Renewable Energy 261 (2026) 125080

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Review

Large-scale resource assessments for solar photovoltaics: A review of potential definitions, methodologies and future research needs

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ARTICLE INFO

Keywords:
Land use
Meteorological data
Energy systems
Social acceptance
Planning constraints

ABSTRACT

Identifying suitable locations for solar photovoltaic (PV) systems is key to a successful global energy transition. However, PV assessments vary widely in terms of input data used, methodological approaches applied, and therefore ultimately in the resulting total potentials, making their comparison and interpretation challenging. Here, we review the current literature with respect to existing definitions of potentials, associated criteria as well as methodologies to identify current trends in this field and potential future research directions with a focus on large-scale assessments covering at least an entire country or a large region within a very large country. We observed a wide range of assumptions and methodologies used in such studies, sometimes combined with lack of transparency in documentation. Furthermore, the literature lacks consideration of system integration costs to account for the variable PV generation profile. The inclusion of non-technical factors is challenged by the lack of consistent theoretical and methodological approaches and interdisciplinary collaborations, as well as limited availability of data. Combined with a frequent lack of validation attempts, these aspects ultimately limit the comparability and reliability of results. The comprehensive overview in this review assists modelers and decision makers in utilizing best-practice methods for PV potential assessments to improve traceability and comparability of future assessments.

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https://doi.org/10.1016/j.renene.2025.125080
Received 10 April 2025; Received in revised form 22 August 2025; Accepted 17 December 2025
Available online 12 January 2026

1. Introduction

The global transition to renewable energy technologies is in full swing. In 2023, total renewable energy capacity reached 40% of global installed power plants, and 83% of total global capacity expansions were renewable technologies, according to IRENA statistics [1]. Solar photovoltaics (PV) is the biggest contributor among these technologies, with 346 GW of installed capacity. This accounts for nearly three-quarters of installed renewable generation capacity and breaches the 1 TW mark for cumulative installed capacity. By 2030, nearly 1 TW of renewable generation capacity is expected to be installed per year, with over half of that being solar PV, according to IRENA [2].

In order to best plan for the anticipated huge expansion of solar PV capacity, large-scale solar PV potential assessments that take into account cost-effectiveness and social acceptability are becoming increasingly important as a basis for reliable decision-making. Identifying the most suitable locations for capacity expansion allows governments and grid operators to engage in strategic planning and scenario generation, as well as enables project developers to make investment decisions.

Several different methodologies have emerged in the field of renewable energy potential assessments, which makes reliable benchmarking and comparisons challenging. This is mainly due to a lack of transparency regarding system boundaries, methodological approaches, and assumptions [3]. This presents a significant challenge for decision-makers, who may encounter a broad spectrum of potential estimates for a given region based on the underlying assumptions and methods employed.

Therefore, a comprehensive comparison of the approaches and assumptions used to derive large-scale PV potentials is essential in order to highlight the differences that lead to discrepancies and ultimately provide suggestions for best practices. Previous reviews of solar PV have focused on specific types or applications of PV, such as east–west bifacial photovoltaics in desert environments [4], in residential buildings [5], legal or political frameworks [6], technical properties of PV modules such as soiling loss [7] and degradation [8], individual methods for potential calculation [9], and hybrid systems including solar PV in specific regions like Asia/Pacific [10]. Previous reviews of large-scale solar potential assessments have covered only selected regions [11] or individual countries , e.g., Libya [12] or Canada [13] One review focused on the methods developed and definitions used for solar, wind, biomass, and geothermal potential [14]. In the future, we expect studies to focus on regional scales and provide specific recommendations to help reach goals like the EU's installation targets [15]. To the authors' knowledge, no global review that assesses the state of the art in large-scale solar PV potential assessment exists.

To close this gap, this critical review categorizes the various types of potential (see Table 1) and systematically compiles the associated methodologies, criteria, and assumptions. Based on this information, we have developed a set of questions and references to provide structured guidance, which can be found in the appendix (see Tables 12, 13 and 14). While we start with an overview of utilized meteorological solar data forming the theoretical potential in Section 3, the subsequent sections are structured along the more prominent types of potentials mentioned in the literature as listed in Table 1. Section 8 discusses current limitations and potential future work while Section 9 concludes the review.

Table 1
Overview of potential definitions.

Potential term	Definition
Theoretical or physical potential (Section 3)	Total energy content of solar irradiation reaching Earth
Geographical potential (Section 4)	The solar irradiation available in a geographical area suitable for installing PV systems
Technical potential (Section 5)	Installed capacity or generated electricity (often after AC conversion) by PV systems within the geographical potential, over a given period of time (present or future) and with a given PV technology (with a particular electricity conversion efficiency)
Economic potential (Section 6)	The portion of the technical potential that is currently economically viable
Feasible potential (Section 7)	The portion of the techno-economic potential that can be feasibly installed in reality, considering non-technical factors such as social acceptance and externalities

2. Methodology

In this study, a systematic literature review has been performed. For this, a search query was used within the Scopus database [16] to identify all journal papers analyzing large-scale PV potentials:

> TITLE (“PV” OR “photovoltaic*” OR “solar PV” AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*)) AND TITLE-ABS-KEY ((photovoltaic* OR PV) AND (power OR generation OR energy) AND (evaluat* OR assess* OR analy* OR pot* OR plan* OR simul* OR optimi* OR model*) AND (potential OR locat*) AND (generation OR cost OR lcoe OR econom*)) AND SRCTYPE (j)

With this broad search query, we found as many relevant papers as possible, but at the cost of manual refinement afterwards. Focusing on large-scale assessments of PV potential covering at least an entire country or a large region within a huge country, such as the United States or China, required manually reviewing each paper. No constraints were set on the type of solar PV installations. Therefore, this review considers open-field, rooftop, facade, and other PV installation technologies. The initial search yielded nearly 3000 studies, which were reduced to 342 articles after manual checks of titles and abstracts (see Fig. 1. In a second step, we screened the full texts to determine if the articles analyzed one of the various types of potential: geographical (see Section 4), technical (see Section 5), economic (see Section 6), or feasible (see Section 7). This resulted in 192 studies remaining, which were supplemented by articles identified through citation backtracking.

Additionally, we analyzed the distribution of the reviewed papers across years and types (see Figure 6 in the Appendix). The shown trends reveal that papers have only recently started to address the feasible potential, and even then, only in a few papers. In contrast, the technical potential has been addressed in an increasing number of papers, though there has been a strong decline in recent years. Geographical and economic potentials are covered in papers that are more evenly distributed across years, but at a much lower level compared to the technical potential. In general, it appears that the peak of papers addressing large-scale PV potential occurred around 2021–2022. Furthermore, the supplementary information provides global maps showing the distribution of countries by potential type (see Figures 7 to 14 in the Appendix).

3. Theoretical potential: Meteorological solar data

The performance of PV systems depends on solar irradiation, ambient temperature, wind speed, and spectral content. Accurate assessments of solar PV systems rely on solar irradiation, which is defined at the Earth’s surface by three key components: global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI). These are commonly measured using specialized radiometric instruments: pyranometers for GHI [18], pyrheliometers for DNI [19], and shaded pyranometers for DHI [20]. In typical synoptic stations, only GHI is measured with a pyranometer, while DNI and DHI are not recorded, except in dedicated solar resource assessment stations [21]. However, DNI and DHI are also important for solar PV assessments because e.g., they can distinguish losses due to self-shading from malfunctions. Various methods have been proposed to derive DNI and DHI from GHI [22]. The potential use of photovoltaic cells as an alternative measurement device has also been discussed in the literature [23].

Notably, the International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS) Task 16 — Solar Resource for High Penetration and Large-Scale Applications [24] — has produced the fourth edition of the Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications. The handbook provides best practices for obtaining and applying solar resource data across a range of solar technologies and emphasizes the importance of reliable solar radiation data as the foundation for all subsequent analyses.

While location-specific solar radiation measurements (hereafter ground-based station measurements) provide precise data, they are limited in spatial coverage [21]. In contrast, interpolation [25], satellite observation-derived [26], and atmospheric modeling products [27] provide continuously distributed solar radiation data over larger areas. Interpolation or composite products are typically based on station and/or satellite measurements and use statistical and/or physical methods to estimate solar radiation values across an entire region [28]. Satellite observation-derived solar radiation products are produced by cleaning and processing signals observed from satellites, often with ground measurements used for data calibration and assimilation [29]. Atmospheric modeling can generate reanalysis products using Numerical Weather Prediction (NWP) with hindcast setup for historical solar radiation at both global and regional scales, assimilating a wide range of measurements from ground, satellite, and atmospheric sounding sources [30]. It can also project future changes in solar radiation using climate models under several climate change scenarios [31]. There are also ready-to-use solar resources maps, known as solar atlases [32], which cover global or regional scales and are usually originated from the aforementioned products.

When it comes to uncertainty information associated with data sets, most ground-based station measurements include metadata documenting the instruments used and their uncertainties. However, the quality and completeness of this metadata disclosing uncertainty information varies between data sets. The same applies to satellite observation-derived products. For atmospheric modeling products, particularly reanalysis products, uncertainty information is addressed by validating the products against observations and/or uncovering the observations involved during the data assimilation stage of product generation. The same applies to solar atlases products.

Table 2 summarizes the detailed spatial and temporal coverage and resolution of various solar radiation products reviewed in this study. As can be seen from Table 2, some of these products have a global spatial coverage, while other databases include data at a more restricted geographical (e.g., country) level. Various temporal coverage of historical averages, historical periods, history to present, and future projections are found in all products. The spatial and temporal resolution also varies from product to product. The temporal resolution of solar radiation measured by ground-based stations are subject to the specific station setup and post-processing. In general, state-of-the-art satellite observation-derived products, such as SARAH-3, have finer spatial and temporal granularity compared to other products. Due to the computation and storage costs, global reanalysis products usual

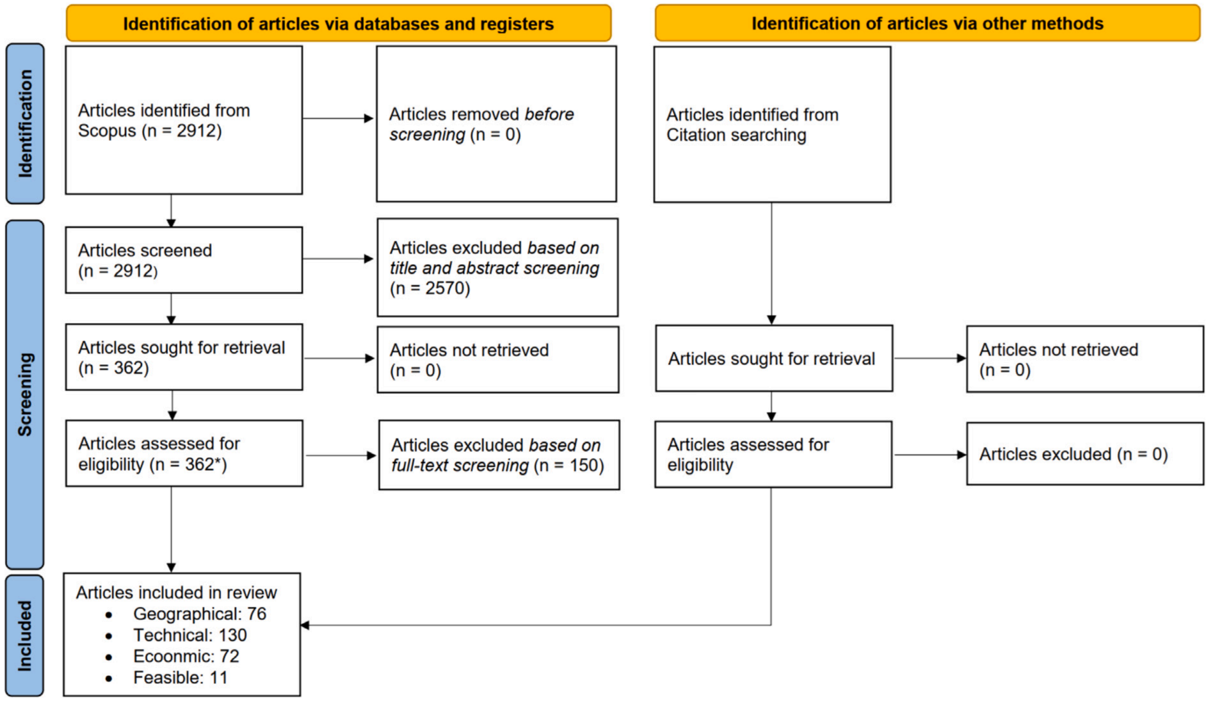

Fig. 1. Flowchart for identifying and classifying relevant articles on PV potential assessments based on the PRISMA 2020 Statement [17].

have a coarser spatial resolution compared to regional reanalysis. The same applies to the global or continental-scale climate projections.

The pursuit of reliable global solar radiation products with higher spatial and temporal resolution is a clear trend in the literature. However, the choice of a solar radiation product for a particular study depends on the research objective, as a high-resolution product is not always necessary. For example, if a theoretical or only strategic perspective is required for a solar PV assessment, a historical temporal average product may suffice. In contrast, for applications such as regional energy system planning, where spatially distributed solar PV power time series are essential [33], high-resolution solar radiation data at both spatial and temporal scales becomes crucial.

4. Geographical potentials

The geographical potentials for solar PV systems is defined as the yearly solar radiation considering geographical constraints in an area [77], the primary energy flux in suitable and available areas [78], the theoretical potential reduced to the suitable area for PV [79], the solar irradiation to the earth surface suitable for PV [80], the solar resources in suitable areas [81] or the solar energy received by suitable areas [82]. An overview of the countries covered by the literature can be seen in Figures 7, 8 and 9 in the Appendix. Most of the reviewed studies, measure the geographical potential in capacity, but also estimated areas (e.g. [83]), percentages of areas [84], or feasible site locations (e.g. [85]).

In the following subsections, more specific definitions, the used methods, and applied criteria are provided. As approaches, and respective data used, vary depending on which type of geographical potential is analyzed, we differentiate between open-field PV (Section 4.1) and roof-top PV (Section 4.2). These two systems dominate literature, further potential types are discussed in a third subsection (Section 4.3). A checklist for future practitioners dealing with geographical potentials can be found in Table 12 in the Appendix, as a suggestion of good practice on documenting the approaches followed in studies dealing with this topic. Links to information contained in this document are also provided as guidance based on previous studies.

4.1. *Open-field PV*

Determining the geographical potential is usually the first step when calculating open-field solar PV potentials [81] or the siting of PV plants [86]. However, it is worth mentioning that some studies for example [87] calculate the theoretical potential or the resource potential without considering the geographical potential. These potentials only deal with solar radiation availability, neglecting geographical constraints.

4.1.1. *Applied approaches*

The methods used to determine the eligible land for open-field solar PV plants vary across studies. Some studies set a threshold for each criterion with or without buffer distances and classify areas as either suitable or unsuitable, with the intersection of suitable areas for all criteria determining the eligible area , e.g., typical study [88]. Other studies define suitability factors, which assign different qualitative levels of eligibility to suitable land, and then formulate the overall suitability considering all criteria [89]. In another approach, all criteria are quantitatively assessed and converted into fuzzy sets, which are then integrated into a final suitability factor using multi-criteria decision analysis techniques such as the Analytic Hierarchy Process (AHP) [85], Analytical Network Process (ANP) [90], and Fuzzy Logic Ordered Weight Averaging (FLOWA) [91]. This approach typically results in multiple rankings of land eligibility based on the calculated suitability factor [92]. Some studies use a combined approach, excluding land by certain criteria and calculating the multiple ranks of land eligibility by other criteria [93].

4.1.2. *Utilized land-cover and geographical databases*

Some geographical databases at continental and global scales are frequently used in the reviewed articles (see Table 3). Most studies consider only publicly available data sets and process the raw data sets further for instance by extracting power transmission lines or substations using Google Earth [94] before conducting the exclusion analysis. Some studies also involve proprietary or closed data sets that are provided by local authorities or personal contacts, for instance the proximity to road, grid lines, and settlement areas in study [88] were

Table 2
Overview of coverage and resolution of meteorological data sets providing solar radiation data.

Type of data source	Example datasets	Open data	Coverage		Resolution	
		Yes/No	Spatial	Temporal	Spatial	Temporal
Ground-based station measurements	HadISD [34], [35]	Yes	Global (irregular)	1931–2023	Site-specific	Hourly to daily
	GEBA [36]	Yes	Global (irregular)	1919–present	Site specific	Monthly average
	METEONORM [37]	Partially open	Global (irregular)	1996–2015	Site specific	Minutes to 1 h
	Global Hourly - Integrated Surface Database (ISD) [38]	Yes	Global (irregular)	1901–present	Site specific	hourly
	World Radiation Monitoring Center - Baseline Surface Radiation Network (WRMC-BSRN) [39]	Yes	Global (irregular), 77 stations from 80°N to 90°S	Station-dependent (1992–present)	Site specific	1–3 min
Interpolation products	WorldClim Version 2 [40], [41]	Yes	Global	1970–2000	~1 km²	Monthly
Satellite observation-derived products	NASA POWER (SSE) [42]	Yes	Global	1984–present	1° × 1° (latitude × longitude)	3 h
	SARAH-3 [43]	Yes	−65° to +65°	1983–2020	0.05° × 0.05° (latitude × longitude)	30 min, daily, monthly
	CAMS [44]	Yes	Global	2004–present	0.2° × 0.2° (latitude × longitude)	1 min, 15 min, 1 h, daily, monthly
	HelioClim-3 [45], [46]	Partially open	−66° to +66°	2004–present	3 km at Nadir, approx. 5 km in Europe	15 min
	Himawari-8/9 [47]	Yes	60°W to 160°E and 85°N to 85°S	2015–present	0.5 km to 2 km	10 min (2.5 min in Japan)
	Solcast [48]	Partially open	Global	2007–present	90 m	5, 30, and 60-minute
Atmospheric modeling: Reanalyses	MERRA-2 [49]	Yes	Global	1980–present	0.625° × 0.5° (latitude × longitude) ~69 km × 56 km [50]	1 h–6 h [50]
	ERA-5 [51]	Yes	Global	1940–present [52]	31 km, land data set 9 km [53]	Hourly [52]
	JRA-55 [54]	Yes	Global	1958–present	55 km [54], [55] (ended January, 2024)	3 h–6 h [54], [55]
	JRA-3Q [56]	Yes	Global	1947–present	40 km [57], [58]	6 h (hourly or daily for some types) [57]
	CFSR [59]	Yes	Global	1979–2017 [60]	38 km [59]	6 h [59]
	20CRv3 [61]	Yes	Global	1836–2012 (20CRv3si)	60 km at equator	3 h
			1981–2015 (20CRv3mo)			
	CERA-20C [62]	Yes	Global	1901–2010	55 km	3 h
	COSMO-REA2 [63]	Yes	Central Europe	2007–2013	2 km	1 h
	COSMO-REA6 [64]	Yes	Europe	1995–2019 [65]	6 km	1 h
	NSRDB [66]	Yes	US and some countries	1998–2021	2, 4, 10 km	5 min–1 h
	BARRA-R [67]	Yes	Australia	1990–2019 [68]	1.5 km locally around Australian cities to 12 km	10 min–1 h (10 min only locally)
Atmospheric modeling: Climate models	CMIP5 [69], [70]	Yes	Global [71]	1850–2100 (some until 2300) [71]	0.125° × 0.125° to 5° × 5° [71]	Hourly to monthly [72]
	CMIP6 [69]	Yes	Global [73]	1850–2100 [57] (some until 2300) [74]	0.125° × 0.125° to 5° × 5° [74]	3 h to daily [75]
	EURO-CORDEX [70]	Yes	Europe [70]	1950–2100 (shorter for some experiments) [76]	12.5 km (EUR-11) or 50 km (EUR-44) [70]	3 h, 6 h, daily, monthly, seasonal [76]
Solar atlases	GSA [32] (also preprocess power output)	Yes	National to global	Historical average	1 km²	Monthly

calculated based on data from authority, which may not be in line with the FAIR principles [95]. Generally, all the involved geographical variables are available with global coverage and high spatial resolution at a scale of hundreds of meters, except for roads and power grid data sets, which require additional efforts to improve their resolution.

4.1.3. Exclusion criteria

Table 4 provides an overview of typical criteria and thresholds used to identify eligible areas for open-field PV in the literature. The criteria and the thresholds of the criteria used in a particular study may vary widely from study to study due to different local conditions, and the ranges reported do not necessarily account for all possible settings. As Table 4 shows, the most frequently excluded areas found in the literature are protected areas of natural conservation, water bodies, and strongly inclined slope. Meanwhile, different "Excluded values or distances" (column 3 of Table 4) are found in the literature, which vary substantially in the literature for case-specific reasons. For example, for the slope sub-criterion, areas with steep slopes are

Table 3
Overview of large-scale databases utilized in determining the geographical potential.

Category	Dataset	Classes	Openly available	Spatial resolution	Regional coverage
Land cover	CORINE Land Cover [96]	44	Yes	100 m linear phenomena, 25 ha areal phenomena	Continental (Europe)
	Sentinel-2 [97]	11	Yes	10 m	Global
	Land Cover Climate Change Initiative [98]	22	Yes	300 m	Global
	GlobCover Land Cover Maps [99]	22	Yes	300 m	Global
	Moderate Resolution Imaging Spectroradiometer (MODIS) [42]	5 different land cover classification schemes primary land cover scheme	Yes	500 m	Global
	Global Land Cover Copernicus [100]	10	Yes	100 m	Global
Roads	Global Road Inventory Project (GRIP) [101]	Roads	Yes	5 arc minutes ($\tilde{8}$ × 8 km)	Global
Power grid	Gridfinder [102]	Power grid	Yes	15 km	Global
Biodiversity, crop, and protected area	Natura 2000 [103]	Sites designated under Birds Directive and Habitats Directive	Yes	Varying	Continental (Europe)
	EU's Database of Nationally designated areas [104]	Individually for each area	Yes	Varying	Continental (Europe)
	World Database on Protected Areas [105]	Individually for each area	Yes	Varying	Global
	Datasets on soil biodiversity [106]	Biodiversity	Limited	–	Global, focus on Europe
	EarthStat Database [107], [108]	Crop distribution	Yes	10 × 10 km	Global
Elevation	Global 30Arc-Second Elevation [109]	Elevation	Yes	30Arc seconds = 926 m at equator	Global
	SRTM 90 m Digital Elevation Data [110]	Elevation	Yes	90 m at the equator	Global
Water bodies	HYDRO1k elevation dataset [111]	Streams and drainage basins	Yes	1 km	Global
	Global reservoir and dam database (GRanD) [112], [113]	Reservoir and dam	Yes	15 arc seconds (450 m)	Global
	Global Lakes and Wetlands Database (GLWD) [114]	Lakes, reservoirs, and rivers	Yes	$\tilde{1}$ km^2	Global
Administrative borders	Harvard WorldMap [115]	Country border	Yes	–	Global
	GADM [116]	All sub-division in countries	Yes	1–100 km	Global
Demographics	WorldPop [117]	Population number and other demographics data	Yes	3arc (approx. 100 m)	Global
Nighttime lights	DMSP-OLS [118]	Nighttime lights	Yes	30arc seconds = 926 m at equator	Global
Various features	OpenStreetMap project [119]	29 primary features with various subfeatures	Yes	Varying	Global
	Google Earth [120]	Various	Varying	Varying	Global
	DIVA-GIS [121]	Various	Yes	Varying	Global

excluded due to installation and maintenance challenges. The slope limits, however, vary based on the local terrain, with higher slope limits allowed for solar PV installations in mountainous areas compared to flat areas [122]. Other criteria such as fault locations include areas with high-risks for landslides and earthquakes and are excluded to ensure safe operation [84], or higher scores are assigned (favorable for solar PV installation) with increasing distance to the fault locations [90]. In addition, some studies also consider different minimum land areas required to install a solar PV plant, such as 5700 m^2 (connected to medium-voltage grid) and 144,000 m^2 (connected to high-voltage grid) [123], 165 acres (ca. 668 m^2) [84], and 5,000,000 m^2 [124]. Further articles such as [125] define eligible land for the solar PV installation as areas without other potentially productive uses and identify them by analyzing the land cover data from remote sensing. Actually, most of the reviewed studies do not exclude agriculturally cultivated land. Usually, installations on such areas are referred to as AgriPV or agrivoltaics, and are distinguished from open-field PV installations, see Section 4.3 for details.

In addition, some criteria considered in the geographical potential actually involve economic aspects. Several studies consider proximity to existing infrastructures such as roads [84], railways [122], power demand centers [126], power grids [89], and substations [86] in order to design an economically viable system. This is done by creating a maximum buffer distance from the center of the infrastructure [84] or by assigning different suitability weights to different levels of distances [89]. Furthermore, a few articles consider future expansions of urban areas by setting a minimal distance from existing urban areas [127] or include the available capacity of the existing grid to connect new solar plants [123].

Table 4
Overview of the criteria used in the open-field (first part), rooftop (second part) and further (third part) solar PV geographical potential calculations.

Criteria	Sub-criteria	Excludes values or distances	References
Climatology	Solar irradiance	<1400–1700 $\frac{kWh}{m^{-2}\ year^{-1}}$	[89,94,122,124,125,127–132]
	Air temperature	>40 °C	[85,124,130,132,133]
Topography	Altitude	>60–5000 m	[84,94,124,134]
	Slope	>2.1–35°	[84,85,88,91,94,122–127,129–132,134,135]
	Continuous area	Sensitive to plant size	[84,123,124]
Infrastructure	Urban and other build-up area	<100 m and >50 km	[77,80,82,85,91,123,128–130,133,136]
	Roads	<50 m and >50 km	[84,85,89,91,122–124,126,130,133,134]
	Railways	<100 m and >5 miles	[89,122,124,126]
	Power line/grid	<6 m and >13 km	[84,85,89,122,124,134]
	Civil and military aviation area	<1000 m	[124]
Natural concerns	Water bodies (seas, river, lake, dam, flood area, wetland, snow, and ice)	<100 m	[77,80,82,84,91,123–126,128,129,133,135–138]
	Protected area (conservation of flora and fauna)	<1000 m	[77,80,82,85,88,122–124,126–129,134,135]
	Forests	No buffer	[77,80,82,122,123,125,128,136]
	National parks	<200 m	[123]
	Agricultural zones	No buffer	[77,80,82,136]
	Tundra zones	No buffer	[77]
	Fire zones	No buffer	[123]
	Sandy zones	No buffer	[91]
	Earthquake/landslide zones	No buffer	[84]
Cultural concerns	archaeological sites	<200 m	[88,123,124]
	Historical and touristic monuments	<500 m	[88,91,124]
Legislation	Military zones	No buffer	[122,124,128]
	Raw materials extraction zone	<100 m	[124,136]
Demographic	Population		[139–148]
Infrastructure	Built-up area		[83,141,142,144,147,149–152]
	Building density		[139,140,144,153]
	Floor area		[139,140,154,155]
	Number of buildings		[156–158]
	Road length		[141,142,147]
	Building topology		[139,140]
Economic	GDP		[79,147,159]
Climatology	Air temperature		[137]
	Cooling		[160–162]
Infrastructure	Structure of the underlying surface (road surfaces, freeway slopes, railroad ties, vessel model, cooling towers)		[137,138,160–165]
	Shadow factor	0–1	[166,167]
	Utilization, Percentage of total area, Coverage	0–1	[137,138,160,161,163,164,166,166,168–173]
	Orientation, Angle of incidence, Roof angle, Tilt		[163,170,172,174,175,175]
	Height, Floor height		[167,176]
	Albedo		[176]
	Household facilities		[167]
	Maintenance		[167]
	Development status of city		[167]
	Efficiency of PV		[175]
	Minimum generation	2 kWp	[162,168]
	Minimum area		[168]
Natural concerns	Water body type (seas, river, lake, dam, flood area)		[137,138]

4.2. Rooftop PV

The geographical potential for rooftop PV refers to the rooftop area suitable for installations [150]. Compared to open-field PV, the challenge lies in identifying roof areas and considering their eligibility based on factors like tilt, orientation, and roof structure.

4.2.1. Applied approaches

Classifications of approaches determining this type of potential use different criteria in literature. For example, categorized methods based on spatial resolution [148]. These methods, ranging from coarse to fine spatial resolution, are classified into low-level, medium-level, and high-level approaches. Meanwhile, some studies categorized methods into constant value, manual selection, and GIS methods [156,177]. The constant value method assumes a fixed fraction of a building's rooftop is available for PV installation. Manual selection involves detailed analysis of individual rooftops using high-resolution imagery. GIS-based method uses geospatial analysis to assess rooftop suitability for PV deployment. Another widely acknowledged scheme is based on the method topology [141]. According to this scheme, methods are categorized into bottom-up, top-down, and hybrid approaches.

The top-down approach is the most widely used approach (60% among the reviewed papers) due to its simplicity [141]. It begins at a local scale by identifying relevant socioeconomic factors influencing rooftop availability. Commonly used factors are summarized in Table 4 Regression analysis is then applied to establish correlations between available rooftop areas and these factors, allowing for extrapolation to larger regions. Although these methods offer quick implementation and computational efficiency [141], issues arise when scaling analyses up towards country or regional levels [83]. This reduced accuracy often arises from inaccuracies in the coarse geospatial mapping of socio-economic data and the diverse nature of built-up areas [148]. Furthermore, while this method is theoretically suitable for large-scale studies, its global application is limited due to the inherent variability of correlations between socioeconomic data and available rooftop areas.

The bottom-up approach (20% among the reviewed papers) uses aerial imagery to identify built-up areas and building footprints [141]. This method employs various techniques, including earth observation, drone-mounted LiDAR, and machine learning (ML) algorithms for building detection [141]. By leveraging high-resolution aerial imagery, bottom-up methods provide accurate and detailed information on built-up areas and building footprints. However, processing aerial imagery is costly and computationally intensive. These resource constraints impose limitations on the scalability of studies employing top-down methods, in many cases rendering them more suitable for smaller-scale investigations, such as city or district level.

Researchers have turned to a hybrid methodology combining elements of top-down and bottom-up approaches because of their limitations. This approach (20% among the reviewed papers) begins by assessing the available rooftop area in small regions, using high-resolution data sources such as satellite images or LiDAR point clouds. Subsequently, like the top-down approach, various socioeconomic variables are identified and incorporated to establish statistical relationships between available rooftop areas and these socioeconomic variables within the small sample regions. These relationships are then extrapolated to larger areas using the identified socioeconomic variables. The hybrid approach offers distinct advantages by addressing processing and data bottlenecks observed in the bottom-up approach, while also improving the accuracy of the top-down approach [141].

4.3. Further potentials

This subsection describes all remaining potentials that are neither rooftop nor open-field as well as those that combine either rooftop PV or open-field PV with another system. Examples include agrivoltaics, floating PV, parking PV and building integrated PV (BIPV) [178]. Studies define the geographical potential as the underlying surface and its impact on PV installations [179], or the solar irradiation on the part of the world that is suitable for PV installations [79], or the map of the Dutch general cargo fleet [171] in the case of PV installations on ship. The potential of these types of solar PV installations is assessed as they provide unique advantages. The most common one is dual use of already occupied areas similar to rooftop PV. Additionally, combining PV systems with other systems can have positive coupling effects. For example, in the cases of agricultural and floating systems, the shade of the PV systems reduces the evaporation of water while the PV system is cooled. In building integrated PV systems, PV replaces building materials or is used for shading purposes. Another advantage is the utilization of areas that are difficult to use for other purposes, such as abandoned mine districts [180] or archipelagos [181]. Such assessments often simply state the potential for national PV capacities [163], address water saving [160] and efficiency increasing effects [161] or discuss the advantageous operation of hybrid applications [161] and designs developed [182] for operation under harsh conditions [137]. Most common methods are shown in Table 5. Spatial analysis uses geographical information systems (GIS), open source and community driven tools and commercial software (see Table 3). The calculated geographical potential are not only presented in form of its capacity, but often also in the number of objects as well as the area covered. The databases to calculate the potentials can be found in Table 3.

Table 5
Methods mentioned across literature used to calculate further potentials.

Method	Sources
Top-down	[161,164,166]
Bottom-up	[137,138,171]
Based on existing systems	[167–169,175]
Multi-criteria-decision-making	[182]

4.3.1. Floating PV potentials

Floating PV systems are PV systems mounted on buoyant structures on water bodies like fish ponds, dams, lakes, rivers, and hydropower reservoirs. All studies estimated the potentials for different coverage levels assuming that water bodies are partially covered to avoid side effects such as abnormal algae growth [163] or utilization for irrigation [137]. The mentioned criteria are are shown in Table 4. One study looked into potentials globally for hybrid systems based on PV, wind near water bodies suitable for hydro power, considering additional areas besides water bodies, requiring additional exclusion criteria such as forests, urban areas, and slopes Wang et al. [182].

4.3.2. Agri-PV potentials

Agri-PV systems are typically placed vertically allowing crops to be cultivated in-between the rows or above agricultural land, while still using the land to farm crops. Only the latter installation type was found within the reviewed papers. Of the two identified studies, the potential is estimated based on the assumption that 20% of agricultural area is used [138] and a global estimation is provided of the agri-PV potential [83]. They classify 18 major crop groups based on their shading tolerance and consider suitability factors of 0.15, 0.25 and 0.5 based on conservatism and technological advances using the Copernicus Land Cover Data [183] and the EarthStat database for crop distribution [107].

4.3.3. Infrastructure integrated PV potentials

Infrastructure integrated PV systems include all concepts that are installed close to roads, train tracks, shipping lanes, airports and buildings. Rooftop PV systems being the only exclusion. The most common advantage of these systems is the increased utilization of otherwise difficult to use space or the installation serves a distinct purpose, e.g. electricity self supply. In Italy [170] and the USA [172], potentials are determined for PV systems integrated into new installations of noise barriers. The mentioned criteria across literature are shown in Table 4.

5. Technical potential

The technical potential of photovoltaic systems refers to the conversion of the solar radiation into electricity, the main output of photovoltaic systems. Some of the reviewed studies defined the technical potential as the amount of geographical potential in a chosen area that can be converted into electricity given the available solar power technologies [80], or as the geographical potential multiplied by the efficiency factors and performance ratios of the solar panels [184]. It has also been defined as the geographical potential in a given area that can be converted into electricity given the available solar power technologies [81] or as the amount of the electricity produced per unit area, based on the amount of solar radiation received at a given site while taking into account the technical factors related to the PV installation, such as panel efficiency [185]. Based on these definitions, we define the annual technical potential of a specific area as the electrical power generated by converting the given solar irradiance into electricity, after considering the technical characteristics of photovoltaic technologies. These characteristics include the solar resource availability (location, season, daytime), conversion efficiencies (PV module and system), solar PV system design, and installation type (useful installation area and PV module orientation).

The technical potential is often expressed as the amount of electricity that can be generated in a given area per year, typically measured in gigawatt hours (GWh) or terawatt hours (TWh) (e.g. [125]). In some cases, the required installable PV capacity is also mentioned in some cases (e.g. [82]) and often expressed in gigawatts peak (GWp) or megawatts peak (MWp). The “p” stands for “peak” and refers to the power under standard test conditions. Another common way of reporting the technical potential is as the ratio of the latter two in kWh/kWp [186], also known as the specific photovoltaic output or energy yield.

Two predominant methods for calculating the technical potential were identified in the reviewed papers. Firstly, the technical potential is calculated as the product of annual global horizontal irradiance (GHI), PV module efficiency, and factors accounting for losses, such as temperature corrections or performance ratio. The latter factor incorporates the deviation from the maximum theoretical performance and the percentage that is typically achieved. This assessment is often carried out for a raster in a particular region or country. The potential is calculated for each raster element, and then summed up for the entire country or area. An example of this approach can be found in one of the reviewed publications [80]. However, the assessment does not consider installation factors such as module orientation, locally specific shading, or the effects of incidence angle on the module plane.

A second, more rigorous approach involves time-resolved irradiance calculations for a given area and meteorological year. This approach requires the use of specialized tools, such as the photovoltaic performance model in the System Advisor Model (SAM) [187] to estimate the technical potential. The installed capacity is derived by accounting for area requirements between PV module rows to minimize row-to-row shading or for maintenance purposes. Irradiance is frequently decomposed into direct and diffuse components. In some cases, albedo is sometimes regarded to calculate additional irradiance reflected from the soil. The orientation of PV modules is considered as well as shading losses. Irradiance reaching the modules is then analyzed. Models for power conversion in PV modules, losses in module strings, degradation, system outages and losses in DC-AC conversion are considered to calculate the annual electricity output for the entire system.

The values of the technical potentials exhibit significant variation in relation to the dimensions of the regions, the PV type and further assumptions such as the cell efficiency [188]. Nevertheless, in the majority of the reviewed cases, the derived potentials often comes close or exceed the TWh scale (e.g. in Indonesia [189]) or even reaches the PWh scale (e.g. in Pakistan [82]). Furthermore, the scope of the technical potential assessments are often limited to single applications such as rooftop or open-field PV. Figures in the Appendix provide an overview of the spatial coverage of the technical potential for the various installation types reported in the reviewed studies. In certain countries such as Germany, research covers all types of PV potentials and now focuses on identifying the most suitable locations [190].

The following subsections describe the most frequently observed characteristics that are considered in technical PV potential assessments in greater detail. A checklist for future practitioners, accompanied by examples and references to pertinent sources of information contained within this document, can be found in Table 13.

5.1. PV installable capacities

Using area utilization factors to derive the PV capacity facilitates the conversion of the geographical potential into installable photovoltaic capacity measured in GWp or any other related unit. The area utilization factor variates depending on the individual assumptions and the type of PV installation. The reviewed papers provide a range of assumptions and methodologies for estimating the potential of photovoltaic installations across different application cases and regions. For instance for open-field PV systems, a study conducted in Morocco assumed a “ground coverage factor” of 0.2 [185]. This assumption is supported by a study conducted by IRENA, which indicates that the ground area required is five times the actual area collecting solar radiation due to spacing and electrical equipment [191]. Moreover, a factor of 32 MW/km^2 is described in another publication analyzing the PV potential in the USA [192]. For Oman, an “area factor” of 70% for open-field applications, representing the fraction of feasible area that can be covered with PV modules was assumed [91]. Similar values of 70% were assumed in a study in China [193]. In Israel, a study considered a capacity of 0.1 kWp/m^2 for open-field PV systems [123]. Globally, a broad range of 0.04 to 0.3 kWp/m^2 was described for open-field systems [194]. The respective assumed number depends upon the efficiency of the module, as well as module layout, the latter often optimized in terms of tilt, azimuth and row spacing, so that shading is minimized and electricity yield is maximized. In addition, the land-use requirements, terminology and best use practice are described elsewhere [195]

Rooftop applications also exhibit variability across regions. In China, a study considered variable “availability coefficients” for rooftops, ranging from 0.3 to 0.7 depending on the location [149]. These coefficients were influenced by factors such as shadows, alternative rooftop uses like air conditioning, reserved space for inspection and maintenance, and geographical conditions. The coefficients were found to be lower in highly developed regions. For Mauritius, a factor of 0.72 for rooftop applications on an island was assumed in a study [196]. A previous publication by the same authors also used this factor [88]. In Hong Kong, a study assumed that the potentially PV-suitable rooftop area equals to 60% of the ground floor area [154]. For Germany, a conversion factor of 0.1–0.13 kWp/m^2 for rooftops of detached, semi-detached, terraced, or other types of buildings was assumed [197].

Specialized PV applications have unique considerations. For parking areas and water deposits in the Canary Islands, a factor of 35% of the area for parking areas and 40% for water deposits was considered [164]. For floating PV systems, a factor of 1 MW/hectare or 0.1 kWp/m^2 was assumed [198]. In China, one of the analyzed papers assumed a factor of 450 kWp/hectare after previously estimating that 20% of the agricultural area and 50% of the fishpond area in the country are suitable for PV installations [199] . Concurrently, a publication assumed a utilization factor of 500 kWp/hectare for floating PV systems [200].

Finally, in one of the publications the use of different factors depending on roof types and ground coverage was noted. This study used a ground coverage factor of 0.5, a construction-related obstruction factor of 0.72, and a module-specific area consumption of 4.55 m^2/kWp, resulting in a capacity density of 0.792 kWp/m^2 [194]. Hence, all of these numbers applied to deriving the installable PV capacities show the broad range of assumptions found in literature.

5.2. PV technology, cell and module efficiency

A recent study has revealed that crystalline silicon modules represent 97.5% of the market, whilst the remaining 2.5% is made up of thin-film based technologies, including cadmium telluride (CdTe) and copper-indium-gallium-(di)selenide (CIGS), as well as amorphous silicon (a-Si), among others [201]. First Perovskite-Silicon tandem modules have been installed in open field configuration in 2024.

As illustrated in Fig. 2, recent assessments have exhibited an upward trend in the assumed efficiency values, which is consistent with the technical progress in terms of cell efficiencies. Only very few publications used efficiencies close to the current top 10 industrial panels with efficiency of approx. 21% [202]. It is acknowledged that such high efficiencies of top-tier modules in large-scale scenarios may be

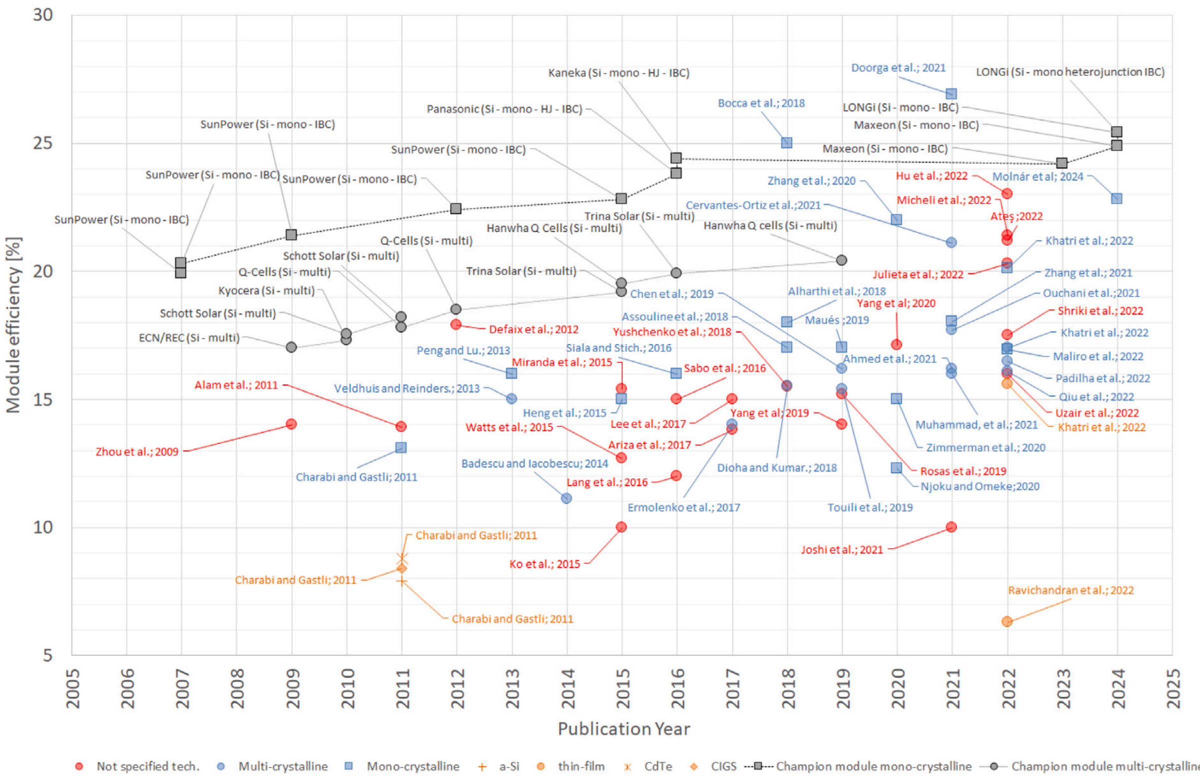

Fig. 2. Comparison between the reported champion module efficiencies for mono-crystalline (gray squares) and multi-crystalline (gray circles) silicon in the champion PV modules of NREL and the module efficiencies assumed in the reviewed literature (other colors). For champion modules, the manufacturer and cell-type are mentioned in the tag. For the reviewed publications, silicon wafer technologies shown in blue (monocrystalline in squares, multicrystalline in circles), thin-film technologies shown in orange and not specific technologies shown in red. For the reviewed literature, each point is tagged with main author and publication yearData for champion monocrystalline silicon and multicrystalline silicon are courtesy of the National Renewable Energy Laboratory, Golden, CO (USA).

unrealistic due to cost; hence, lower-efficiency assumptions might be deemed as realistic and used conservatively by authors. Nevertheless, the assessment of future potentials might include efficiencies exceeding current records with the underlying assumption that technological development will allow to achieve higher values in the future.

Two outliers above the line for Si-mono IBC cells can be observed in Fig. 2. A module efficiency of 25% was assumed [203], referring to cell record cell efficiencies [204]. Moreover, a module efficiency of 26.7% was also mentioned in a publication [196] and referred to a documented notably exceptionally high record efficiency [205]. In general, a trend emerges from Fig. 2, indicating that conservative assumptions have been made regarding module efficiencies in the reviewed publications, particularly by assuming values under reported records. In addition, updates to efficiency values have been made when higher efficiencies have been achieved. Emerging technologies like perovskite solar cells in tandem with silicon-based cells have so far reached a cell efficiency of 34.6% without optical concentration [206] and more than 30% in industrial modules. Subsequent studies might make reference to this emerging technology.

Information regarding the specific type of module or PV technology was identified in 37 of the papers analyzed in this regard. Out of these papers, 20 papers were identified as making reference to specific PV modules for calculation purposes, including “MSX 240 Solar Panel from BP Solar” [207], “mono-Si GE AP-120” [208], “Kaneka, n-type rear type IBC” [196], “Rosen Solar RS600M-120HC monocrystalline” [209], “SunForte PM096B00” [164], “Jinko Solar JKMS 350 M72 V Maxim” [167], “PV (CS6K-280M-T4-4BB)” [210], “Canadian solar CS6X-325P” [211], “Globo Brasil 320 W GBR320p” [212],1u “STP260S mono-Si PV module” [213], “Yingli Solar YL260C-30 b” [135], “ Yingli Panda YL250P-29b module” [214], “SPM100-M” [215], “BP Solar (BP4175)” [216], “Kyocera LA361K51” [217], “CS6X-315P by Canadian Solar” [218], “Longi PV LR4-60HPB” [171], “SolarWorld Sunmodule Plus SW 260 poly” [156], “First Solar FS-4100” [172] and “First Solar FS-4110-3 cadmium telluride module” [176] Other publications referred to generic PV technologies. Some examples of these references include “monocrystalline silicon modules” [186], “standard, thin-film and premium” [82], “different efficiency scenarios for the monocrystalline module as an assumption” and “this latter represents the top 10 suppliers in 2020” [185], “Multi-c Si (Sandia/Crystal): 24 cells/Multi-c Si (ECN/REC): 36 series cells/Multi-c Si (Shott Solar), 60 serial cells thin transfer 35 μm thick (Solexel)” [87], “crystalline silicon solar cells” [203], “Crystalline wafer based module” and “Thin film modules” [155], “polysilicon modules” [125], “Polysilicon materials” [126], “multi-crystalline Si” [219], “polycrystalline modules” [220], “Thin-film PV panel using amorphous silicon (a-Si)” [221], “poly-c”, “amorphous, monocrystalline and polycrystalline” [222], “mono or polycrystalline silicon PV modules” [223], “Monocrystalline silicon 6in” [165] and monocrystalline silicon cells [31]. Thin-film technologies are considered in a limited number of publications. For instance considered a “thin-film” technology [82], amorphous silicon (a-Si) [221], and amorphous silicon as well as monocrystalline and polycrystalline silicon [222]. Finally, CdTe modules were also assumed in some publications [172,176].

From the analyzed papers, only one mentions bifacial modules for vertically-mounted PV [176]. Bifacial PV modules (glass-glass modules with cells that have non fully-metallized and, thus, PV-active rear sides) have not been widely considered despite having a higher power output due to the contribution of the rear irradiance [224,225]. According to estimations of the Mechanical Engineering Industry Association (VMDA) from 2024, bifacial cells and modules made up a global market share of 85% and 50% in 2023, respectively [226]. By 2030, 90%

of the cells and more than 70% of the modules are expected to be bifacial [226].

Note that first modules of the upcoming perovskite technology, which has reached efficiency records far above 30% in tandem configuration with silicon and can basically be implemented as an add-on in manufacturing, have just entered the market. The perovskite technology could play a crucial role as future PV technology if stability, scalability and lead-free alternatives are enhanced [227] and long-term durability is achieved [228].

5.3. Factors affecting irradiance in the plane of array (PoA)

The tilt and azimuth for open-field installations is optimized to maximize the amount of irradiance on the plane of array (PoA) and hence the electricity yield over one year. In addition, the collection of irradiance in the PoA can also be enhanced by 1-axis or 2-axis trackers, which follow the sun position and constantly modify tilt, azimuth, or both. However, this might induce increased distances of module rows to avoid self-shading. Additionally, diffuse and beam radiation in different locations may further impact the final power yield. Finally, the per area output may not increase a lot when using tracking.

Nevertheless, tracking is theoretically another technical factor that can change the technical potential of an eligible area, which is usually limited to open fields. Although rooftop and floating PV installations are typically not tracked, agricultural PV systems increasingly incorporate trackers to optimize light distribution for crops and enhance yield [229]. For example, nearly half of the existing agrivoltaic sites in the United States employ single-axis tracking [230]. The installation of solar trackers with 1 or 2 axis depends on economic arguments.

In general, the optimum azimuth orientation is facing North on the Southern hemisphere and South on the Northern hemisphere. However, local conditions like frequent morning fog may influence optimal orientation. For the tilt angle, a simple rule of thumb is a value close to the latitude of the installation. Some publications explore location-optimized tilt angles. For instance, different mathematical approaches for optimized tilt were analyzed and compared particularly in Iran [231]. Also, optimal angles were calculated using hourly radiation data and compared against theoretical tilt values in China [232].

In practice, the optimum tilt varies with the specific weather conditions of the considered year, also with the assumed height of the horizon and regarded shadowing objects like growing trees with their seasonal change of leaves, as well as bright reflecting surfaces like neighboring buildings, snow on mountain slopes. There is also a different optimum tilt depending on cleaning cycles by rain or done on purpose. For locations with low latitudes, a minimum tilt of a few degrees that is not optimal for the theoretically achievable maximum yield is beneficial in enhancing cleaning properties and decrease soiling issues [233]. This method is commonly practiced by PV companies as dust sticks to flat lying modules and is washed off more easily in the case of steeper installation [234]. A general recommendation for an optimum tilt can hardly be given as dust is location-specific, and therefore also cleaning costs. Rough estimates of optimum tilt data is, for example, made available by SolarGIS or as world maps [235].

In contrast, depending on the roof type, roof installations have less freedom in choosing the orientation. Installations on tilted roofs are mostly confined in their freedom to the roof's orientation and tilt. On flat roofs, PV modules can be freely oriented and tilted to a certain extent. Such installations can be optimized with respect to area use and optimum yield either for maximum self-consumption depending on the load profile or for maximum yield.

The analyzed studies employed various approaches and assumptions, yielding to different results. In total, 78 studies were classified according to the particular PV application. Additionally, the way in which tilt is assumed was also categorized. To distinguish between the studies' assumptions, the approaches were classified into different categories, including "not specified", "set to angle", "optimized", "set to latitude", "horizontal irradiance", "multiple angles", "formula" and "multiple angles with optimization".

Table 6
Default PV System losses included in the online tool PVWatts(R) by NREL.

Loss factor	Default value (%)
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-induced degradation (LID)	1.5
Nameplate rating	1
Age	0
Availability	3

The most simplified approach is to use the "horizontal irradiance" not considering any tilt of the PV modules. In other studies, the tilt was "set to latitude". The labels "set tilt angle" and "multiple angles" were assigned when a particular tilt angle was assumed that differed from the latitude and was chosen without a mentioned optimization (e.g., for a roof). The label "optimized tilt" refers to cases of mentioned tilt angle optimizations, labeled "formula" if the calculation is based on a given formula. Sometimes multiple optimized tilt angles were assumed labeled "multiple angles with optimization". In the category "other", additional approaches were subsumed, such as "lidar-based", "set to angle and tracking", "roof optimal and facade vertical", "1-axis tracking", "experience tables", "2-axes tracking" and for a particular case with roads "depending on road orientation".

Fig. 3 shows that a significant share of the studies do not specify tilt explicitly, that is, 35%, 23%, 43% and 29% of the studies on open-field, rooftop, floating and other, respectively.

In open-field installations, a common approach is setting the tilt to the latitude. For rooftops, a set tilt angle is assumed in approximately one-third of the studies sometimes with optimization (10%) and multiple angle assumptions (13%). For floating PV, besides the cases for which no particular method was described, setting a particular angle was assumed for one-fourth of the cases and multiple angles with optimization were also considered in 17%. Optimized angles, setting to latitude and multiple angles were assumed in 8% of the cases. For other applications, the approaches of setting an angle, setting the slope to latitude, and optimization were assumed in 17% of the cases, respectively. These were followed by horizontal irradiance and multiple angles with optimization, which were assumed in 8% of the cases.

Axis tracking, is also considered in some studies. A fixed angle of 20° as well as 1 and 2-axis tracking were considered in one study in Chile [236]. Single and double-axis tracking were also considered for a study in China [81]. Finally, a study in Serbia estimated PV yields with fixed as well as two-axis tracking systems [223].

5.4. Yield corrections and losses

PV systems are subject to losses e.g., shading or system outages. Across the reviewed studies, the level of detail of considered losses varies. Some authors consider each type of loss individually. For instance, minimum and maximum values, typical or average values and values used in the were reported for nearby shadows (2%), incide angle modifier (2%), Module degradation (1%), temperature (2.2–4.9%), soiling (4.5%), mismatch (3%), wiring (1%), maximum power point tracking (1%) and inverter (3.5%–4%) [217]. Moreover, in another publication the losses for pollution (2%), mismatch (2%), wiring (2%), connection (0.5%), light-induced degradation (1.5%), nameplate rating (1%), availability (0.5%) and shading (0.5%) were assumed [149]. Finally, in one of the reviewed publications, factors and reported numerical values of 0.99 for AC wiring, 0.93 alignment loss, 0.97 DC module mismatch, 0.97 DC wiring loss, 0.99 for diodes and connections, 0.95

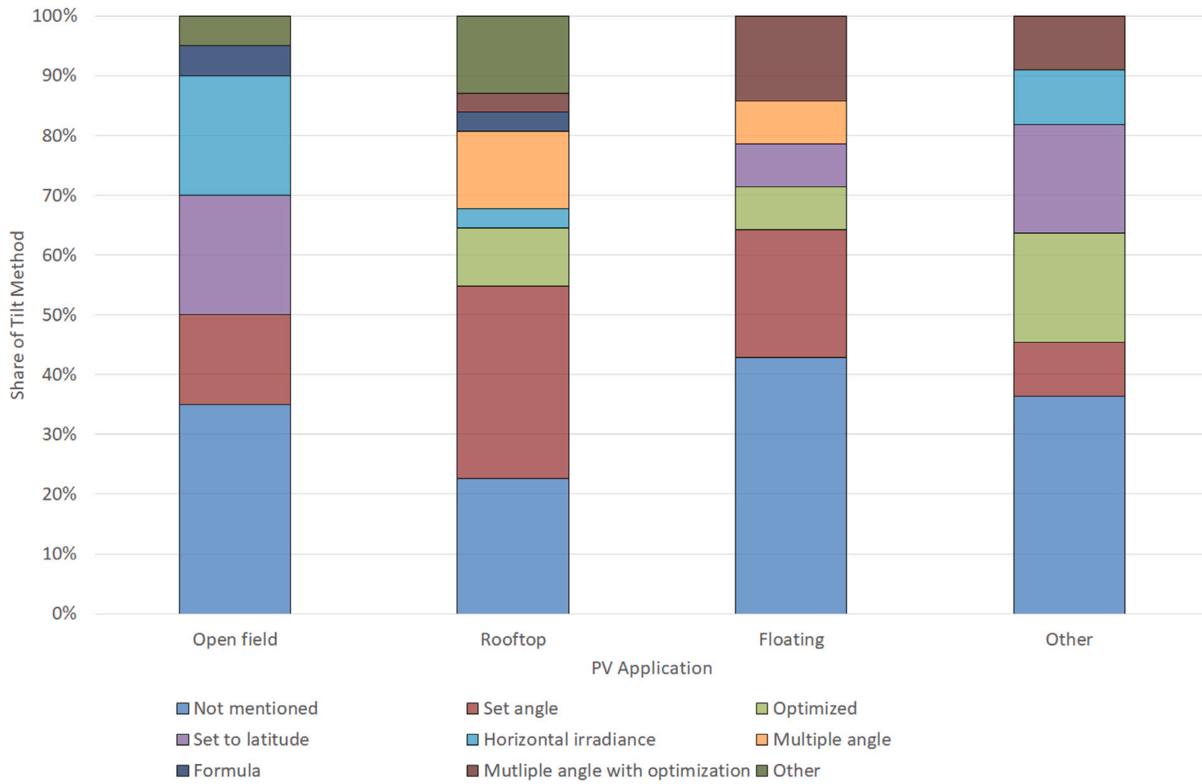

Fig. 3. Categorization of the tilt methods used in different papers for open-field, rooftop, floating, and other PV applications.

for soiling and 0.98 for tracking error were reported [237]. In contrast, other authors aggregate the losses instead and include the so-called 'performance ratio' (PR) between the actual and theoretical electricity output. Typical PR values like 75% [179], 75% [135], 75% [238], 0.75 [239] and 0.75 [240] are reported in the literature. Moreover, higher PR values of 0.78 [165], 78% [241], 79.63% [78], 0.8 [81,164], 80% [210], 83% of module output transformable into electricity [242] and 85% [80] were also reported in other publications. In addition, in some of the studies, rather values within a range were used. For instance, in one of the publications it was mentioned that the PR is typically 75% but assumed 80% due to future improvements [155]. Other studies assumed values within the ranges 0.77–0.92 [123], 0.75–0.76 [223], 80.8–82.9% [243], 83.1–87.1% [221], 0.75, with sensitivity between 0.6 to 0.75 [188]. Also, different values of PR were assigned depending if the installation occurs in rural areas (70%) rural areas, urban cores (75%) or suburban areas (80%) [219]. Also different PR values of 73.27, 73.8, and 74.8% were reported depending on the location for MENA, USA and Spain, respectively [214]. In general the reported values for this parameter are often range between 70 and 85%. Those numbers match other studies, which found that the performance ratio has risen from 70 to 83% between the 1990's and 2010 [202]. In turn, this trend likewise increases the technical potential of eligible areas over time.

Often, losses are included by default in software solutions for deriving technical potentials. As an example, the losses and standard settings in the software PVWatts [244] are provided in Table 6.

Environmentally-induced losses depend on the location. As mentioned before, in some locations, dust needs to be considered [245] with flatter installations closer to lower latitudes often requiring denser cleaning cycles [234] while snow cover might also decrease the yield in locations where snow might occur [246]. Losses can also be technology-specific. For instance, snow can decrease or completely reduce the electrical output of monofacial modules by covering their front surface. In contrast, bifacial modules, although also affected by snow coverage in the front, can in turn also capture reflected irradiance from the rear side and even profit from the higher albedo of snow-covered surfaces, therefore helping to overcome this particular issue. Mismatch refers to different voltage-current characteristics between modules due to manufacturing imperfections, whereas losses like "wiring" or "connections" result from the balance of plant in which some of the energy converted into electricity is dissipated. Light-induced degradation refers to an accelerated loss of efficiency in the first hours of exposure due to the presence of oxygen impurities in the silicon used for c-Si-based cells in modules, affecting primarily p-silicon or in other words, boron-doped silicon. Apart from that, PVWatts accounts for manufacturer-induced deviations from the nameplate capacity of up to 1% referred to as "nameplate rating" and also offers the option to enter and age-specific degradation with a default value of 0%, i.e., the modules are assumed to be new. Finally, availability accounts for planned and unplanned module shutdowns, e.g., for maintenance or due to grid outages.

Important yield corrections on their own are the effect of temperature and irradiance, which will be described in the following subsection.

5.5. Temperature and irradiance correction

The performance of PV modules is reported under standard testing conditions (STC), which imply a cell temperature of 25°C, an irradiance of 1000 W/m^2, and the defined AM1.5 g spectrum. The performance of solar modules depends on both, temperature and irradiance. Under low irradiances, below 400 W/m^2, the efficiencies decrease compared to the reference value at 1000 W/m^2 [247]. Conversely, as high temperatures typically coincide with high irradiance and high generation, the temperature effect is more pronounced.

Cell temperatures are known to exceed the ambient typically by 20 to 30°C. This phenomenon is accompanied by a decline in efficiency. In numerical terms, at 50°C, an exemplary commercial module with an efficiency of 22.3% at STC and temperature coefficient of −0.28%/K [248] would have an efficiency of 20.7%. The PV module temperatures are not only location-, but also application-specific.

Building-integrated PV installations might operate at slightly elevated temperatures compared to other installation types. In contrast, floating PV modules may be affected in both ways, either being cooled down or warmed up because the water underneath can have a lower or higher temperature than air depending on the environmental conditions. Furthermore, distinctions between air-cooled and water-cooled systems exist, leading to a higher complexity when it comes to including temperature corrections of these systems [249]. Consequently, even in direct proximity to each other, both application types may be subject to different temperature corrections..

Not all the publications under consideration specify the value of the temperature coefficient. Representative values like −0.15%/°C [237], 0.0034 [200], −0.38%/°C [149], −0.40%/°C [250], −0.40%/°C [125], −0.40%/°C [251], −0.40%/°C [208], −0.41%/°C for c-Si [188], −0.42%/°C [126], −0.42%/°C [135], 0.43%/°C [212], −0.5%/°C [210], −0.51%/°C [147] and 0.8%/°C [215] were found in the reviewed publications. In some cases, several values were reported depending on PV technology assumed for calculating the potential, like −0.47, −0.2 and −0.35%/°C to standard, thin-film and premium modules [82]. In summary, the values for this parameter were found to be within the range of −0.15 to −0.8%/°C, with preponderance of values closer to −0.40%/°C". The temperature coefficient included in the software PVWatts has recently been updated and is set to −0.37, −0.35 and −0.32%/°C for crystalline silicon, premium crystalline silicon and thin-film modules, respectively [244]. PVGIS, another software repeatedly used for the calculation of PV output potential, also carries out temperature and irradiance corrections [252]

5.6. Shallow angle and spectral effects

At shallow angles, the reflectivity of a surface increases. In a PV module this equates to a reduction in electricity generation under such angles. Shallow angle corrections are considered by online tools like PVGIS based on the results from other publications, which are named "Angle of Incidence" effects in the original source [253]. These effects can decrease the irradiation between 1.5 to 4.0% depending on the latitude.

Spectral effects are likewise considered by some tools and depend on the local spectra and the spectral range (more precisely the quantum efficiency or spectral response) of a photovoltaic technology. Spectral effects can be positive or negative compared to an STC spectrum [253]. High elevation regions in Asia such as Tibet are affected by spectral effects due to low water vapor content in the air allowing a higher portion of infrared irradiance to reach the ground [253]. The corrections are minor in most regions of the world and for silicon technologies and were not explicitly mentioned in the reviewed studies. They can be included by the use of tools like PVGIS, which autonomously calculate correction factors for these effects. Note that spectral corrections will become more relevant when investigating upcoming tandem technologies that consist of two solar cells each absorbing a narrower spectral range.

5.7. Inverter efficiency

Inverters convert the direct current (DC) electricity into alternative current (AC) electricity at the desired voltage and frequency. This conversion leads to efficiency losses that are considered in different ways. Some approaches included in software solutions include correlations or part load curves for the inverters [187].

In the literature, different approaches are applied. Some authors assume particular inverters and disclose the brand and the model, like "Dasstech DSP-M331000K" [214], "SPM3000MS" [215], "GE Solar inverter" [156], "SC2200-US 385 V by SMA Solar" [218], "20 kW Fronius SYMO 20.0-3-M 3-phase" [209], or "ABB PRO-33.0-TL-OUTD-400" [254]. Often, data on the electrical behavior of these devices is included in software tools or explicitly considered in individual calculations. Microinverters for each of the modules with a lower efficiencies (95%), as well as string inverters (95%), with central inverters (98.5%) were compared [255]. The efficiencies for inverters were assumed as 90% [207,208,215,256], 95% [78,216,219], 96% [192,200], 97.3% [214], 97.6% [237], 98% [254] and 98.3% [245]. Therefore, the efficiency for these devices are often assumed to fall in the range between 90 and 98%. An exception can be found in one publication, in which an inverter efficiency curve is reported [217]. Two widely used and standardized ways to report inverter efficiency make use of weighted efficiencies obtained by factoring the percentage of the time an inverter is in an operating range. Under the "European efficiency", the factors of 0.03, 0.06, 0.13, 0.1, 0.48 and 0.2 are multiplied by the inverter efficiency at a power of 5%, 10%, 20%, 30%, 50% and 100% [257]. The other widely-spread reporting standard is the one of the California Energy Commission (CEC), considering the factors of 0.04, 0.05, 0.12, 0.21, 0.53 and 0.05 multiplied by the inverter efficiency at 10%, 20%, 30%, 50%, 75% and 100% of the rating [258]. Other approaches include IEC Technical Specification 63 156.

5.8. Software

Specialized software is frequently used to calculate the generated power from the given insolation and considering certain installation features. These packages provide default integration with solar resource databases, such as SARAH2, SARAH3 or ERA5 (see Section 4), which provide the data inputs for the technical potential assessment. Based on the obtained data, the software carries out stepwise calculations to determine the electricity output, often hourly or in any other sub-hourly resolution. These results are often aggregated in broader temporal timeframes, like months or years. In some cases, the authors program their own packages making use of commercial software like MATLAB® to carry this out. MATLAB®, SPSS®, and GIS software was used in one of the publications for this purpose [259]. The use of a self developed GIS software together with data from the Meteorology, Climatology and Hydrology (MCH) was also reported [188]. The software MATLAB® was also mentioned as basis for the calculations in another paper [203]. A self developed software using this commercial solution was also reported in another publication [251]. The software "HOMIE" developed also upon this commercial software was reported in one of the studies [242]. Also a Matlab® solution was developed for carrying out the calculations in one of the studies [171]. With open data policies implemented, data is used that was provided by state entities, such as the Sonnendach database in Switzerland for rooftop PV and BIPV [140], or the platform EO Solar by the German Aerospace Center for the technical potential of rooftop PV provided as interactive map [260].

While these software solutions offer the advantage to be easily applicable and rely on validated models, a downside is that they may be used with a lack of understanding and without proper reporting of underlying assumptions, negatively affecting reproducibility in the case of software updates. Table 7 provides an overview of software solutions used for technical potential assessments for PV.

6. Economic potential

PV systems' economic potential is defined as their portion of the technically viable economic potential. Rather than considering social welfare and its associated externalities, it addresses the economic aspect of a prospective PV project by estimating its potential costs or benefits from an investor's perspective. Since it examines the economic practicality of PV projects, economic potential assessment is crucial and is considered in 48% of all reviewed studies. This section introduces commonly used economic assessment criteria, analyzes the various economic characteristics of photovoltaic (PV) systems, summarizes findings from various studies, and finally highlights the limitations inherent in most methodologies. A checklist, examples, and links to the contents of this paper can be found in Table 14.

Table 7
Overview of software used for PV technical potential assessments.

Software name	Type of user interface	Wheather data	Free of charge?	Link to software	Studies using the software
System Advisor Model (SAM)	Desktop	NSRDB, AUSTELA, Climate.OneBuilding, PVGIS, NASA MERRA-2	Yes	[261]	[82,152,218,237, 262]
RETScreen Clean Energy Project Analysis Software	Desktop	NASA	Yes	[263]	[207,208]
PVSOL	Desktop	Deutsche Wetter Dienst (DWD), Meteonorm 8.1	No	[264]	[196]
Photovoltaic Geographical Information System - PVGIS	Online	SARAH2, SARAH, ERA5, NSRDB (Coverage location dependent)	Yes	[265]	[150,200,266]
pvlib python	Desktop	PVGIS and NSRDB	Yes	[267]	[200,268]
Hybrid Renewable and Distributed Generation System Design Software (HOMER)	Desktop	NREL, NASA, Solargis	No	[269]	[210,215,216]
PVSyst	Desktop	Meteonorm 8.1, NASA SSE, PVGIS, NREL NSRDB, Solcast TMY, Solar Anywhere TGY, Solargis	No	[270]	[123]
Greenius - The Green Energy System Analysis Tool (DLR)	Desktop	NSRDB, SatelLight, EnergyPlus Weather Data (US-DOE), Meteonorm, MESOR	Yes	[271]	[214]
PVWatts	Online/Desk-top	NREL NSRDB, SWERA, IWEC and CWEC	Yes	[244]	[268]
Solargis	Online	Meteosat, GOES, MTSAT, Himawari, ERA5, ERA5-Land, CSFR, MERRA-2, IFS, GFS, ICON, ICON-EU, HRRR	No (Global Solar Atlas free of charge)	[272]	–
Global Solar Atlas	Online	Solargis,ERA5-Land	Yes	[273]	–

6.1. Economic assessment criteria

The reviewed studies assess economic potential using criteria like discounted cash flow analysis [274] in the energy sector, such as Net Present Value (NPV), Internal Rate of Return (IRR), discounted payback time, Levelised Cost of Electricity (LCOE). The NPV represents the total value (profit or loss) of a project throughout its lifetime, adjusted to the present year (commission time), discounting the future (see Eq. (1)) [166].

$$NPV = -C_i + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \quad (1)$$

where C_i is the initial capital investment in local currency paid in year zero, CF_t is the annual cash flow of the same currency, r is the discount rate, and n is the assumed lifetime (years) of the system.

The IRR, as shown in Eq. (2), is the discount rate, with the defined project lifetime, necessary for the NPV to be zero [164]. The project is profitable when the discount rate is lower than the IRR. From a private investor's perspective, the discount rate should be risk-adjusted to reflect market-specific rates instead of risk-free from a government's perspective [275].

$$0 = -C_i + \sum_{t=1}^{n} \frac{CF}{(1+IRR)^t} \quad (2)$$

The reviewed articles often investigate discounted payback time to indicate the year when the project starts making a profit [266]. The LCOE estimates the cost of electricity generation over the project's lifetime, considering the discount factor. It is the most used economic indicator among large-scale PV potential studies, intuitively reflecting the present value of average electricity generation costs. Eq. (3) shows the calculation of LCOE, where C_t, O_t, and E_t are the capital costs, operational and maintenance (O&M) costs, and electricity production in year t, respectively. C_t can be staged annual payments [276,277] or front loaded with upfront payment in year zero [246,278], depending on the assumption. Value-adjusted LCOE (VALCOE) is an enhancement of the standard LCOE [279], which includes the value that electricity provides to the power system. It accounts for temporal value, dispatchability, and grid support, but requires much more regional and temporal data, making it hard to assess in large-scale studies.

Table 8
The frequency of commonly used criteria in 87 economic potential studies.

Economic criteria	Number of studies
LCOE (cost of energy)	45
NPV	23
IRR	21
Discounted payback time	21
Benefits (bill savings)	8
Benefit-cost ratio	4
Return on investment	3

$$LCOE = \frac{\sum_{t=1}^{n} \frac{C_t+O_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (3)$$

Indicators like these are used in PV potential studies to evaluate projects. Other criteria include the benefit-cost ratio [216], bill savings [215], and return on investment [210]. These are economic interpretations derived from cash flow analysis. The frequency with which these indicators are used in economic potential studies is shown in Table 8. Due to the diversity of economic assessment criteria, economic potential can simply be referred to as an economic assessment of the technical potential. In other words, the technical potential is characterized by its economic properties. In this review, we categorize studies that apply economic metrics such as the discount rate, capital expenditures (CAPEX), and operational expenditures (OPEX) to PV systems as economic potential assessments.

6.2. Economic characteristics of PV systems

The economic potential depends on the perspective, often represented by the discount rate. The discount rate profoundly impacts the economic viability of renewable energy systems [280] and is one of the most critical parameters in discounted cash flow analyses. Approximately 60% of the studies assumed a constant discount rate across the entire region or country under consideration, ranging from 2% [164] to 20% [243] depending on the region. Some studies vary the discount rate to examine the difference between weak and strong discounting [141,281]. Yet, it remains spatially invariant. Only two continental studies [200,276] varied the discount rates spatially based on the national Weighted Average Cost of Capital (WACC), but was kept constant within countries.

The typical CAPEX of a PV system consists of the PV modules, power conditioning unit (inverter), controller, transport, installation, cables/wiring, combiner box, mounting structure, licensing/contracting charge, insurance, and engineering costs. Depending on the application, there can be additional costs such as land preparation costs for ground-mounted PV [282] and floating platforms for floating PV [266]. Fig. 4 shows how often these cost components are considered in different studies. It should be pointed out that the cost of PV module manufacturing is projected to decrease rapidly [283]. In contrast, other costs will remain constant or even increase, such as costs of land or labor for installation, which will be increasingly important in the CAPEX. Despite the diverse composition of the CAPEX, most large-scale studies do not specify which cost components scale with capacity and which do not. Instead, a constant cost per unit of capacity is used, which ranges from 623 $€_{2023}$/kW [284] to 6118 $€_{2023}$/kW [285] for non-tracking ground-mounted systems in different European studies, with inflation adjustment to the year of 2023 according to the publication year. Similarly, CAPEX for non-tracking rooftop systems ranges from 689 $€_{2023}$/kW [286] to 7477 $€_{2023}$/kW [285]. Ground-mounted systems tend to have lower CAPEX due to economies of scale. Although 85% of the economic potential studies stated that the estimated CAPEX includes the system installation cost, around half of these studies did not specify the exact details of cost components included.

Cost considerations for OPEX include labor, replacement, rent, and insurance. OPEX can be estimated as a percentage of the CAPEX, constant cost per unit of capacity, or cost per unit of energy produced. The first two are fixed yearly costs, which range from 1% [266] to 5% [281] and from around 9.9 $€_{2023}$/kW [185] to 69.7 $€_{2023}$/kW [287], respectively. The cost per unit of energy produced is a variable cost, rarely adopted (7% of the reviewed studies). Only 25% of the economic potential studies specify the details of the cost composition, among which only a few consider replacement costs of different components [149,173] and land rent [188,288]. The lifetimes of different components are required to calculate replacement costs, complicating data inputs and the annual cash flow calculation. Therefore, most of the studies that consider replacement costs only include the replacement of inverters and PV modules, assuming replacement costs of other components are negligible. As for land rental costs, a constant fee per unit area [173,184] or unit capacity [288] is assumed for utility-scale PV systems, but the spatial and temporal variations of land prices are typically not considered.

6.3. Economic assessment results

Economic assessments of PV systems have been the final step of most potential studies to determine the economic feasibility of solar projects using the criteria introduced in Section 6.2. However, comparing the results between studies is challenging due to unclear base years, different locations, and inconsistent techno-economic assumptions. It should be noted that the economic (along with the technical) potential changes over time because it depends on dynamic techno-economic technology characteristics and energy-political framework conditions. Therefore, the results presented below are solely intended to provide an overview of typical ranges for various criteria.

Ground-mounted systems tend to have a lower LCOE than other applications. The lowest obtained value for ground-mounted systems is around 0.012 $€_{2023}$/kWh in Pakistan [282]. Rooftop PV has the highest value of 1.25 $€_{2023}$/kWh in an unsubsidized scenario in France [285]. Floating PV is generally more expensive than ground-mounted PV due to floating and anchoring devices [221,282]. In some cases, it can cost more than rooftop systems [281]. However, the lack of economic potential studies on niche applications other than ground-mounted and rooftop systems, so representative LCOE values for such systems cannot be given. The base year and currency are important information for LCOE due to changing inflation and exchange rates. Although most studies used LCOE as the economic criterion, only a few clearly stated the base year [287,289].

Besides cost analysis using LCOE, many studies also investigated the economic benefits of a PV system using NPV [266], IRR [290], discounted payback period [291], lifetime revenues [173], or benefit-cost ratio [216]. Profits from energy sales rely on local electricity prices, which are spatially and temporally dynamic. Most benefit analyses use a national annual average for electricity prices, which misrepresents the expected revenues due to declining capture rates (the proportion of generated electricity that can be sold at a profitable rate) of solar PV in energy systems with high shares of PV electricity. The estimated IRR and discounted payback period for ground-mounted PV systems vary from 0.8% in Austria [285] to 13.6% in Italy [292] and from 3 years in Zimbabwe [293] to over 20 years in the Republic of Serbia [223], respectively. As for rooftop systems, the IRR can range from below −15% in Iraq [290] to 21.8% in Iran [294], and payback is between 3 years in Jordan [295] and 25 years in Indonesia [296]. Considering the dynamics of electricity prices can better reflect the economic value of PV electricity, the implementation is challenging due to the large geographical scales and the market modeling complexity.

7. Feasible potentials

In the previous sections, eligible areas and installable capacity for solar PV are defined based on solar irradiance resources, geographical constraints, and technical feasibility. The eligible areas are then translated into the technical, electricity generation potential and evaluated for their economic viability. In practice, the economic potential is not fully realizable. For planned PV system installations on designated areas, according to [297] there are often non-technical barriers to implementation [298], creating a gap between the calculated potential and the realizable ones [299]. For example, from 2008 to 2021, 2200 MW of solar PV potential remained unrealized due to canceled or delayed projects in 28 US states alone [298]. In this review, we follow earlier definitions from previous case study [297] and reviews on potential assessment for onshore wind power [300] and renewable energy [301], which refer to studies that further include non techno-economic considerations (e.g., social acceptance or externalities) as studies that assess the “feasible potential” of solar PV. Feasible potential results can vary widely depending on the local context [284], but they can provide more realistic estimates beyond mere techno-economic considerations [302]. This review identifies eleven studies that utilized non techno-economic criteria to derive feasible potentials of PV systems. Figures 13–14 in the Appendix provide an overview of the spatial coverage of the feasible potential for the various installation types reported in the reviewed studies. In addition, guidance on which information should be documented in future studies and links to information compiled in this study about each of these topics can be found in Table 14.

7.1. Defining feasible potential assessment criteria

Large-scale open-field solar PV projects face non-technical barriers including land inaccessibility due to land use competition with the agricultural sector [303] or other renewable energy resources. Some studies show that areas with solar potential and high wind speed are exclusively used for onshore wind power development [304], or areas with mutual solar and bioenergy potential were assessed for their

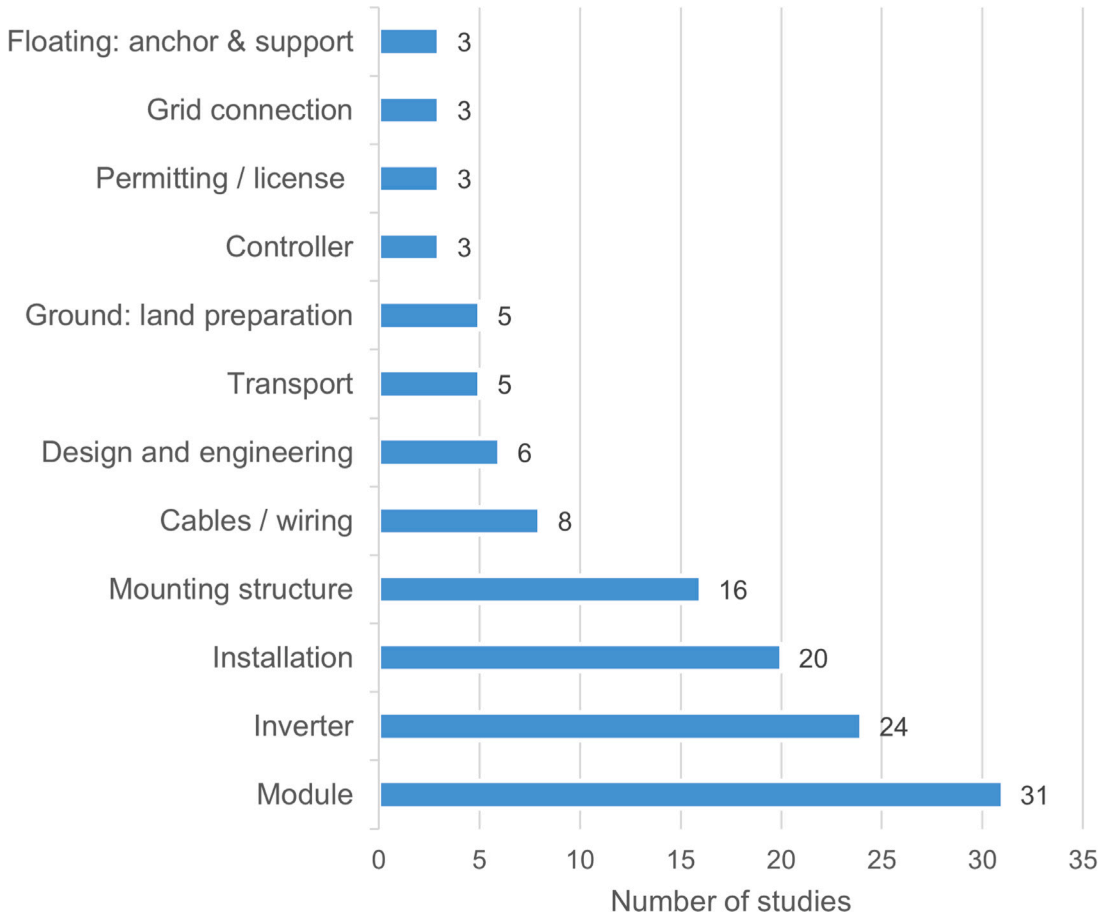

Fig. 4. Different cost components in the CAPEX of PV systems and their occurrence among 87 reviewed studies.

trade-offs [305]. Expanding solar electricity generation on a massive scale requires a significant number of produced modules and other equipment as well as a designated amount of land area in case of open-field PV. To have more options of efficient land use [306] and boost local acceptance [307], other dual land use systems such as agrivoltaics [307], hybrid solar and wind energy systems [308], or rooftop and building integrated PV have been promoted in several countries.

Besides land use competition for open-field PV, non-technical barriers to large-scale PV projects may result from local concerns over potential environmental impacts of large-scale PV systems. This encompasses concerns over impacts on biodiversity [298], concerns of groundwater contamination [299], or perceived risk of landslides due to coincidental occurrence of landslide near large-scale open-field PV facilities [309]. The visual impact of large-scale solar PV systems on landscape aesthetics, although less significant compared to wind turbines [310], also triggers local opposition [299] and affects supports towards the projects [311]. Limited participation of local communities in the planning process [299], disregard for the traditional land rights of local indigenous [298] and traditional communities [312], as well as the perceived inequitable distribution of associated costs and benefits from the projects may also lead to local opposition [313]. For rooftop PV or BIPV, although their visual impacts are often considered lower compared to open-field PV [284], aesthetics concerns due to the interference of the PV panel with building's appearance [176] may impact the acceptance of such systems as well. Other potential barriers to adoption include the ownership structure of the rooftop PV system [242] and government implementation of net-metering and subsidies. Market acceptance of these rooftop PV and BIPV (i.e., affordability for homeowners) [314] plays a pivotal role in determining their feasible potential.

7.2. Methods to integrate non-technical aspects into potential assessments

The potential assessment can include non-technical considerations in an exogenous and endogenous way (see Fig. 5) [315]. Endogenous inclusion models non-technical factors quantitatively and uses them as one of the criteria or within an objective function within the simulation or optimization process. In contrast, exogenous inclusion only uses non-technical factors to define model scenarios or discuss them qualitatively in the output discussion. We first discuss the endogenous inclusion of non-technical factors within the land eligibility, the (partial) welfare analysis, and within multi-criteria frameworks (see Table 9. Similar analyses have been done for onshore wind systems [316]). To derive feasible potentials, land eligibility studies can be extended to include non-technical constraints, such as land use competition [284] or social preferences [317], in addition to legal and technical constraints. This normative land eligibility approach (Table 9) uses binary indicators to dictate where to build or not to build ground-mounted solar PV. For example, a study [317] incorporates social preferences for acceptable distances from various land features which was obtained through a survey with local citizens (i.e. acceptable distances from residential areas, historic sites, recreational areas, nesting sites, and agricultural land) into a land eligibility model for utility-scale solar PV. The study shows that suitable areas for ground-mounted PV are reduced by 78% compared to when social preferences were not incorporated.

Other study [318] excludes siting locations for ground-mounted PV that would be visible from scenic or densely populated areas. This approach could identify feasible potential for large-scale ground-mounted PV, excluding areas that might face opposition due to significant visual impacts on the landscape [299]. In Germany, excluding siting areas that are visible from the most scenic locations reduces the capacity potential

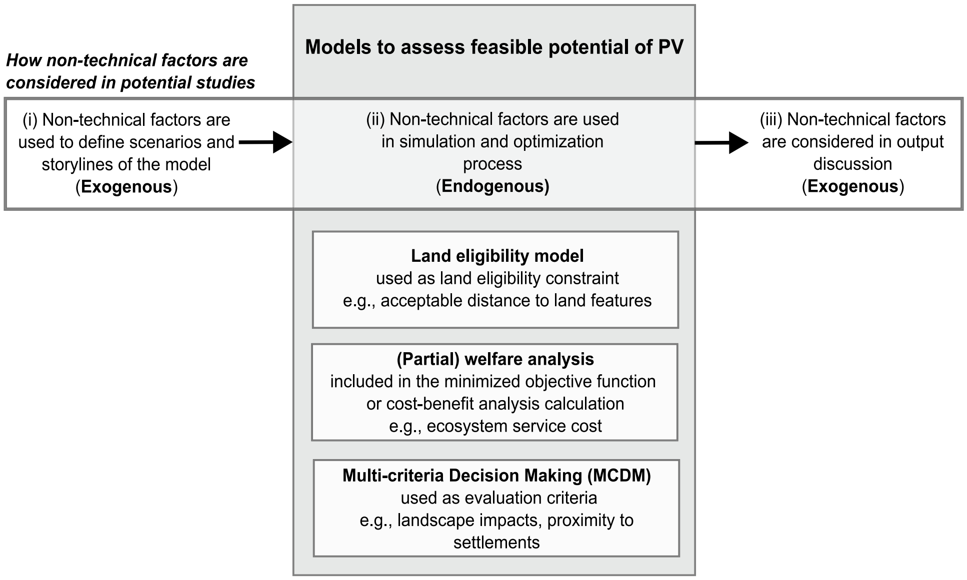

Fig. 5. Endogenous and exogenous inclusion of non-technical factors into potential analysis studies of solar PV.

Table 9
Examples of modeling approaches to determine feasible potentials for solar PV.

Modeling approach	Details	Non-technical factors	Technology	Region	Ref.
A. Land-eligibility					
A.1. Normative approach					
Participatory modeling	Suitable locations are determined by acceptable distances from land features based on surveys	Public acceptance	Ground-mounted PV	US	[317]
Excluding sites with high visual landscape impacts	Exclude areas visible from scenic & densely populated places	Visual landscape impacts	Ground-mounted PV	Germany	[318]
Excluding area with past social hazards	Exclude areas with past social unrests	Security	Ground-mounted PV	Ghana	[127]
A.2. Positive approach					
Projection using past deployment pattern	Regression models with techno-economic and socio-demographic predictors are used to predict spatial pattern of PV deployment	All relevant placement factors, as observed in the past	Rooftop PV	Switzerland	[319]
B. (Partial) welfare analysis					
(Partially) minimizing social costs	Consider ecosystem services costs in the minimized total costs	Ecosystem services	Ground-mounted PV	Great Britain	[320]
C. Multi-criteria analysis					
Trade-off analysis	Explore trade-offs between landscape impacts, land use competition, and resource quality	Landscape impacts	Ground-mounted & rooftop PV	Great Britain	[284]
	Trade-offs between ecosystem service, social preferences of landscape, and resource quality	Ecosystem services & landscape preferences	Ground-mounted & rooftop PV	Switzerland	[321]
Multi-criteria decision making (MCDM)	Land cost and transport convenience as evaluation criteria in AHP-MCDM to derive suitable location	Land cost and land accessibility	Ground-mounted PV	China	[126]
	Proximity to residential areas as one of evaluation criteria in AHP-MCDM to derive suitable location	Land accessibility	Ground-mounted PV	Mauritius	[88]

for open-field PV by 4%, while in a scenario of high sensitivity to the visual impact of PV systems, excluding siting areas that are visible from landscapes of average scenicness would reduce the potential by 93.5% [318]. The mentioned approaches are straightforward and can be used to enhance participatory planning [316]. It must be noted, however, that this approach must be utilized considering local input and preferences. In the absent of such consideration, the normative land eligibility methods may implement buffer distances in an arbitrary manner, lack consistency [322], and are often time not subject to rigorous empirical analysis that would justify the indicators and thresholds selected to reflect social preferences. In contrast to the normative land eligibility approach, a positive land eligibility assessment (Table 9) would evaluate past deployment patterns to better understand where solar PV is actually being placed [319] and use the indicators and thresholds to project the feasible potential for future solar PV placement. Nevertheless, this positive land eligibility assessment reflects past patterns of acceptance of solar PV systems, which may not necessarily guarantee future acceptance. The acceptance of renewable energy projects is dynamic and influenced by a number of factors [323], including time [324], familiarity [325], and experience with renewable energy projects [326] . When using a positive land eligibility approach for future planning purpose, it is important to recognize and address the potential sensitivities that may arise from the dynamics of acceptance.

Due to its binary nature, pragmatic land eligibility analysis may not capture the complexity of actual solar PV siting decisions [300]. An approach that is more consistent with economic welfare analysis acknowledges (dis)amenities of solar PV when deriving total costs of solar PV installations. Such (dis)amenities have been observed in the literature. For example, changes in property values due to the presence of PV installations in the neighborhood [327]–that is comparable to external effects of wind turbines in some cases [328]– or overall positive health and environmental benefits [153]. These (dis)amenities create positive or negative external costs. Once they are incorporated in the total cost of solar PV projects, the definition of potential areas becomes obsolete. Instead, the socially optimal spatial deployment of PV systems can be derived by minimizing the total social cost of the energy system. Determining the monetary value of externalities is a complex task, as prices of public goods cannot be observed on markets and therefore have to be derived indirectly. However, a wide range of valuation methods has been developed in economics [329], and has also been applied to assess renewable energy projects, in particular wind power [330], but also solar PV using stated preference [331] or revealed preference methods [332]. As these externalities are rarely estimated in a spatially explicit way, they are mostly not included in studies assessing the optimal deployment of renewable energies. However, notable exceptions exist for wind power, for instance, disamenity costs estimated as a function of distances to settlement [333], zoning areas [330], or other attributes of wind turbines [334] have been integrated into optimal deployment of wind turbines. Another noteworthy example utilizes disamenity costs estimated using ecosystem service costs for the spatially explicit placement of utility-scale solar photovoltaic (PV) systems, wind farms, and bioenergy facilities [320].

As with onshore wind turbines [300], no complete welfare analysis for solar PV placements has been conducted so far, but there are partial attempts (see Table 9.B). For example, a recent study [320] employed a spatially explicit optimization model to incorporate ecosystem service costs (e.g., land use change emissions, visual disamenity costs) into a total system cost minimization, thereby facilitating the identification of potential sites for renewable energy placements that exhibit minimal environmental and financial costs. When ecosystem service costs are considered, the study finds a slight shift in the optimized locations of solar PV to areas further from settlements to minimize visual impacts.

Beyond cost minimization, siting decisions for renewable energy technologies involve multiple, sometimes conflicting objectives [335]. Multi-criteria frameworks (see Table 9) are often used to explicitly capture the trade-offs between multiple objectives and to find compromise solutions. A study [284] examines the trade-offs between landscape impact, land use competition, and resource quality in the siting of wind and solar PV in Great Britain, while other [321] investigates the trade-offs between energy output, ecological costs, and social preferences for the siting of wind and solar PV in Switzerland. The study revealed that spatial configurations that minimize social costs represent a compromise between the other two objectives. Other studies for China [126] and Mauritius [88] use multi-criteria decision-making (MCDM) to determine suitable locations for solar PV by aggregating multiple decision attributes (i.e., techno-economic, environmental, social) into one indicator (i.e., suitability). Various MCDM methods are available to derive attribute scores, determine attribute weights, and compare alternatives. One of the most widely used weighting techniques in MCDM is the Analytic Hierarchy Process (AHP) [316]. However, the suitability of this method for tailored decision making problems needs to be carefully considered and justified to avoid sub-optimal decisions due to mismatches between the problem formulation and the selected MCDM method [336].

In addition to the limited number of quantitative modeling approaches to assess the feasible potential of solar PV, several studies also incorporate non-technical factors exogenously . These studies qualitatively discuss possible political [337] and social barriers [242] to adoption of solar PV in a considered region, potential opposition due to noise and visual impacts [176], or discuss additional benefits unaccounted [164] in the calculation of technical and economic potentials.

7.3. Data sources and indicators

Various indicators can be used to estimate or quantify non-technical factors that affect the feasibility of solar PV deployment (cf. Table 10). These factors include the impact on the local environment, such as the visual impact of solar PV on landscape aesthetics. This can be approximated using a revealed preference method by measuring the changes in property values near solar PV installations [327], although a recent study on wind turbines found that their visual impact on property values is minimal and decreases over time and distance [338]. The approximation of social costs through the landscape-fit of renewable infrastructure could also be achieved through the use of a photographic choice experiment [321]. Nevertheless, this approach needs to be replicated at different times and locations, as it may only capture one populations' preferences at a time. Geospatial analysis of reverse viewshed methods can also be used to map visible areas from scenic landscapes that may not be preferable for large-scale PV installations [318]. Furthermore, indicators such as ecosystem service costs that cover monetized emissions from land use change, visual disamenities, and quantified biodiversity impacts resulting from solar PV systems are also utilized. In addition to their negative externalities on the local environment, positive externalities of solar PV systems on the overall climate and human health have also been quantified. Indicators such as monetary valuation of mitigated GHG emissions [320], saved lives, and reduced health burden [153] are commonly used to measure these impacts. The positive externalities linked to solar PV may also indirectly enhance its feasible potential by improving public perceptions of this technology or resulting in planning decisions that prioritize low-carbon technologies over fossil fuel-based alternatives [339].

Solar PV land disputes are a major cause of project delays and cancellations [298]. Participatory planning or surveys can be used to map land access based on locals' preferences of acceptable distances from various land features to solar PV facilities [317]. Additionally, land use data sets [284] may provide valuable information to assess the magnitude of trade-offs with other sectors' demands, such as agriculture, human settlements, or other infrastructures [344].

The current rapid expansion of solar PV has also increased land tenure conflicts in several countries, including Brazil [312] and China [345]. In this context, *green grabbing* refers to an appropriation of land

Table 10
Example indicators for modeling non-technical factors for feasible potential analyses of solar PV.

Type of factors	Indicator	Data sources	Geographical scale	Applicable to	Ref.
Land access	Acceptable distances to land features (residential, recreational, bird-nesting sites)	Survey	Several counties in the US	Land eligibility	[317]
	Property rights & land tenure information	Community land maps	Global (partial)	Land eligibility	[340]
		Land tenure maps	Brazil (country)		[312]
	Land cost (land price)	Local authority database	China (country)	Multi-criteria,	[126]
		Agricultural model	Great Britain	(partial) welfare analysis, land eligibility	[341]
	Proximity to residential areas	Local authority database	Mauritius (country)	Multi-criteria, land eligibility	[88]
		OpenStreetMap	Global		
	Areas with past social unrests	Global terrorism database	Ghana (country)	Land eligibility	[127]
	Land use category	Local authority websites	Great Britain (country)	Multi-criteria, land eligibility	[100,284]
		Copernicus Land Cover	Global		
(Dis)amenities	Rating of landscape quality	Photo rating experiments	Great Britain (country)	Multi-criteria, land eligibility	[284]
	Social cost from landscape preference	Online choice experiment	Switzerland (country)	(Partial) welfare analysis, multi-criteria, land eligibility	[321]
	Visibility from scenic or populated areas	Reverse viewshed analysis	Germany (country)	Land eligibility, multi-criteria analysis	[318]
	Reduction in property value	[328]	Netherlands (country)	Multi-criteria, (partial) welfare analysis, land eligibility	[327,328,332]
		[327]	Two US States		
		[332]	England & Wales		
	Ecosystem services costs (GHG emissions, effects on pollination, visual impacts)	ADVENT-NEV model	Great Britain (country)	Multi-criteria, (partial) welfare analysis, land eligibility	[320]
	Ecosystem services costs (land use, biodiversity, tourism, cultural heritage)	[321]	Switzerland (country)	(Partial) welfare analysis, multi-criteria, land eligibility	[321]
	Monetized lives saved and reduced health issues	[125]	China (country)	(Partial) social cost-benefit, multi-criteria analysis	[125]
Spatial distributional justice	Gini coefficient of installed capacities, of RE generation per potential, absolute difference of household income level at different districts, composites benefits & vulnerabilities index	Own analysis	Germany (country), Europe (continent)	Multi-criteria, (partial) welfare analysis	[197,342,343]

or resources from communities in the name of environmental protection or the energy transition. This can lead to forced displacements and damage to the livelihoods of these – often rural – communities. Therefore, when assessing and planning for solar PV expansion, it is essential to refer to available property rights and land tenure information [312]. Formal land rights are often neither established nor documented for indigenous or smallholder farmer communities. Therefore, they are highly vulnerable to *green grabbing* phenomena, and researchers as well as practical planners should actively address these issues in regions where insecure land tenure regulations prevail. As a starting point, these areas have been documented globally to some extent [340].

Finally, recent studies have also considered spatial distributional justice, as it may affect local acceptance of solar PV projects [313]. This factor has been quantified through the Gini coefficient of planned solar PV capacities per region [197], Gini coefficient of planned renewable electricity production per potential in each region [342], or a composite of benefits and a vulnerability index as compound indicators for impacts of renewable energy systems [343].

8. Discussions

After reviewing the literature on different types of PV potential, it is clear that some aspects require additional information and discussion to achieve a balanced view of the current state of PV potential assessments. Therefore, this section will revisit each topic to provide an overview of the remaining research gaps and initial ideas for future research directions.

8.1. Theoretical potential

There is extensive, openly available data on solar radiation, and most solar radiation products can be retrieved from accessible databases. Several software packages also have direct links to these databases. One example is the PVGIS platform [346], which provides information about solar radiation and PV system performance. PVGIS retrieves data from databases like SARAH [43], CMSAF [347], ERA5 [51], and COSMO [64]. However, some studies refer to a particular software without mentioning the database used for calculations, causing reproducibility and comparability problems for other studies. Additionally, the studies reviewed often do not reflect on the limitations of the software or databases used. Future publications should openly discuss these constraints and clearly state which software and databases they used, including the version numbers.

An atmospheric model must resolve many details to realistically simulate key processes related to solar radiation, such as orographic effects on precipitation and wind, localized convective systems and thunderstorms, planetary boundary layer dynamics, and extreme weather events. Thus, higher resolution and physics-based simulations are imperative [348], ideally at a global scale. However, this type of publicly available data is lacking, and its impact on solar PV assessments compared to results obtained from relatively coarser datasets remains unknown. Future work in this area should be considered. Machine learning's potential to improve solar radiation simulation is an emerging topic that deserves further exploration.

8.2. Geographical potential

Fortunately, the availability of detailed land-use data, which is crucial for assessing geographical potential, is improving. However, the literature often lacks justification for chosen exclusion criteria and buffer values, which needs improvement. Furthermore, sufficiently assessing rooftop PV requires 3D building data combined with construction details regarding carrying capacity, a resource that is still lacking on a global scale. Additionally, future research should focus more on PV types that allow for the dual use of land to close this literature gap.

Although existing studies provide meaningful results, further consideration is needed to improve the detailed planning of real-world implementations. One general limitation is the lack of validation or standardized validation schemes. Validation is essential for ensuring the reliability of results and should be prioritized in future research. The increasing availability of detailed, openly accessible data on land use, irradiance, and existing solar PV power plants provides a reliable source for validating calculations.

One aspect often missing from open-field PV is the sensitivity analysis of criteria and buffers. A threshold is usually chosen without further explanation and is often based on existing studies, e.g., [85], although the impact is recognized as important. For example, [77] found that the calculated potential for the USA is highly sensitive to the available grassland area. Additionally, the impact of future land use changes on land availability is largely absent from the literature.

A notable limitation of rooftop PV is the absence of exclusion criteria. It is important to recognize that not all rooftops are suitable for PV installation [349]. For instance, roofs with excessive shading, inappropriate orientations, or incorrect tilt values are deemed unsuitable for PV installation [143]. Omitting these factors could lead to an overestimation of the geographical potential. While some studies have addressed this issue through some exclusion criteria in Brazil [152], Nigeria [156], Switzerland [139,140] and the USA [143], the variation in building typology and density necessitates a comprehensive investigation on a large scale for a more accurate estimation.

The reviewed literature has analyzed further potential in only 11 countries. Additional investigation is needed on suitable crops and the potential utilization of animal enclosures for agricultural PV. Additionally, while most authors assume that only a certain percentage of water bodies can be covered by floating systems, they only provide general reasons why coverage might be restricted. Infrastructure-integrated potentials are limited in size. The potential of façade-integrated PV systems is considerable, but it is inhibited by many restrictions.

8.3. Technical potential

Some studies make assumptions that lead to uncertainties in calculations conducted at the country level. There does not seem to be a consensus regarding the methods used, and many studies did not fully report their assumptions. Future publications should disclose the technologies, efficiencies, yield corrections, and losses considered, as well as the version of software employed, to increase the reusability and reproducibility of the findings.

Currently, most technical potential assessments are limited to a single application type rather than combining different PV applications, such as building skins, roofs, open fields, and agricultural land. Therefore, combining applications is an interesting area of study, even including other types of renewable energy sources, such as CSP and wind, which compete for limited eligible areas.

We also noted that none of the studies considered a combination of older and newer modules. Efficiencies were assumed to be the same throughout the entire country. If the assessment is followed by a question on recommended installation locations, old installations would need to be considered. If modules have not been replaced, they may be inefficient due to outdated technology, degraded, or inoperable. In the future, as the average age of PV installations increases, a country map could categorize PV modules by age.

Bifacial PV modules have only been studied to a limited extent. However, bifacial modules (glass-glass modules with cells that have non-fully-metallized and thus PV-active rear sides) have the potential to increase electricity output 5%–30% compared to monofacial PV modules [350], depending on installation angle, tracking, and location. Other recent studies report a modest bifacial gain of 4.53–8.42%, depending on the type of soil over which the systems are installed [351]. The global market share of bifacial modules is expected to increase to 70% by 2030 [226]. Emerging PV-cell technologies using tandem or triple junction configurations like perovskite/c-Si tandems are entering the market and increasing efficiency. New assessments considering these technological progress [352] are needed to determine the potential to increase area-specific electricity output. For detailed future studies considering tandem or triple junction technologies with higher temporal resolutions, we recommend accounting for spectral losses. Publications on the subject explore losses in different locations compared to standard testing conditions (STC), due to spectral differences, optical losses, and DC-AC conversion. These publications report different results for single junction cells and tandem cells [353], as well as for two-terminal and three-terminal tandems [354].

Technical potential assessments are integral to energy system frameworks [355] like ETHOS.FINE [356] and serve as side constraints for maximum capacity expansion. Temporally resolved potential assessments use capacity factor time series for location-specific technology sizing [357], but most have hourly resolution [358], omitting critical situations [359]. Growing computational power and advanced techniques enable energy system models to handle higher-resolution capacity factor time series [360], creating the need for higher-resolution weather reanalyses or data imputation methods [361].

Current research topics like automated maintenance may reduce system downtime and costs due to outages [362,363] and enhance PV system resilience against cyberattacks [364]. Recycling and resource scarcity, crucial for future installations, may affect material quality and performance [365,366].

PV output may be affected by climate change, though only three of the reviewed publications [186,367,368] consider this impact. Higher temperatures and changes in cloud cover may impact locations, potentially rendering current assessments obsolete. Different optimal module orientations due to changing irradiance and temperatures have also been derived [369]. Authors note that not adapting to these developments reduces PV potential, which may be balanced by technological improvements. Extreme weather events, like flooding and high wind events, have also been studied, as they can cause considerable losses to individual installations [370,371].

Overall, future research should focus on three main areas: joint potential assessments that consider different and potentially competing technologies, application types, and age cohorts simultaneously; the integration of potential assessments that consider technological progress into energy system models with increasing resolution; and uncertainty aspects related to cybersecurity, weather, and climate.

8.4. Economic potential

Although most reviewed studies acknowledge the economic potential, several aspects require improvement for future research. Once again, validation with real-world data is lacking, and several crucial parameters are either vague or absent, such as the base year and system boundaries. Additionally, cost differences are usually only driven by weather variations, not by other regional cost elements, such as land cost, discount rate, or system integration cost. Some of these limitations stem from a lack of suitable, open-source data. We also propose that future studies include the capture rate as a crucial economic indicator to encompass the economic value of a PV installation.

More specifically, a limited number of studies [250] have validated the results using real-world data from a PV plant. In some instances, the results were validated against the outputs of other models [208,284], which is a useful approach, but it does not provide insight into how well a model approximates real-world systems. A lack of validation is a general problem when determining the potential of renewable energies. A recent review revealed this issue in wind power resource assessments as well [3]. Therefore, an important future research avenue is obtaining real-world data from PV plant operators or the electricity market for validation purposes.

The economic criteria estimate the cost and benefits of PV projects in different regions. However, the details of economic assumptions are often missing. Accounting for spatial and temporal variations in economic assumptions can substantially affect the outcomes of large-scale studies. However, incorporating these variations necessitates extensive data, which is often inaccessible. To enable consistent comparison and realistic discounting, the base year and region-specific real WACC as discount rate must be clearly stated. While few studies disclosed the base year [141,294] or used national WACC [200,276], sub-national WACCs are essentially absent. Thus, a realistic estimation of economic potential will depend on data availability.

The cost of land is the most often missing category for PV systems. For utility-scale PV systems, both ground-mounted and floating, the large surface area occupied incurs significant land costs. Yet, these costs have been overlooked in 90% of economic potential studies. Land costs can be divided into two parts: land preparation costs [282], which are part of CAPEX, and rent [173], which is part of OPEX and paid annually. Due to decreasing system component costs [283], land costs will become a larger proportion of the total system cost. The challenge of including this detail is the lack of data on land costs, which vary greatly by location and over time.

Most economic studies overlook the cost of integrating non-dispatchable solar production into existing energy systems. These costs can include profiling, balancing, and network costs [300]. However, none of the studies investigated profiling costs, which refer to the costs of additional dispatchable generation technologies needed to meet residual loads. Estimating this cost requires data on local dispatchable generation costs. Balancing costs refer to the costs induced by the deviation between the forecasted and actual non-dispatchable solar generation. These costs are considered a fixed cost per unit capacity in around 11% of economic potential studies [176,208]. However, this cost is system-specific and temporally-varying, making detailed calculation hard to scale. Network costs are observed in few studies [277,278], and it is approximated as a fixed cost per unit capacity.

This simplified approximation cannot reflect existing infrastructure characteristics like location and capacity of the nearest substation. Future research can integrate open-access GIS data of existing infrastructure to provide a more realistic estimation of integration costs, similar to the estimated connection cost to the nearest transformer for onshore wind farms [372]. These three types of system integration costs will change in the future with increasing shares of renewables. This will affect the assumption of constant cash flows and, hence, the NPV. With battery storage costs for accessibility, profiling, balancing, and network connection can be reduced due to a more stabilized grid and lower demand for extensive network infrastructure.

Finally, no studies have investigated solar PV capture prices or rates. The capture price is the average price per unit of electricity generated, considering the timing of generation relative to market prices. The capture rate, also called the value factor, is the percentage of the capture price relative to the market price available for the power produced [373]. Solar PV in Germany has already fallen below 60% [374], and it will continue to decrease with further expansion of solar PV systems. The capture rate is a key economic indicator in revenue estimation for solar PV since it reflects the actual market value of the electricity produced. Introducing capture rates of PV electricity can be a simple approach to yield more realistic results for economic potential assessment. Usually, the capture rate is included into the geospatial analysis.

8.5. Feasible potentials

The feasible potential is a relatively new topic within potential assessments that is becoming increasingly relevant. The biggest challenges are the limited availability of suitable data and the lack of established approaches. The latter is further complicated by the interdisciplinary nature required to assess this type of potential. First attempts to consider aspects related to feasibility have been made thus far. However, a rigorous selection of criteria is still pending and is an urgent need for future studies.

Solar PV projects often encounter non-technical challenges during deployment. Incorporating non-technical factors into the determination of solar PV's feasible potential would provide decision makers and project developers with more accurate estimates that consider societal concerns from the beginning of the planning process. Nevertheless, the number of studies that have assessed the feasibility of solar PV is still very limited. The current lack of consistent theoretical and methodological approaches, as well as limited data availability, makes it difficult to fully capture and integrate non-technical factors into potential assessments. As a result, assessments often rely on arbitrary assumptions about the feasibility of different types of land. Therefore, defining the concept of feasible potential with a sound theoretical and empirical foundation remains a crucial research topic.

In practice, it is essential to disclose the rationale behind choosing non-technical criteria and their values to be incorporated into potential analyses. For example, if an area is excluded due to acceptance issues, clear theoretical and empirical evidence demonstrating lower acceptance of projects related to this land characteristic must be provided. Studies that incorporate external costs in (partial) welfare analyses must also explicitly disclose the assumption that PV projects have externalities, clearly differentiating them from studies that solely assess the private costs of solar PV projects.

One important research stream, developed for analyzing wind power generation, directly assesses externalities such as visual impacts through scenicness assessment [284] or visibility assessment [318]. This research shows the trade-offs between landscape impacts and electricity generation. Another research direction moves beyond the concept of potential and is based on economic welfare analysis. This approach aims to partially monetize the externalities of solar PV systems. Notable examples include including external costs for ecosystem services [320] and visual landscape impacts [321]. However, these studies are still in the early stages of development.

Another important topic is the assessment of criteria for understanding energy justice. Currently, these methods are limited to the spatial distributional dimension [375]. Additional work is required to expand the scope and capabilities of these methods. A recent study [323] also highlighted the dynamics of social acceptance of renewable energy technology along the project timeline, different institutional arrangements, and across the scale of analysis. Investigating how these dynamics may impact modeled non-technical factors [338] and feasible potential would be an interesting avenue for future research.

In conclusion, integrating non-technical factors into potential assessments requires collaboration between different disciplines. For example, economists can provide useful tools for monetizing the externalities of solar PV, while social scientists can contribute to understanding the local impacts of solar PV and exploring the drivers of acceptance or rejection of renewable energies.

9. Summary and conclusion

Rapid deployment of solar PV technology is critical to the global energy transition. However, there are significant challenges in determining its true potential across different applications, geographical areas, and energy systems. This review examines key methodologies and assumptions used to evaluate solar PV potential in large areas. It shows that, although considerable progress has been made, challenges remain for more accurate and comprehensive assessments. The most pressing limitations and most promising avenues for future research were addressed in each section including references to most promising studies, while this section presents the derived conclusions from a holistic perspective.

This review highlights one of the key challenges: the lack of consistency and transparency in databases, assumptions, methodologies, and software used to assess solar PV potential. Studies often differ in their assumptions about geographical databases, technological efficiencies, economic viability, and system boundaries. These differences make comparisons difficult and limit the usefulness of the results for decision-makers. For instance, studies aiming for a future perspective often overlook recent technological advances and make conservative assumptions about future PV efficiencies. In addition, explicit quantification of system integration effects of variable PV generation is commonly absent from resource assessments, and the associated costs (e.g., profiling, balancing, and network) are typically omitted or roughly approximated. These differences in the underlying input data and methodologies make it difficult to form a coherent picture of the true potential for large-scale PV potential assessments.

Another key issue is the frequent exclusion of non-technical factors from assessments of solar PV potential. Although technical potential is often examined in great detail in studies, it is the non-technical factors, such as social acceptance, land use competition, and policy frameworks, that often determine the feasibility of deploying solar PV on a large enough scale to transform the energy system. Currently, however, many of these non-technical considerations are addressed only qualitatively or in an ad hoc manner rather than being rigorously integrated into modeling processes. Integrating these factors into solar PV assessments requires an interdisciplinary approach combining insights from engineering, economics, social sciences, and environmental science. It is essential to develop more sophisticated methods for quantitatively integrating these factors into PV potential assessments. Currently, these assessments are hampered by a lack of consistent theoretical and methodological approaches and data availability. Consequently, the few available assessments rely on arbitrary assumptions about which types of land are "feasible". Incorporating these factors could improve the assessment of optimal solar PV spatial deployment, and more communication with social scientists, including psychologists and sociologists, could improve our understanding of renewable energy acceptance. Ultimately, this could lead to a sound theoretical and empirical basis for defining feasible potential, including more detailed, participatory modeling approaches to assess social acceptance and spatially explicit welfare analyses to weigh the environmental and economic costs and benefits of PV installations. Additionally, research should focus on the dynamic nature of renewable energy acceptance, recognizing that public opinion and policy frameworks can shift over time due to factors such as the visibility of installations, local employment opportunities, and broader environmental concerns.

Future research should improve the transparency of methods and assumptions used in PV potential assessments, especially regarding underlying assumptions and system boundaries. High-resolution, spatially explicit data is needed to produce more accurate assessments. As PV technology continues to evolve, models need to incorporate new advances, such as bifacial PV modules and floating PV systems, which can significantly change the technical potential. Automated model workflows that allow assessments to be updated with the latest data could improve the transparency and accuracy of renewable potentials. Checklists with questions are provided in the Appendix to guide this effort in the future. This list is far from comprehensive, and differences might exist depending on the application and technology developments. We believe this helps to verify the information that needs to be included to make PV potential assessments more reproducible and transparent.

In addition to improving transparency, it is necessary to validate model results with observations in order to determine where model outcomes and actual deployment patterns align or diverge. Although a large amount of historical solar meteorological data is available and continuously improving, there is still a knowledge gap regarding existing PV installations worldwide. This gap lacks sufficient detail, including full information such as the year of installation, capacity, module type, and feed-in time series. This information is essential for validating assessment models but is currently one of the biggest obstacles to validation efforts. The ongoing evolution toward open data should be pursued and supported by policymakers and PV operators to overcome this challenge in their shared interest.

Current approaches use historical data for meteorological inputs or land use. More emphasis should be placed on future developments, especially climate change and extreme weather events, as well as land use change and options for dual land use, like agri-PV. Extending approaches to using climate scenarios remains challenging due to their low temporal resolution, which usually does not suffice the needs of energy system models, i.e., to reveal energy storage needs correctly. Furthermore, land use changes or their impacts on potentials highly depend on the type of land use changed. This can cover topics like urbanization, forest conversion, or renaturation efforts. Land use change impacts might even outweigh climate change effects for PV potentials on a global scale.

Therefore we suggest the following **key avenues for future research directions:**

Data availability: Sufficiently detailed and openly accessible data are still partly missing, especially for extended atmospheric models, measured data of installed PV modules, global 3-D building data including construction details, and global cost of land, to mention only a few.

Transparency: Many data, software, models, and parameters have to be used and assumed. Being precise about version numbers and the reasons for their selection is crucial. Utilizing best-practice examples from the FAIR community on how to design metadata properly is highly advisable. However, how to document model assumptions in a transparent way is not standardized beyond model fact sheets, which typically do not include specific model assumptions. Closing this gap would benefit not only renewable energy potential assessments but also the entire energy systems modeling community.

Validation: Achieving useful results that reflect real-world conditions requires proper validation procedures. While this is closely linked with the data availability challenge, efforts to establish such procedures based on already available data are imperative to improve the reliability of results for decision-makers. Making those efforts open source and open data would further facilitate the entire research community in this area.

Implementation orientation: To realize PV projects, potential assessments must account for aspects that go beyond purely technical considerations. Future studies should focus on aspects relevant for decision-makers, including the real market value of generated electricity and the feasibility of project realization. While some concepts for the economic dimension already exist and await full implementation, the methodological foundation for feasible potential remains in urgent need of basic future research.

In summary, significant progress has been made in assessing the potential of solar PV. However, these assessments still need improvement to fully capture the complexities of real-world deployment. The previous highlighted aspects provides essential avenues for future research derived from this review. Addressing existing methodological gaps and incorporating a broader range of non-technical factors is critical to improving the accuracy of PV potential assessments and supporting the global transition to a sustainable energy future. These methodological advances should ultimately be pursued with the aim of achieving a fully integrative framework that combines methods and indicators to consider diverse impacts and explore trade-offs. This is of the utmost importance in order to overcome the shortcomings identified in the literature, and it is not limited to PV potential assessments, but extends to all renewable energy assessments.

CRediT authorship contribution statement

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used the tools “ChatGPT” and “DeepL” in order to check grammar and spelling, and to make improvements to readability and style. After using these tools, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

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.

Acknowledgments

This work was partly supported by the Helmholtz Association, Germany as part of the program “Energy System Design”. RM gratefully acknowledges the financial support of the Joint Initiative project “Swiss Center of Excellence on Net Zero Emissions” (SCENE), funded by the ETH Domain. This work was partly funded by the European Union (ERC, MATERIALIZE, 101076649). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.renene.2025.125080.

Data availability

The authors do not have permission to share data.

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