The results of the land use associated with free-field PV power plants per kWh of electrical energy generated were compared with data for other energy generation technologies, including biomass (wood chips and biogas from maize), wind power, geothermal heat, and solar thermal heat. The findings present concluding recommendations for PV-specific policies and contribute to the broader perspective of the future EU energy transformation.

Data quality

A significant number of locations were excluded from the study because of the unavailability of comprehensive public data on PV power plants. This necessitated an

[1] In most cases, the data sources do not specify whether it is the nominal power according to standard test conditions in [kW_p] or the real nominal power (bottleneck capacity).

exhaustive search for data on the sample. In some cases, the PV power plant in question could not be found with the search engines. In other instances, the data were incomplete, no clear assignment was possible in cases where multiple PV power plants were present in the same region, or there has been an extension of an existing power plant.

A further noteworthy issue was that in numerous cases, the comparison was made between the number of households that can be supplied with the corresponding PV power plant and the amount of CO_2 emissions that can be saved rather than the electrical energy that is generated. In this instance, however, neither a general harmonised conversion factor dependent on the region is defined nor provided in the specific case. The existing national databases for renewable energy power plants also do not meet the requirements for comprehensive data analysis.

All applicable data were adopted in their original form, as presented in the data sources and used for calculation. Consequently, the following data uncertainties result:

- In the majority of cases, the installed nominal power (also referred to as "capacity"), the annually generated electrical energy and the number of modules were predominantly represented in most cases as rounded numerical values.
- Only a limited number of literature sources provided detailed technical specifications for PV modules. In some cases, the module lengths and widths were estimated using measurements taken via Google Earth, with the area calculated on the basis of the estimated angle of inclination and standard dimensions of the PV modules and photos. The procedure used was designed to minimise systematic errors (bias), assuming an approximately normally distributed random error for the aggregated evaluation.
- With regard to the installed power, a distinction was made only once between the nominal power under real conditions and the nominal power under standard test conditions (STCs) [37, 38]. In this case, the difference was 12.9% from the higher value to the lower value [39]. In the majority of cases, it was not defined whether the other literature power data refer to real conditions or STC. Consequently, any difference is unknown. No dataset specified the onsite energy demand or conversion losses. For the aggregated analysis over time, it was assumed that there was no time-dependent systematics in this information. On the basis of the above comments, to avoid misinterpretations between "watt peak" [W_p] and "watt" [W], it was decided to express all related units in watts.
- The information on the respective annually produced electrical energy can refer either to the calculated expected value or to the actual measured value. No information is available on this topic. Similarly, it is assumed that the data are free from any time-dependent systematic errors.

Results

The following sections present the results of the calculated specific land use of free-field PV power plants over time, beginning with a descriptive evaluation of the sample. The results are divided into two categories: those that are independent of geographical location and those that are dependent on geographical location.

Spatial and temporal distributions of the investigated free-field PV power plants

The land use of free-field PV power plants has varying values depending on local solar irradiation, the technology generation at the time of installation, and the applied mounting technology. The principal mounting technologies of free-field PV power plants, which are the focus of this study, are as follows (see Fig. 7):

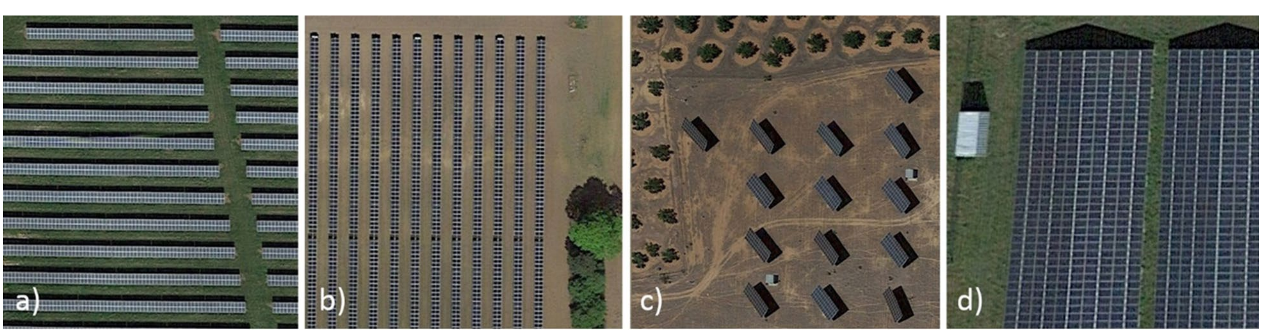

Fig. 7 Mounting technology types of free-field PV power plants: **a** South-oriented fixed-tilt PV modules in multiple rows, **b** Row-mounted east-west tracking PV power plant, **c** Pole-mounted tracking PV power plant, **d** Fixed-tilt east-west-oriented roof-shaped PV power plants. Screenshot source: Google Earth satellite images [35]

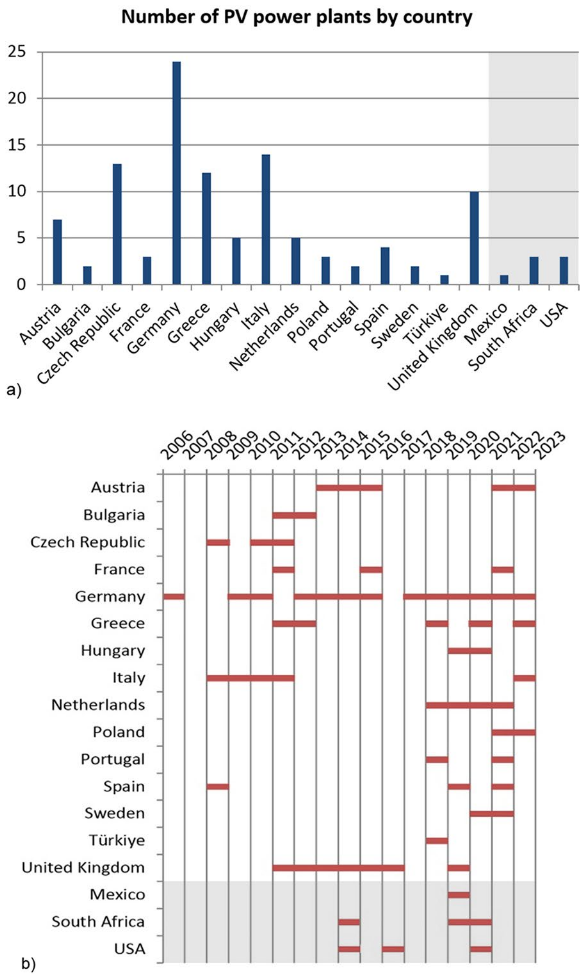

Fig. 8 Distribution of the sample by country: number of investigated PV power plants (**a**) and period of first commissioning (**b**)

(a) South-oriented fixed-tilt PV modules in multiple rows (largest share of installation type),
(b) Row-mounted east–west tracking PV power plant,
(c) Pole-mounted tracking PV power plant,
(d) Fixed-tilt east–west-oriented roof-shaped PV power plants.

In this context, system type a) is referred to as *conventional*, whereas types b), c) and d) are referred to as *special mounting designs*.

The free-field PV power plants selected for the sample are located in different geographical regions with different commissioning dates. Figures 8, 9, 10 illustrate the distribution of PV power plants by country, PV energy potential, and year of installation. The grey areas represent samples that are geographically situated outside of Europe.

The results presented in Figures 8, 9, 10 demonstrate a total sample period spanning from 2006 to 2022, during which no PV power plant was recorded in 2007. The regional PV energy potential, as estimated by Solargis, ranges from approximately 950 to 1750 kWh/kW$_p$ in Europe and up to 2000 kWh/kW$_p$ in the comparative countries [18]. However, the distribution of the PV energy potential is not homogeneous, both by country and by initial commissioning year. The results at the country level are of interest from a regional policy perspective. However, for a supraregional overall evaluation, the location of the PV power plants in relation to the PV energy potential, together with the year of construction, and consequently the respective location and technology status, influence the results of the specific electrical energy generation-dependent land use. The temporal distribution of the PV power plant commissioning year included in the sample (Fig. 10) aligns with the European market trend [33] until approximately 2021. Moreover, the sample was selected to align closely with the data presented in Fig. 2 and the related PV power potential. However, the pronounced PV expansion in 2021 and 2022 is not fully reflected in the sample because of the delayed provision of satellite images in Google Earth.

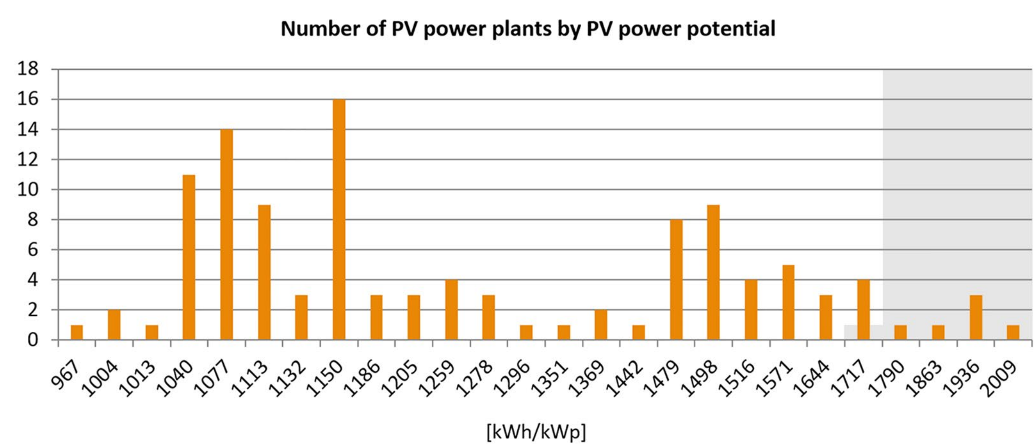

Fig. 9 Distribution of the sample by PV electricity potential of the respective geographical locations according to data from the Solargis maps [18]

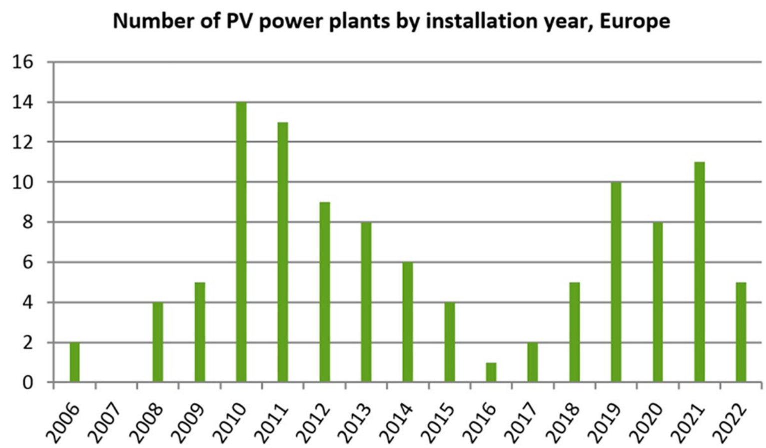

Fig. 10 Distribution of the sample by the year of first commissioning

The sample comprises a variety of PV module installation types, as illustrated in Fig. 7. Among the 107 European PV power plants, 93 are of the conventional design, comprising south-oriented fixed-tilt PV modules arranged in multiple rows (see Fig. 7a). This equates to 87% of the total sample. A further four PV power plants are installed as pole-mounted tracking systems, which were constructed during the early phase of PV expansion between 2006 and 2011 (Fig. 7c). Another four PV power plants are row-mounted east–west tracking systems installed between 2019 and 2021 (Fig. 7b). Two PV power plants are fixed-tilt, oriented east–west and installed in roof shapes in 2015 and 2021 (Fig. 7d). Finally, bifacial modules have been increasingly applied since 2019, with five PV power plants being part of the sample. The non-European PV power plants are all installed as a row-mounted east–west tracking system (Fig. 7b). The results of the trendlines presented in the following sections include all special mounting designs. The influence of these designs on the overall trends was investigated by sensitivity analyses, as explained in more detail in the respective section.

Installed power per module area

The data collected from PV power plants allow for the determination of the European average values of the annually installed nominal power per m^2 module area. The results of this determination are presented in Fig. 11 and Table 1. It should be noted that the average values represent the real applied PV technologies in addition to possible best practice technology within the sample.

The linear trend indicates that the installed power per module area has approximately doubled over the study period of approximately 15 years. The distributions of countries and installation locations according to solar irradiation are relatively balanced over long distances. However, an analysis of the samples from 2011, 2012 and 2018 reveals significantly higher installed nominal power per module area in southern European countries.

The low value of the data point in 2008 is associated with a PV power plant utilising thin-film modules. This value was retained as an illustrative example, given the growing prevalence of this technology in the 2010s.

The sensitivity analysis, conducted using a polynomial trend line, indicates the occurrence of three significant technological advancements in solar cell efficiency at approximately 5-year intervals. This wave-shaped trend is reflected in all subsequent calculations of land use in connection with installed power or energy generation.

Specific land use independent of the geographical location of the PV power plants

This section presents the trends of key performance parameters of the specific land use of free-field PV power plants, which are *independent* of electrical energy generation. Consequently, these parameters are independent of solar irradiation and thus of the geographical location of the PV power plant.

The following trend results of the land use values should be understood as a selected snapshot, the veracity of which would need to be confirmed or corrected with a comprehensive regional in-depth study dependent on the intended application of the data. Land use results that are solely related to technical plant parameters and not to the generated electrical energy have a much higher representative validity of the sample.

Land use per PV module area

The European development of land use within the fenced area per module area of free-field PV power plants is

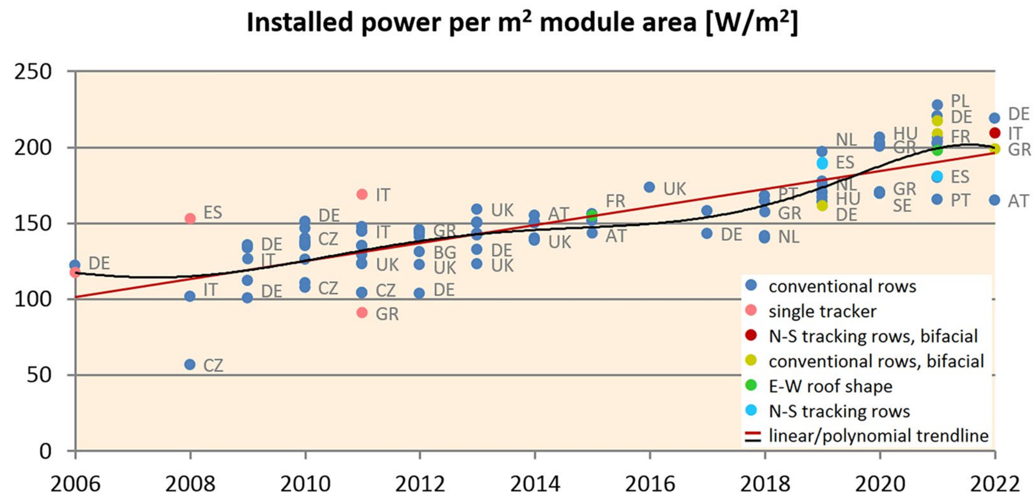

Fig. 11 Development of the installed power per module area

illustrated in Fig. 12. The module area was calculated in accordance with the physical geometric area, as opposed to the area projected on the ground.

This representation is independent of the solar cell efficiency and the energy output and demonstrates trends in the mounting technology, which consequently affect the value of the land through efficient or generous use of space. The results demonstrate that the distribution of countries over the course of a year does not display any discernible pattern.

The mean value of the land use per module area for the entire sample is 3.12, with a median value of 3.05. This indicates that for a free-field PV power plant, more than 3 times the land area is required for the electrically usable area of the PV modules. For comparison, an ideal packing factor of 2.5 for conventional free-field PV power plants, including assembly and maintenance paths, was published in the literature in 2009 [25].

The linear trend line indicates a reduction of 41% in the specific module land use between 2006 and 2022. The deployment of pole-mounted single-tracker systems in the initial years of the period under review significantly affected the slope of the trendline. The highest land use for pole-mounted PV power plants was observed in Germany in 2006, with a factor of 10.87; Spain in 2008, with a value of 7.38; Italy, with a value of 5.77; and Greece, with a value of 5.18, with the latter installed in 2011. In contrast, a single PV power plant was constructed in France in 2015, comprising an east–west roof shape with a land use factor of 1.29.

The sensitivity analyses with a polynomial trend curve demonstrate a wavy decrease with an increase in 2022. This is not solely attributable to the increased use of row tracking mounting systems; it is also driven by conventional mounting types. Excluding all special mounting designs, the linear trendline reveals a total reduction in land use of approximately 30%.

Table 2 lists the annual average values of land use per module area. As with the preceding dataset, the year 2016 is not representative due to the small sample size.

Land use per installed power

The European development of the land use per installed power of free-field PV power plants related to the fenced area is illustrated in Fig. 13. The results represent a combination of the trends observed in Figs. 11, 12, which demonstrate either a positive or negative correlation.

The linear trendline indicates a decline from 34.5 m^2/kW in 2006 to 11.0 m^2/kW in 2022, representing a reduction of 68%.

Table 1 Average values of the installed module power by installation year

Year	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value W/m^2	120	104	122	133	127	135	143	147	151	173	150	154	176	186	201	198
Median value W/m^2	120	101	126	137	129	143	143	150	153	173	150	157	173	185	204	204

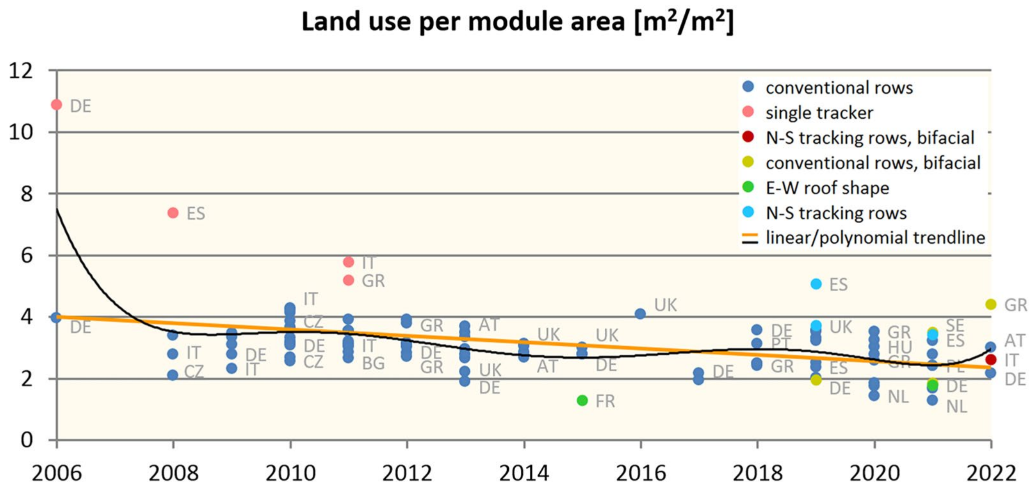

Fig. 12 Development of specific land use per module area

Table 2 Average values of the land use per module area by installation year

Year	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value m^2/m^2	7.4	3.9	3.0	3.5	3.6	3.2	2.9	2.9	2.5	4.1	2.1	2.8	3.1	2.5	2.4	3.0
Median value m^2/m^2	7.4	3.1	3.1	3.5	3.5	3.1	2.9	2.9	2.8	4.1	2.1	2.5	3.3	2.7	2.4	2.8

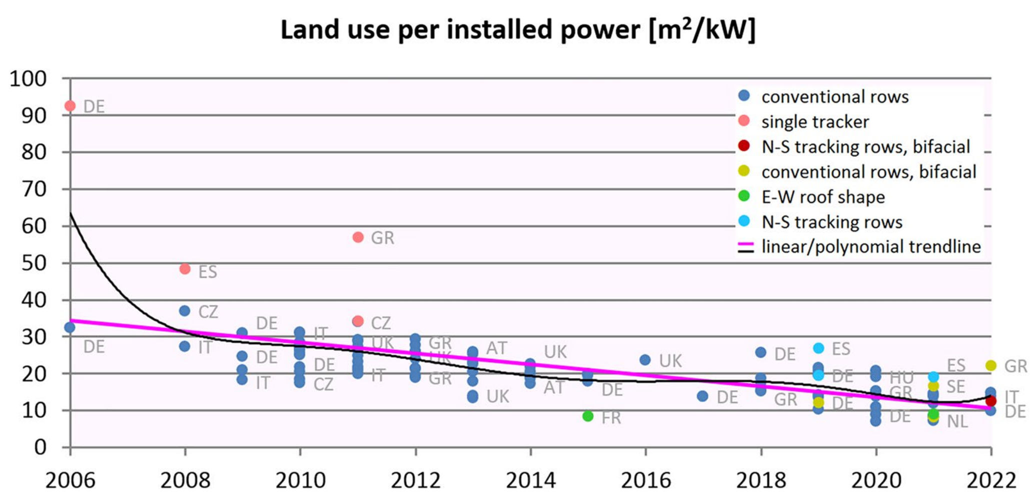

Fig. 13 Development of specific land use per installed power

The results of the sensitivity analysis likewise indicate the significant impact of pole-mounted single-tracker PV power plants, as previously described in Sect. "Land use per PV module area". The exclusion of all special mounting designs from the analysis demonstrates a land use reduction of 62%. As no energy data were available for 2006, the development between 2008 and 2022 was additionally calculated using a linear trendline, again for *all* PV power plants, which shows a land use reduction of 60%.

However, the polynomial trend curve indicates that as of 2021, land use slightly increased again due to the increased application of north–south row-mounted tracker systems (Fig. 7b), which require more space. The sporadic application of east–west roof-shaped mounting designs (Fig. 7d) significantly reduces land use, but

Table 3 Average values of the land use per installed power by installation year

Year	2006	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value m^2/kW	62	38	25	25	29	23	20	20	16	24	14	18	18	14	12	15
Median value m^2/kW	62	37	25	26	27	24	22	19	19	24	14	18	20	14	12	14

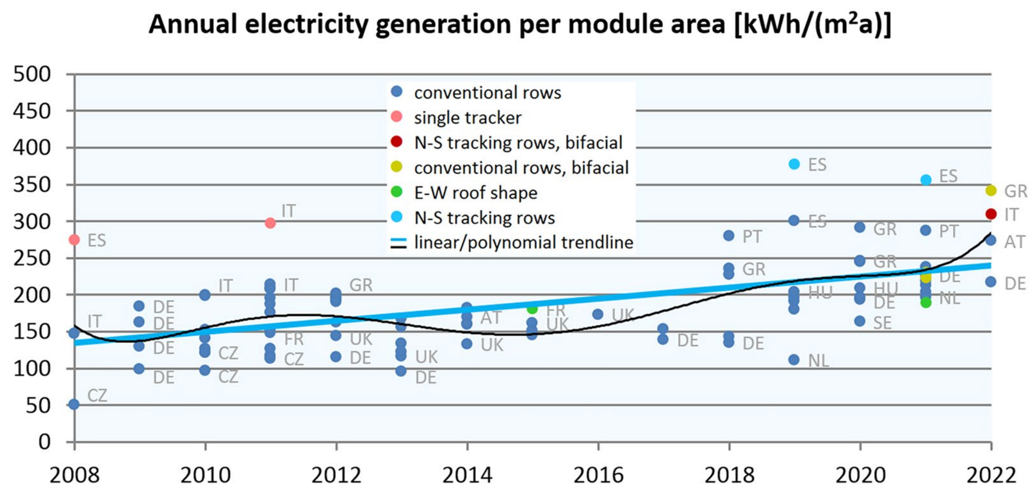

Fig. 14 Development of the annual electrical energy generated per module area

this technology has no overall impact. Furthermore, this mounting technology leads to complete shading of the ground, which could have ecologically problematic consequences.

The observed trend is consistent across all countries, reflecting an increase in module efficiency. However, the slope of the linear trendline slightly varies across individual countries (see supplementary materials).

Table 3 shows the calculated average sample values of land use for each year, whereby the years 2016 and 2017 are less representative due to the low sample number.

In the existing literature, an average value of 2.2 ha/MWp (=22 m^2/kWp) was reported for Germany in 2018. Furthermore, the US National Renewable Energy Laboratory provides average data for the area occupied by a PV power plant in the USA, which is in the range of 3.2 to 6.1 acres/MW (with 1 acre = 4046.86 m^2: 12.9–24.7 m^2/kW) [40].

Specific land use depending on the geographical location of the PV power plant

In contrast to the findings presented in Sect. "Specific land use independent of the geographical location of the PV power plants", the parameters that are proportional to the annually generated electrical energy are dependent on the geographical location of the PV power plant (cf. Figure 4). Consequently, in addition to the annual data determined in Sect. "Specific land use independent of the geographical location of the PV power plants", the results of this section are affected by the different local solar irradiation values.

Given the statistical distribution of the samples in Sect. "Spatial and temporal distributions of the investigated free-field PV power plants", it is only possible to rate the following results as a single case study from which a potential general trend and questions for further analysis can be derived. It was not feasible to obtain data on energy generation for the year 2006. Consequently, the timeline is not identical to that in the preceding sections.

Electrical energy generation per PV module area

The initial part of this section presents the results of a trend analysis in which the fenced land area is not employed as the reference value. Instead, the module area of the PV power plant is utilised. This corresponds to the development of the applied efficiency of the PV modules, as illustrated in Fig. 11, and is additionally influenced by the specific geographical area in which they are deployed. Figure 14 illustrates the trend of the annual electrical energy generation per m^2 of module area, thereby representing the average implemented technological progress in solar cell efficiency (cf. Figure 11) in combination with the geographical distribution across all countries.

Table 4 Average values of electrical energy production per module area by installation year

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value kWh/(m^2.a)	157	144	145	179	177	132	161	159	173	146	204	223	224	235	285
Median value kWh/(m^2.a)	147	146	134	182	194	128	160	156	173	146	227	196	227	223	291

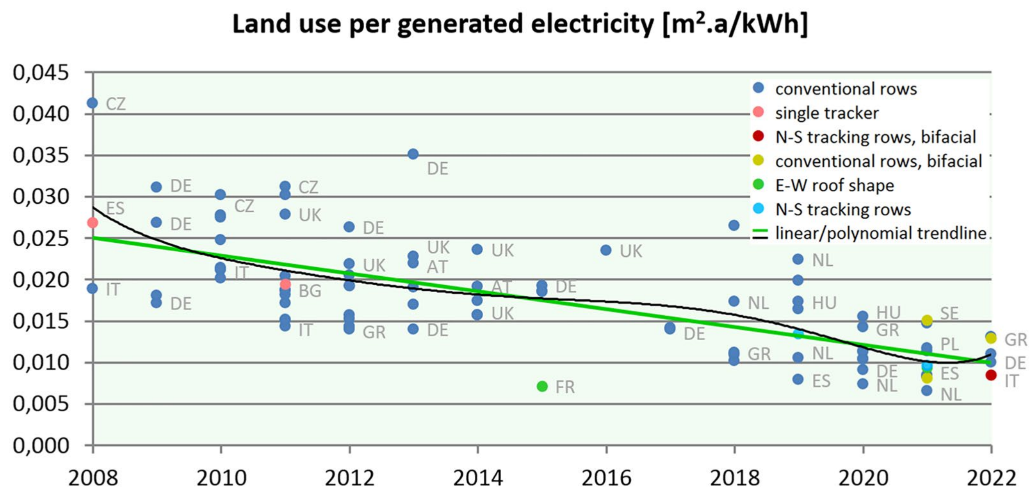

Fig. 15 Development of specific land use per kWh per annually generated electrical energy

The distribution of the countries along the vertical axis is in accordance with the theoretical considerations of Fig. 4 (see supplementary materials). In 2008, the median value was 147 kWh/(m^2a), and by 2022, it had increased to 291 kWh/(m^2a), which is equivalent to doubling.

The analysis of data from 2008, 2011, 2021, and 2022 indicates that the application of tracking systems and the utilisation of bifacial modules lead to a significantly higher energy yield per module area. In comparison, the space-saving mounting type of east–west fixed-tilt modules results in significantly reduced energy generation per module, as anticipated. Table 4 lists the average values of electrical energy generation per module area by installation year.

The sensitivity analysis with the polynomial trendline indicates a maximum in 2011, which is attributable to the high sample number in Italy corresponding to Figs. 2, 4. Since 2014, there has been a discernible upwards trajectory in the polynomial trendline, which has persisted until 2022.

The exclusion of pole-mounted single-tracker PV power plants from the linear trendline indicates an increase of 94% in energy generation per module area. However, when all special mounting systems are excluded and only conventional PV power plants are considered, the linear trendline reveals an average European increase of 71% from 2008 to 2022.

Notably, large countries such as Germany or Italy encompass regions with different levels of solar radiation, a factor that is not differentiated in Figs. 2, 3. Consequently, a further sensitivity analysis was conducted, in which the distributions and trends were determined according to locations with the same solar radiation. In addition to a few exceptions, the trends shown in Fig. 4 are confirmed (see the Supplementary materials).

Land use per generated electrical energy and energy density

The following section presents the annual electrical energy generation in relation to the entire fenced area of the free-field PV power plant. Figure 15 illustrates the development of the land use per kWh for all examined European PV power plants, which combines Figs. 12, 14. The land use per kWh decreases from a mean value of 0.029 m^2.a/kWh in 2008 to 0.011 m^2.a/kWh in 2022.

The linear trendline indicates a reduction in land use per annually generated kWh of 60% between 2008 and 2022. However, since 2019, specific details have become apparent: three PV power plants in the Netherlands and four in Germany present significantly low land use values. This is because highly efficient modules are used in conjunction with tight and space-saving mounting technology. Conversely, two PV power plants in Greece demonstrate high land use values. One of them employs modules with relatively low solar cell efficiency, whereas

Table 5 Average values of the land use per generated electrical energy by installation year

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value m^2.a/kWh	0.029	0.023	0.024	0.021	0.018	0.022	0.018	0.016	0.024	0.014	0.015	0.015	0.011	0.010	0.011
Median value m^2.a/kWh	0.027	0.022	0.023	0.019	0.019	0.020	0.017	0.019	0.024	0.014	0.011	0.016	0.011	0.009	0.011

Table 6 Average values of the annually generated electrical energy per m^2 fenced land area by installation year

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value kWh/(m^2.a)	38	46	42	52	56	50	56	75	43	71	75	73	94	105	93
Median value kWh/(m^2.a)	37	46	44	53	52	49	57	54	43	71	90	61	92	107	91

the other is located in mountainous terrain with considerable spacing between the module groups.

Table 5 lists the average land use results per unit of generated electrical energy per installation year.

The sensitivity analysis, which was conducted with the polynomial trendline for all samples, reveals a land use minimum in 2021 and a moderate rebound in 2022.

The trendline, which excludes all special mounting designs, demonstrates that the total trend remains stable. The land use per kWh decreased by 60% between 2008 and 2022. This notable result indicates that variations in the mounting design have less influence on the average electrical energy generation and that the higher land demand of tracking systems is compensated by a higher energy output.

A comparison of the results presented in Fig. 15 with the analysis presented in Sect. "Land use per installed power" reveals a correlation between the two sets of data, indicating an equal trend: the trendline of the land use per installed power (cf. Figure 13), considered as of 2008, also decreased by 60%. This indicates that the spatial distribution of PV power plant expansion with respect to solar irradiance has remained constant over the period of investigation. This is contrary to the findings of Fig. 2, which demonstrate a clear shift in development towards northern European countries since 2019. Consequently, the decline in the trendline for land use per generated electrical energy, as illustrated in Fig. 13, is anticipated to result in a lower percentage.

In the existing literature, the one-off *land transformation* has been calculated for a free-field PV power plant with an operating time of 30 years. For an insolation of 1800 to 2400 kWh/m^2/a, the land transformation is 329–438 m^2/GWh for a module efficiency of 10.6% [25]. A further study from Vietnam, published in 2021, determined the annual rate of land use at 7.18 m^2.a/MWh (mono-Si), 8.04 m^2.a/MWh (multi-Si), and 8.26 m^2.a/MWh (tracking system) on the basis of the respective fenced area [32].

Energy density An additional form of representation is that of the *energy density*, which is defined as the annual quantity of electrical energy generated on 1 m^2 of fenced area. Table 6 presents the mean/median values of the energy density for each installation year. The basic data are in accordance with the reciprocal *single* values of the results presented in Table 5.

As a consequence of the nonlinearity of the distribution of reciprocal values, it is important to note that there is no mathematical correspondence between the average values in Table 7 and the reciprocal values in Table 5.

Capacity factor

The capacity factor, also known as the *annual utilisation rate*, illustrated in Fig. 16, is a measure of how much electrical energy is annually generated by the PV power plant compared with its maximum possible output [41]. The

Table 7 Average European capacity factor by installation year

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value [1]	0.16	0.13	0.12	0.15	0.15	0.11	0.12	0.12	0.11	0.11	0.15	0.14	0.14	0.14	0.15
Median value [1]	0.16	0.14	0.12	0.16	0.15	0.11	0.12	0.12	0.11	0.11	0.16	0.14	0.14	0.12	0.14

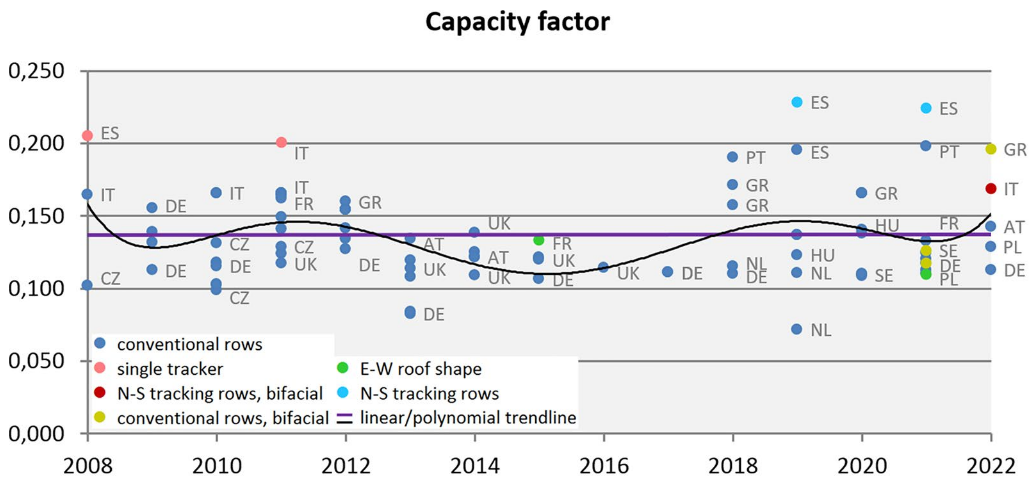

Fig. 16 Capacity factors of the sample by installation year

capacity factor was calculated for each PV power plant according to the following equation:

$$CF = \frac{E}{P_N * 8760}, \quad (1)$$

where CF = capacity factor, E = annually generated electrical energy of the respective PV power plant, P_N = installed nominal power of the respective PV power plant, and 1 year = 8760 h.

The trendline of the capacity factor is almost horizontal, with a European average value of 0.137 or 13.7%. The horizontal position of the trendline indicates that the spatial distribution of PV power plant expansion with respect to solar irradiance has remained constant, as previously discussed in Sect. "Land use per generated electrical energy and energy density". This type of visualisation is appropriate for a more detailed examination of the development of the European distribution of PV power plants, specifically whether the expansion trend is shifting towards northern or southern Europe.

The sensitivity analysis, which was conducted with a polynomial trend line, yielded the following results: the implementation of single-tracker pole-mounted photovoltaic (PV) power plants in the early expansion stage in 2008, the introduction of row-mounted tracking systems, and the application of bifacial modules in 2022 led to an increase in the average capacity factor up to a value of more than 0.15, representing a 15% increase.

When considering only conventional PV power plants, the linear trendline demonstrates a reduction in the capacity factor of 5%. This indicates that the geographical expansion of PV power plants has shifted towards the north, as illustrated in Fig. 2. This indicates that the sample is biased towards special mounted PV systems.

Germany, which has the largest share of European installed PV power (cf. Figure 2), reports an expected capacity factor of 11.1% for free-field PV power plants [42]. In comparison, the U.S. Energy Information Administration provides monthly data on the capacity factors for utility-scale PV power plants in the range of 0.25, which is considerably higher and not applicable to Europe [43].

Power density

The term "power density" is not consistently defined in the literature. The most common method for determining the power density of a free-field PV power plant is through calculation with reference to the full load hours of the PV power plant and the relation to the fenced ground area. The subsequent calculations are performed according to the following equation [44]:

$$PD = \frac{P_N}{A_f} \cdot CF, \quad (2)$$

where PD = power density, P_N = installed nominal power of the respective PV power plant, A_f = fenced area, and CF = capacity factor.

The power density is calculated in proportion to the reciprocal of the single dataset for land use per generated electrical energy, as presented in Sect. "Land use per generated electrical energy and energy density". As a consequence of the nonlinearity of the reciprocal value distribution, the sequence of data is inverted in a mirror image, whereas the vertical distances of the data points and the position of the trend line undergo a transformation.

Figure 17 illustrates the development of the power density of the European sample from 2008 to 2022. Table 8 presents the respective mean and median values per year.

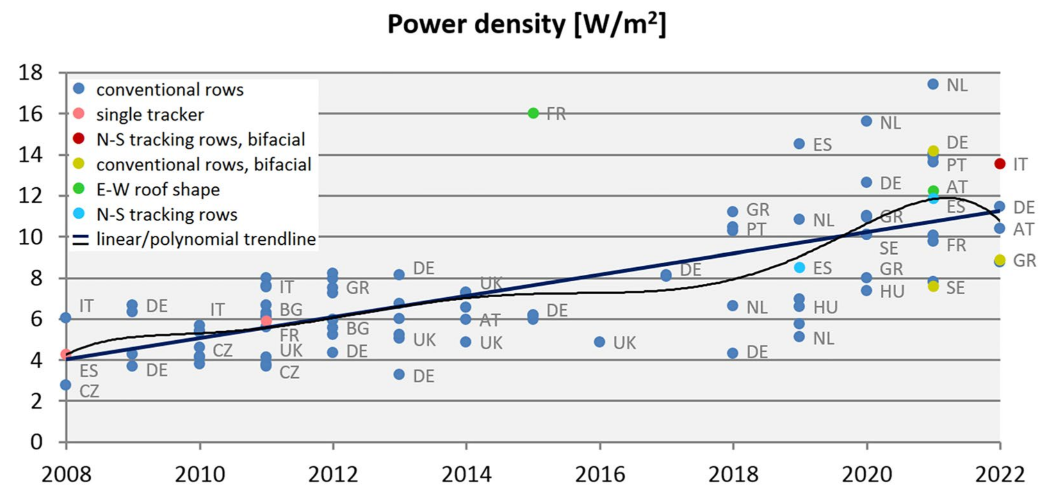

Fig. 17 Power density of the European sample by installation year

Table 8 Power density by installation year

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Mean value W/m^2	4.4	5.2	4.8	5.9	6.4	5.7	6.4	8.6	4.9	8.1	8.6	8.3	10.7	12.0	10.6
Median value W/m^2	4.3	5.3	5.0	6.1	5.9	5.6	6.6	6.2	4.9	8.1	10.3	7.0	10.5	12.2	10.4

The power density related to the land area used increased from a mean value of 4.4 W/m^2 in 2008 to 10.6 W/m^2 in 2022. The associated linear trendline demonstrates a 2.8-fold increase in power density. The interpretation of the data is analogous to that presented in Sect. "Land use per generated electrical energy and energy density". However, the representation of power density in Fig. 17 provides a more illustrative overview of the data points with particularly low land use values. Conversely, the data with high land use values are more clearly distinguishable in Fig. 15.

Another approach to calculate the power density of free-field PV power plants is described in the literature ([22], p. 51). The power density refers to the proportion of the local solar irradiation of the fenced area that is transferred to the module area and subsequently converted into electrical energy. The ratio between the total module area and ground area is taken into account, which is not the case for Eqs. (1) and (2). The following equation provides an explanation for this:

$$PD = \frac{GHI}{8760} \cdot \eta \cdot p \cdot \frac{A_M}{A_f}, \tag{3}$$

where PD = power density of a PV module, GHI = annual average local solar irradiation, 1 year = 8760 h, η = conversion efficiency of the PV modules, p = performance factor of the PV module, A_M = total module area of the PV power plant, and A_f = fenced area of the PV power plant.

In the absence of precise module data, a comparative analysis is not possible. It would be interesting to verify individual results in a subsequent study.

Comparison to the land use of other renewable power plants

This paper has focused primarily on the area yields of photovoltaic power plants in Europe. Here, "area" refers to the horizontally occupied land area, as described in Fig. 5. This integrated approach is crucial for measuring, understanding and incorporating these areas in future energy scenarios.

Nevertheless, to accelerate the energy transition beyond its current pace, it is insufficient to model individual energy sources in isolation. Instead, the emphasis should be on thinking in and calculating a "swarm" of diverse power plants, which, when combined and regionally adapted, can yield significantly larger amounts of energy in the future.

Therefore, it is necessary to compare area yields in kWh/(m^2.a) between different databases. Dumke [45] employed a database catalogue approach. The author surveyed 89 existing power plants and determined their energy yield, specifically per area in kWh/(m^2.a). In contrast to the PV power plants shown in Chapter 3.3, this database catalogue contains power plants for both thermal and electrical energy. The geographical focus of the records is Austria (30 power plants), Germany (15 power plants) and other European countries (20 power plants), while the other examples are in the USA and Asia. The objective of this comparison is not to present a comprehensive overview of the characteristics of all renewable energy sources, but rather to provide a reliable assessment of their annual energy yields per area (see Table 9). Despite the inherent differences in grid operation characteristics between irregularly producing energy sources, such as wind and solar, and those with a more consistent output, such as the combustion of biomass and the use of geothermal heat, the comparability of these two databases remains interesting. For quality control of the data, the energy yield values provided by the power plant operators were compared with those of literature benchmarks. Figure 18 illustrates four types of power plants. The following bullet list explains the area types within the horizontally measured areas:

- Wind farms and solar parks have similar spatial appearances because the areas contain both the power plant itself (including foundations of wind turbines or PV collectors and other nonusable areas) and the spaces between individual turbines or collector modules. In Dumke's PV power plants, the areas were measured in the same way as shown in Fig. 5, except for the ruderal site/wetland;
- For biomass, the area value includes the potential yield area where the plants grow, as well as the sealed area of the power plant site. The latter may be within or at a distance from the potential yield area;
- With respect to geothermal energy, the potential yield area encompasses all areas containing heat collectors, irrespective of whether they are shallow or deep probes or are located under or beside buildings utilising geothermal heat;
- Hydropower plants were not included in Dumke's data catalogue owing to methodological reasons, as the calculation of the area required for direct and indirect land use would have been considerably more complex.
- The area requirements of any energy storage do not affect the yield calculations because the database records do not contain this information separately.

Figure 19 and Table 9 illustrate the energy yields in [kWh/(m^2.a)] of the energy yield area, which are presented in both an area comparison (treemap, [m^2·a/kWh]) and tabular form with absolute yield values. Given that the dataset under consideration pertains to areas, a treemap is a more appropriate representation than a bar chart. This is because a treemap allows for the visualisation of proportional differences in area efficiency between sample data points, given that the discrepancy between the most and least efficient energy sources is over two orders of magnitude.

The thermal energy sources are marked by a red border, and the electrical energy sources have a grey border. The energy yield values were determined with a method similar to that previously reported for PV power plants: either economic data from enterprises (if present), combined with measurements from satellite images of the power plant site, or sometimes additional extrapolations of standard values from the scientific literature.

Some of the photovoltaic power plant yield values are in a similar range, as shown in Sect. " Land use per generated electrical energy and energy density". In the m^2.a/kWh column, there are also some other comparable yield values from the literature.

The comparison of different area yields reveals the following differences:

- The highest area yield is observed for solar thermal installations on pitched roofs without gaps between collectors. The lowest area yield is associated with obtaining heat from burning wood chips from the forest. The latter scenario only utilises wood residues that cannot be used for higher-value purposes and does not compete with other areas. The area size relationship between these two extremes is 1:131, indicating a significant variation in area yield efficiency.
- With both solar thermal and photovoltaic systems, the area yield efficiency between full-surface module occupancy and an arrangement with spaces between the module rows is in the ratio of approximately

Table 9 Comparisons between the measured energy yield values from these papers' databases and the literature benchmark data

Plant, Location and installation year ddb	**Type** ddb	**Subtype** ddb	**kWh/(m².a)** ddb	**m².a/kWh** ddb	**m².a/kWh** fdb	**m².a/kWh** ldf
Default value of a solar thermal unit on a single-family house 2006	Solar thermal heat	Full coverage of a pitched roof	232	0.0043		0.03 [46]
Large wind turbines, Potzneusiedl, Burgenland 2011	Wind power, electrical energy	Onshore, single turbine unit, plain land	120	0.0083		0.014 [47]
Vienna 2011	Solar energy, PV	Photovoltaic small mobile unit	112	0.0089	Numerical area value is in the same data range as in Figure 14: approximately 0.008 (installation year: 2011)	
Wels, Oberösterreich 2011	Solar thermal heat	Flat roof system, elevated collectors	96	0.0105		
Tauernwindpark, Steiermark 2002	Wind power, electrical energy	Onshore, Row, mountain ridge	74	0.0135		
Oberzeiring, Steiermark 2011	Solar energy, PV	Photovoltaic, ground-mounted system, elevated collectors	52	0.0192	Numerical area value is in the same data range as in Figure 15: approximately 0.02 (installation year: 2011)	
Default value (Clay soil) 2010	Geothermal heat	Shallow geothermal heat, flat-plate collectors	36	0.0278		0.02 (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2010)
Nordbahnhof, Vienna (project planning) 2014	Geothermal heat	Shallow geothermal heat, deep probe field	30	0.0328		0.02 (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2010)
Wind farm Neusiedl am See, Burgenland 2003	Wind power, electrical energy	Onshore, Cluster, plain land	21	0.0472		0.07 (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2010)
Default value 2010	Biomass, heat	Agrarian, maize (biogas)	6	0.1695		0.1695 [48]
Rankweil, Vorarlberg 2010	Biomass, heat	Forest, wood chips (burning of residues from the forest, not competing with other wood uses)	2	0.5680		0.490 (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2010)

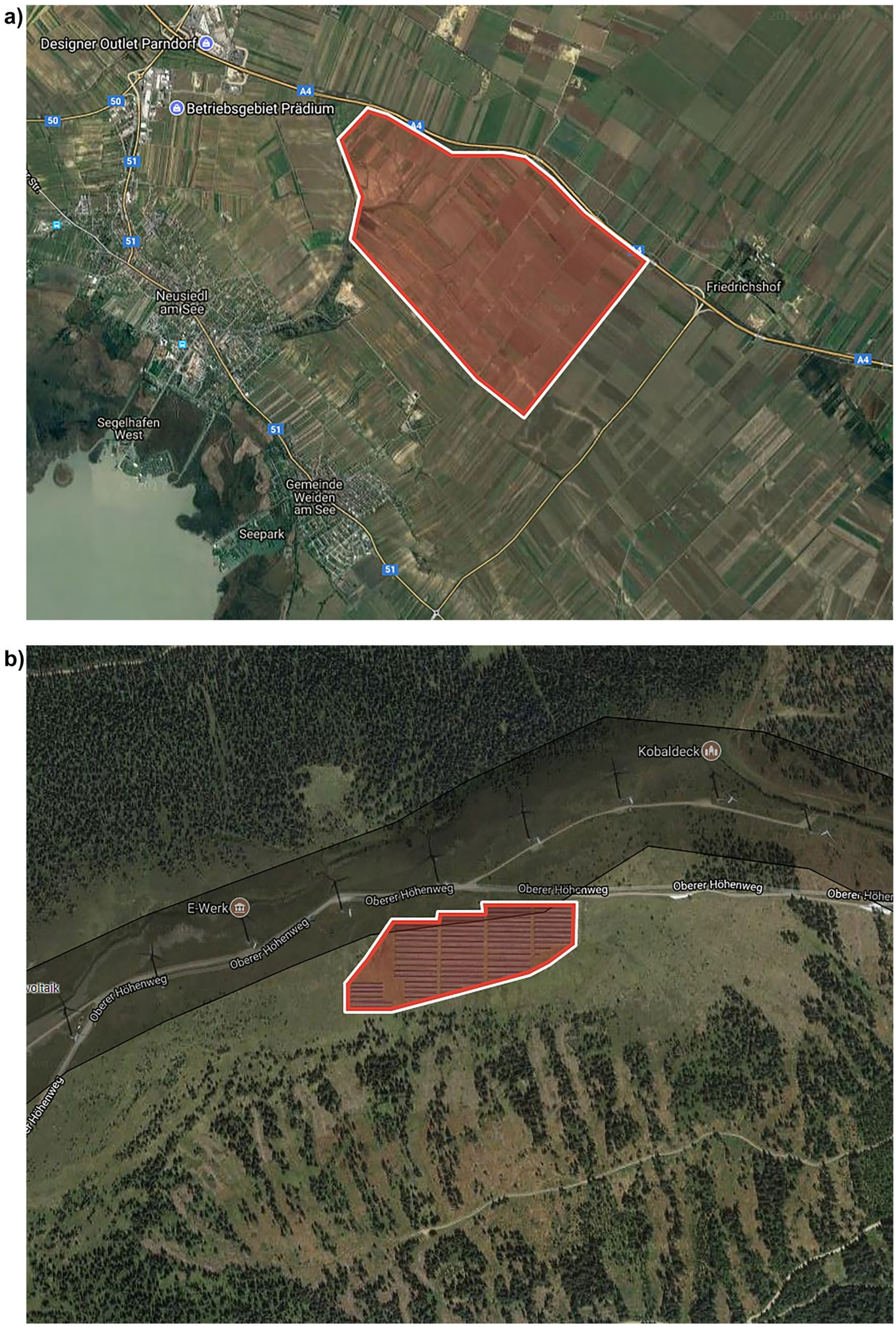

Fig. 18 Selected examples of various potential yield areas for energy generation plants: **a** Wind Park, Neusiedl am See, Burgenland, Austria, **b** Photovoltaic Plant, Oberzeiring, Styria, Austria, **c** Woodchip heating plant, Rankweil, Vorarlberg, Austria, **d** Geothermal heat plant under the ATRIO shopping centre, Villach, Carinthia, Austria (Own work, data source: [45])

Fig. 18 continued

1:2. However, the examples considered here do not encompass newer or less common types of PV power plants, such as those with single- or multi-axis tracking, bifacial vertical modules, or multiple uses such as agri-PV or façade-integrated PV. Although these types of constructions are still rather rare and not the subject of this paper for reasons of data availability, they should be added to future comparative series.

- The data validity is clearly greater for wind power and solar energy than for biomass and geothermal energy. Wind power and solar energy can be more accurately observed and measured spatially. On the other hand, information on the area required for biomass and geothermal energy is often unsatisfactory.

Table 9 provides a summary of the differences in area yields that have been previously outlined. The columns indicate the dataset that is being referenced (ddb = Dumke's catalogue, fdb = Franz' database,

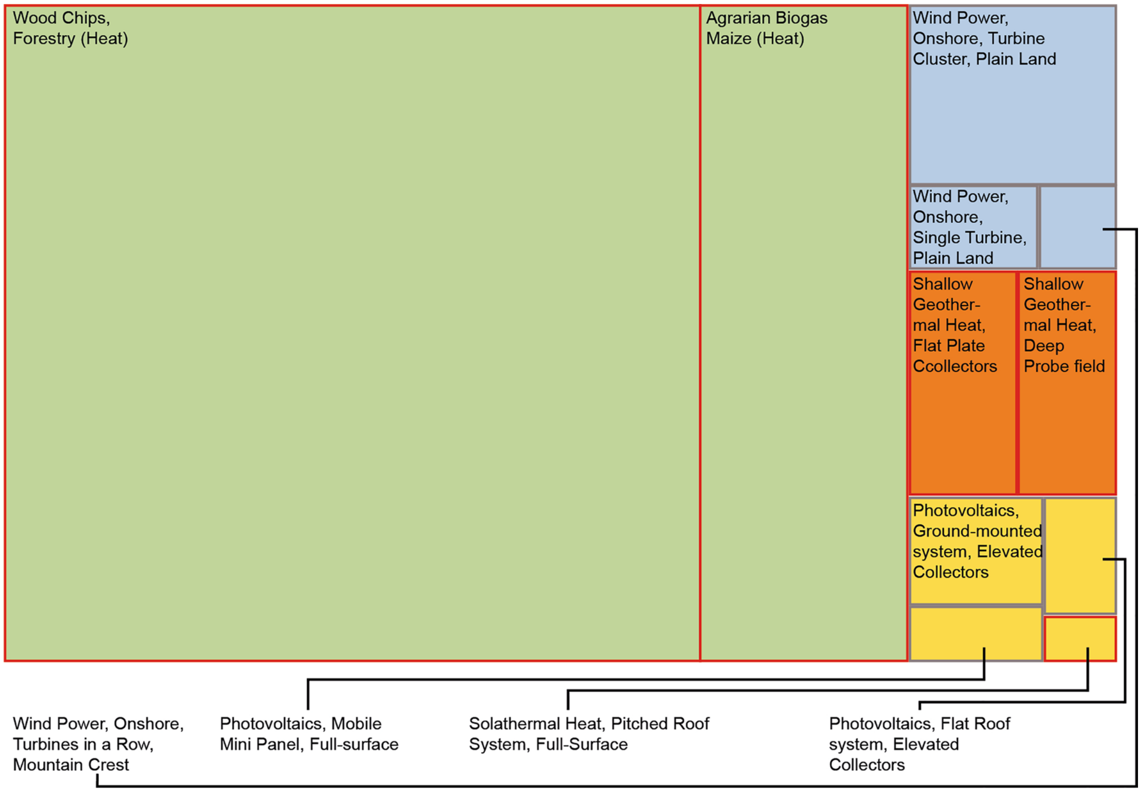

Fig. 19 Treemap visualisation of selected energy yields [kWh/(m^2.a)] of existing renewable energy power plant sites in Austria

ldf = default values from the technical literature on energy yields per area and year- incl. reference).

Comparative studies are essential in defining what constitutes a potential that can become system-relevant in the future energy landscape. These potentials should be substantial, indicating the existence of additional resources that are spatially available to a greater extent than those currently in use. Ideally, such potentials should have minimal negative environmental impacts during operation and be largely independent of temporal variations. Additionally, they should not compete with or displace other essential location-independent land uses, or if there is competition, it should be minimised.

Discussion and conclusions

The study presented a series of area-related key performance parameters for free-field PV power plants, with the objective of offering a European comparative overview of development over time. The results demonstrated a 60% reduction in land use per kWh of electrical energy generated over the course of the study period. This reduction can be attributed to three main factors: first, an increase in solar cell efficiency by a factor of two; second, a reduction in the specific land requirement by 30%; and third, the selection of the geographical location of the PV power plant.

The sample selection encompasses a cross-section of European photovoltaic (PV) installations. With respect to the representativeness of the data, it is assumed that the location-*independent* trends approximately reflect the European situation. It is acknowledged that the location-*dependent* European trends may deviate to a greater extent from the actual average in terms of their slope and vertical position. However, it is assumed that the actual European trends fall within the bandwidth of the sample. Currently, there are no linked Europe-wide comprehensive datasets for free-field PV power plants available. It is thus recommended that this study be regarded as an initial evaluation.

In general, tracking systems and transparent PV modules can reduce the specific land requirements of free-field PV power plants in favour of multiple uses. However, the trend towards reducing land requirements will reach its technical limits. Moreover, the European energy strategy for the electrification of mobility, heating and cooling is expected to double the demand for electricity by 2050, with PV power plants playing a key role in achieving the targets. This will necessitate the development of new spatial strategies and scenarios:

- While small-scale scenarios may be valuable, they may have a limited impact on the overall energy transition. To achieve significant progress, interregional and international solidarity is required in terms of synthesising and analysing existing and future energy needs as well as appropriate geographical locations for the energy infrastructure.
- Future European energy strategies should also include integrated balancing and modelling of PV, which are not isolated from other renewable energy potentials. Compared with biomass and hydropower, wind power, solar energy and geothermal energy have different energy yield profiles but considerably greater potential.
- It is recommended that regions with excess PV potential provide support to those with limited potential. However, this transformation has yet to commence. The majority of additional PV potential in the past decade was harnessed in areas with only moderate energy yield values, for example, in Germany, Poland, and the Netherlands, rather than in southern Europe.
- This requires a comprehensive revision of energy policies, moving away from parochial regional or national considerations and investments towards a more integrated approach that encompasses European solidarity. Furthermore, the potential of multiuse and multilayer systems, such as agri-PVs and façade-integrated PVs, which have been undervalued to date, should receive greater attention.

Integrated energy scenarios should be pursued within the next 15 years, as the European power grid prepares to accommodate these "new" energy landscapes, which will comprise vast swarms of small energy generation plants. This will mark a move away from the era of a few giant power plants, which characterised the past. A promising strategy for achieving sustainability would be to develop different models of multiple uses of agricultural and energy landscapes both at the European level and in local regions. This could be achieved through interdisciplinary integrated spatial and energy planning, incorporating feedback mechanisms and sociocultural contexts.

Abbreviations

a	Year (lat.: annus)
A_f	Fenced area (of a PV power plant)
A_M	Total module area of the PV power plant
agri-PV	Simultaneous use of areas of land for both PV modules and agriculture
ALO	Agricultural land occupation (LCA impact category)
AT	Austria
BE	Belgium
BG	Bulgaria
CF	Capacity factor
cf.	Compare (lat.: confer)
CH_4	Methane
CO_2	Carbon dioxide
CZ	Czech Republic
dc	Direct current
DE	Germany
DK	Denmark
E	Annually generated electrical energy
E–W	East–west
EJ	Exajoule
ES	Spain
EU	European Union
EU27	European Union with the status of 27 member states
FR	France
GHI	Annual average solar irradiation
GIS	Geographic information system
GWh	Gigawatthour
GR	Greece
h_a	Hours of one year (8760); H2: hydrogen gas (dihydrogen)
h_{PN}	Full load hours
ha	Hectare
HU	Hungary
i.e.	That is (lat.: id est)
ibid.	In the same place—refer to the source cited in the preceding note or list item (lat.: ibidem)
IT	Italy
kW	Kilowatt
kWp	Kilowatt peak
kWh	Kilowatthour
LCA	Life cycle assessment
LCI	Life cycle inventory (data)
m^2	Square metre
MW	Megawatt
N–S	North–south
η	Conversion efficiency of a PV module
NL	Netherlands
p	Performance factor of a PV module
P_N	Nominal power
PD	Power density
PL	Poland
PT	Portugal
PV	Photovoltaic
PWh	Petawatthour
R^2	R-squared value (a number from 0 to 1 reveals how closely the estimated values for the trendline correspond to the actual data)
RO	Romania
SE	Sweden
Si	Silicon
STC	Standard test conditions (for the measurements of PV module specifications)
UK	United Kingdom
US	United States (of America)
USA	United States of America
W	Watt
%	Percent

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-024-00504-w.

Additional file 1.

Additional file 2.

Acknowledgements

The authors acknowledge the TU Wien Bibliothek for financial support through its Open Access Funding Program. The authors would like to express their sincere thanks to Springer Nature Author Services for the language check of the manuscript.

Author contributions

MF designed and organised the study; contribution: "Methods", "Spatial and temporal distributions of the investigated free-field PV power plants" to " Specific land use depending on the geographical location of the PV power plant" Sects. HD contributed "Comparison to the land use of other renewable power plants" Sect. All other sections were jointly written. All authors read and approved the final manuscript.

Funding

Open access funding provided by TU Wien (TUW).

Availability of data and materials

All the literature and data used are included in this article and related supplementary materials are available according to the references.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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Received: 9 September 2023 Accepted: 19 December 2024
Published online: 13 February 2025

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