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A GIS-based method for assessing the economics of utility-scale photovoltaic systems

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HIGHLIGHTS

- A GIS-based model for utility-scale PV system planning and investment.
- The approach accounts for country-specific cost elements.
- The GIS-based approach is demonstrated through the case study of Poland.
- 3.61% of available land is suitable for utility-scale solar PV systems.
- The LCOE ranges from €0.043/kWh to €0.049/kWh.

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ABSTRACT

Solar photovoltaic capacities have experienced remarkable gains worldwide. The accelerated deployment of photovoltaic (PV) systems has emphasized the need for methods and tools that can assist in planning and investment decisions of utility-scale photovoltaic systems to ensure a sustainable energy transition. This study bridges the gap between research and current solar PV project evaluation practices by proposing a geographic information system (GIS)-based approach for analyzing land eligibility and performing techno-economic assessments of utility-scale photovoltaic systems. To tackle the issue of country-specific cost elements, the model incorporates a levelized cost of electricity (LCOE) breakdown often used by governmental and intergovernmental organizations. The proposed GIS-based model can assist in mapping the distribution of eligible land for utility-scale solar systems while considering exclusion constraints, estimating PV capacity and generation potentials, as well as determining the average LCOE of utility-scale solar photovoltaic systems at a spatial resolution of 100 m. The GIS-based approach is demonstrated through the case study of Poland. The model estimates that 3.61% of the total area of Poland is suitable for the installation of utility-scale solar PV systems. Implementing PV installations in these areas would result in solar capacities ranging from 394.64 to 563.77 GW. Furthermore, the findings of the case study indicate that the LCOE would range from €0.043/kWh to €0.049/kWh, with a national average of €0.045/kWh. The proposed approach can be utilized to develop national and regional strategies focused on large-scale PV installations, facilitating the attainment of renewable energy goals. The study fills a significant gap in the literature as it provides a GIS-based tool for planning the sustainable development of utility-scale PV systems at the regional scale. In addition, it is the first to comprehensively assess the capacity and generation potential of utility-scale solar photovoltaics in Poland at the NUTS-2 level.

1. Introduction

Solar energy has emerged as a crucial renewable source for combatting climate change, decarbonizing power systems, and supporting sustainable economic growth [1,2]. Due to the vast solar resource potential in different countries, as well as the rapid technological advancement and cost decline of photovoltaic modules, utility-scale photovoltaic (PV) capacities have seen remarkable gains worldwide —particularly among developed economies like the United States, Australia, and Western Europe [3,4]. However, it is only recently that utility-scale solar installations have become economically accessible to developing regions and are more frequently considered critical technologies for fostering the energy transition [5,6]. Utility-scale

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Nomenclature

Abbreviations

CAPEX	Capital Expenditures
CDDA	Common Database on Designated Areas
DEM	Digital Elevation Model
EU	European Union
GDAL	Geospatial Data Abstraction Library
GIS	Geographic Information Systems
GLAES	Geospatial Land Availability for Energy Systems
HPC	High Performance Computing
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Electricity
LE	Land Eligibility
LNG	Liquified Natural Gas
NREL	National Renewable Energy Laboratory
NUTS	Nomenclature of Territorial Units for Statistics
OPEX	Operational Expenditures
OR	Output Resolution
QGIS	Quantum Geographic Information System
PL	Poland
PV	Photovoltaics
RES	Renewable Energy Source
SAM	System Advisor Model
SRS	Spatial Reference System
SILICON	SpatIo-temporaL scIentific ComputatiONs

Symbols

CRF	Capital Recovery Factor
i	Discount rate (%)
H	Hardware costs (€)
I_0	Installation costs (€)
N	Project lifetime (yrs)
SC	Soft costs (€)
θ	Yearly operating and maintenance costs given as a fixed percentage of installation costs (%)

systems, which differ in size and capacity from residential and commercial photovoltaic systems, are widely employed today in urban and rural areas to convert solar energy into electricity [7]. Typically, utility-scale systems are classified as those with capacities greater than 5 MW. In contrast, residential PV systems usually have capacities ranging from 4 kW to 10 kW, while commercial systems fall within the range of 100 kW to 5 MW [8,9].

Site selection for deploying utility-scale photovoltaic systems requires detailed information about solar irradiation and meteorological conditions of a region or specific location and a comprehensive assessment of land availability and land cover characteristics [10]. Research on spatial and spatio-temporal modeling of renewable energy technologies has gained momentum in recent years. This growing interest is partly driven by the advancements in computational power, remote sensing, earth-bound survey, and cartography, which have given rise to integrated mapping tools commonly referred to as Geographic Information Systems (GIS) [11]. These powerful computational tools have become critical for making sound planning and investment decisions since they simultaneously consider temporal and spatial information about a region/location, represented either as a vector (points, lines, and polygons) or raster data (point features by single —pixel— cells in a two-dimensional matrix). Geographic information systems typically comprise four main components: hardware (computers for data processing), software (programs and applications), GIS professionals (skilled individuals capable of interpreting the results), and a GIS organizational environment (supporting GIS training, data collection, and dissemination) [12]. Furthermore, the elements of GIS can be categorized into geospatial data, data acquisition and management, data display, data exploration, and data analysis [12]. Despite the increasing need for spatio-temporal analysis of renewable energy sources, computational approaches that facilitate the systematic investigation of solar resource potential, land use, and bankability of utility-scale photovoltaic systems remain scarce in the literature.

Most research works use simulation and/or optimization models at the individual plant level to solve the complex problem of planning and development of utility-scale photovoltaic systems. For example, Shakeel and Mokheimer evaluated the levelized cost of electricity of utility-scale solar PV plants in 40 cities in Saudi Arabia using the simulation software System Advisor Model (SAM) [13]. Sreenath et al. conducted an energy, exergy, economic, and environmental analysis of a conceptual 5 MW utility-scale solar photovoltaic power plant using RETScreen and an Excel-based mathematical model [14]. Similarly, Kumar et al. developed a techno-economic model to evaluate the performance of a 10 MWp grid-connected canal-top PV plant in India [15]. Mensah et al. investigated the performance of a 2.5 MW solar photovoltaic power plant at a specific site in Ghana [16]. The study assessed the final energy output, capacity factor, and levelized cost of electricity of the grid-connected PV system. The tools mentioned above are commonly used to investigate the techno-economics of the system under various scenarios. However, they do not necessarily address the problem of identifying feasible deployment sites within large amounts of land. Hence, GIS-based studies have shown great promise in evaluating and selecting ideal locations for wind and photovoltaic systems.

Among the recent studies that have focused on the land eligibility of renewable energy systems using GIS-based models, the work by Ryberg et al. is noteworthy. It evaluated thirty-six commonly used land eligibility constraints in the European context and ranked their significance based on independence, exclusivity, and overlap [17]. The results showed that the criterion of proximity to agriculture and woodland areas is among the most important, whereas airports and camping sites rank low in significance. Alhamwi et al. conducted an analysis of GIS-based urban energy systems models and their applications in cities [18]. The results demonstrated that GIS-based platforms that consider special features of urban objects are useful for the flexibilization of technologies, including wind, solar, and storage units.

Spatio-temporal modeling has found a wide range of applications in urban and smart city planning, wind and solar farm site selection, and the quantification of renewable energy technical potentials. Camargo et al. proposed a GIS-based method to improve the decision-making process for deploying solar photovoltaic panels [19]. Pea Sanchez et al. carried out a techno-economical assessment of wind (onshore and offshore) and photovoltaic (open-field and rooftop) systems in Mexico and assessed their installable potential by 2050 [20]. In the study, the authors conducted a land eligibility analysis that incorporated 34 land constraints, including physical, economic, environmental, and socio-political exclusion criteria. In addition to the aforementioned land eligibility criteria, the authors applied seven exclusion constraints specific to Mexico: military areas, harbors, liquefied natural gas (LNG) terminals, geothermal sites, primary jungles, active volcanos, and hurricanes. A notable contribution of their study was the evaluation of the installable potential of renewable technologies and the levelized cost of electricity for each technology. Similarly, Watson and Hudson conducted a land eligibility analysis to assess the potential of wind and solar production in South-Central England [21]. The constraints applied in the study were agricultural lands, historically important areas, landscape designations, residential areas, slope, and wildlife designations. The results showed that environmental constraints account for over 60% of the area available for wind and solar technologies.

Recent research efforts have begun to direct more attention to estimating renewable energy potentials using GIS-based models. Cheng et al. carried out a GIS-based assessment of the technical and economic resource potential of solar photovoltaic, wind, and pumped hydro in Bolivia [22]. The study considered terrain slope and other factors like proximity to major roads, protected areas, urban centers, lakes, and rivers as essential exclusion criteria. In a more recent study, Cheng et al. conducted a renewable resource assessment for Japan [23]. The evaluation considered resource constraints and used an optimization model to find the power system configuration that would meet the power demand only with renewable energy sources. Fatima-Zahra et al. performed a techno-economic assessment of solar PV resources in Morocco using a GIS-based method [24]. The authors conducted a scenario analysis and examined the levelized cost of electricity considering the weather conditions and terrain constraints. Asare-Addo analyzed land eligibility for large-scale or utility grid-connected solar PV systems in Ghana [25]. The results indicate that about 85% of the total land area in Ghana is suitable for solar systems deployment. Doorga et al. provided a GIS-based assessment for identifying optimum wind and solar sites in Africa to face the challenges related to decarbonization [26]. The spatio-temporal analysis revealed that Egypt and South Africa are the most favorable locations for deploying renewable generation units.

Compared to other studies, Samsatli et al. proposed an optimization model that incorporated land eligibility constraints [27]. The model focused on wind-hydrogen-electricity networks with the objective of satisfying domestic transport demands. The authors considered the spatial distribution and temporal variability of energy demands as well as wind availability in Great Britain. The study applied technical and environmental land constraints, including distance from urban areas, rivers, roads, woodland, and others. Welder et al. developed a spatio-temporal optimization model of onshore wind technology for power-to-hydrogen applications in Germany [28]. The authors applied land eligibility, weather constraints, and turbine data to develop regional power profiles. Three types of exclusion criteria were used to investigate the deployment of wind turbines: physically limiting land cover characteristics, policy and societal preferences, and observation of protected areas.

The studies reviewed above point to a number of gaps in the literature regarding the geospatial modeling of renewable energy systems (RES) and show that to successfully implement large-scale RES projects, both spatial features of the region/area of interest and sociotechnical criteria must be thoroughly explored. Furthermore, previous research efforts indicate that country-dependent cost elements significantly influence the economics of utility-scale solar photovoltaic systems. This is particularly relevant in countries where fossil fuels are the main energy vectors, and the competitiveness of RES systems is primarily impacted by local installation, hardware, and soft costs. Thus, this study aims to bridge the gap between research and current solar PV project evaluation practices by facilitating the identification of suitable sites and the assessment of economic potential with the use of a GIS-based model that pays special consideration to the variation in the levelized cost of electricity due to labor-related costs like PV system installation, mechanical and electrical installation, and other expenditures.

The scope of this study is focused on examining utility-scale solar PV installations in both urban and rural settings, with a particular emphasis on ground fixed-tilt solar PV systems. These systems have been selected due to their significant presence in developed and developing markets [29,30], as well as their cost-effectiveness (lower installation and maintenance costs) and durability when compared to tracking systems [31]. Rooftop installations are excluded from the analysis due to the unique context in Poland and other European countries, where solar panels mounted on residential and commercial rooftops frequently benefit from compensation mechanisms and various financial incentives.

Despite the considerable advancements introduced towards the development of GIS-based tools for planning and modeling renewable energy systems, to the best of the authors' knowledge, no study has established a GIS-based method that comprehensively breaks down the techno-economic factors that affect the levelized cost of electricity of utility-scale solar PV systems —such factors are imperative for a better understanding of cost drivers— and considers the impact of geospatial factors on the feasibility of their large-scale deployment. Moreover, while there is an increasing interest in implementing large-scale solar PV systems in Europe, no prior research has examined the land eligibility and potential spatial distribution of utility-scale PV systems in Poland at the NUTS-2 level. Therefore, this paper aims to address these gaps by (i) proposing an innovative method for analyzing land eligibility, installable capacity, solar energy potential, and performing techno-economic assessments of utility-scale photovoltaic systems and (ii) testing its effectiveness through the geospatial analysis of the Polish territory and its 17 NUTS-2 regions.

It is worth noting that Poland is an important case study since it has one of the highest carbon intensities of electricity in Europe and has experienced substantial growth in solar PV capacity in the last four years, accounting for approximately 18% of the country's total installed capacity. Moreover, only one study has explored the research problem of the spatial, temporal, and cost distribution of renewable technologies in Poland. However, the work focused on potential areas for the deployment of wind power. Sliz-Szkliniarz et al. developed a spatio-temporal distribution model which applied technical, environmental, economic, and social acceptance criteria to assess the potential levelized cost of electricity generated by wind farms [32].

In this context, the key contributions of this study can be summarized as follows:

- Firstly, a GIS-based method is proposed for analyzing land eligibility and performing techno-economic assessments of utility-scale photovoltaic systems. The main novelty of this method lies in its ability to account for variations in the levelized cost of electricity due to labor-related costs such as PV system installation, mechanical and electrical installation, and other expenditures while considering sociotechnical criteria that may limit the deployment of utility-scale PV systems in certain areas.
- Secondly, the study offers a unique tool for assessing both installable capacity and electricity production potential of utility-scale solar photovoltaics at high spatial resolutions. The GIS-based tool also enables the computation of the levelized cost of electricity by applying techno-economic parameters of solar PV systems and land constraints from open and publicly available datasets. Additionally, it identifies the regions with the most significant potential for job creation associated with utility-scale PV installations.
- Thirdly, the paper presents valuable findings on installable capacity and electricity generation potential at a resolution of 100 m for Polish NUTS-2 regions, providing insight into the opportunities and costs associated with utility-solar PV systems. The results can assist policymakers and local governments in better planning and allocating funds, as well as designing support mechanisms for such investments to fulfill climate goals related to increased renewable capacity.

The remainder of the paper is organized as follows. Section 2 describes the GIS-based model developed for the analysis of land eligibility and the techno-economic assessment of utility-scale photovoltaic systems. Section 3 defines the case study and the main techno-economic assumptions adopted. Section 4 presents the results of the land eligibility and techno-economic assessments of utility-scale photovoltaic systems, including the installable potential and levelized cost of electricity. Finally, section 5 draws conclusions about the method and the potential deployment of utility-scale PV systems.

2. Method

This section presents the method for analyzing land eligibility and performing techno-economic assessments of utility-scale photovoltaic systems. The method is designed for spatio-temporal scientific computations aimed at investigating the suitability of a region/site for the potential deployment of utility-scale photovoltaic systems and estimating the levelized cost of electricity of such installations in the selected sites.

A visual representation of the approach is illustrated in Fig. 1. The method proposed in this paper, denoted as SILICON (SpatIo-temporaL scIentific ComputatiONs), facilitates computations at a spatial resolution of 100 m. In the initial step (Step 1), the entire land area of the country is transformed into matrices with rows and columns containing cell values representing categorical and numerical data. Subsequently (Step 2), datasets encompassing geometries and attributes of diverse objects are employed to identify eligible land (available sites) within each cell. To accomplish this, various land exclusion constraints are taken into consideration to evaluate the available land and assess the installable and generation potential of utility-scale solar PV systems. Once the eligible land is identified, the method proceeds to estimate the levelized cost of electricity in each cell (Step 3). This estimation incorporates local techno-economic parameters of renewable energy technologies, including both capital and operational costs, as well as the electricity produced over the lifetime of the solar PV installation.

2.1. GIS-based model

Geographic information systems are advanced tools used to explore and analyze maps and terrain features. They also enable the creation of spatially explicit models capable of separating or categorizing areas based on a set of selection criteria. Furthermore, GIS systems can be integrated with advanced methods that are capable of performing mathematical operations on data primitives describing geographical phenomena like points, lines, polygons, and pixels. These data types are typically stored in different geographical database structures, such as raster and vector datasets [11,33]. In recent years, there has been an increasing interest in developing new theoretical concepts and decision-support tools capable of estimating the amount and distribution of land available for the deployment of renewable energy technologies. Due to the significant decline in solar PV module prices, utility-scale solar has become a competitive option for expanding power capacity while reducing fossil fuel dependence and potentially substituting traditional fossil-based power plants. However, to guarantee the successful implementation of utility-scale solar, it is essential to develop effective evaluations of land eligibility, policies, and physically limiting attributes of regions of interest.

In this context, this study proposes a computational method for (1) mapping the distribution of eligible land for large-scale solar systems considering exclusion constraints, (2) estimating the installable solar power potential of a region of interest using geographic information systems, and (3) determining the average levelized cost of electricity from utility-scale fixed-tilt solar photovoltaic systems.

The computational method proposed in this study builds upon the land-eligibility model previously developed by Ryberg et al. [17,34]. This method offers a more comprehensive approach by considering geospatially constrained eligible land and providing a detailed breakdown of techno-economic factors that impact the levelized cost of electricity of utility-scale photovoltaics. These factors include land use efficiency, installation, soft, and hardware costs. The proposed method aims to bridge the gap between research and current solar PV project evaluation practices by facilitating the identification of suitable sites and the assessment of economic potential.

The method comprises two main modules: one dedicated to the analysis of land eligibility and the other focused on techno-economic assessment of utility-scale photovoltaics. An overview of the method developed in this study is presented in Fig. 2. In the first module, depending on the structure of the databases, different procedures are executed. In the case of vector datasets, geometries are either expanded through the application of a buffer or converted into a raster format. For raster datasets, map pixels representing the geographic extent of the country are assigned binary values ('true' or 'false'). Subsequently, exclusions pertaining to the availability of land are applied to indicate buffer distances and land specifications. The output of the first module is a land indication matrix that represents the available land suitable for the installation of utility-scale PV solar systems. A comprehensive description of the procedural steps involved in the land eligibility analysis module can be found in Section 2.1.1.

In the second module, the land indication matrix is overlaid with rasterized datasets that describe solar resources and techno-economic parameters of solar photovoltaic systems. These digitized maps are utilized to calculate the installable capacity and energy potential for each cell. Moreover, they are essential for computing the levelized cost of energy for each cell, which represents the final output of the second module within the SILICON model. A detailed procedure for the PV techno-economic analysis is further described in Section 2.1.2.

2.1.1. Land eligibility method

As concerns over climate change continue to rise, there is an urgent need to reduce fossil fuel consumption and decarbonize the global

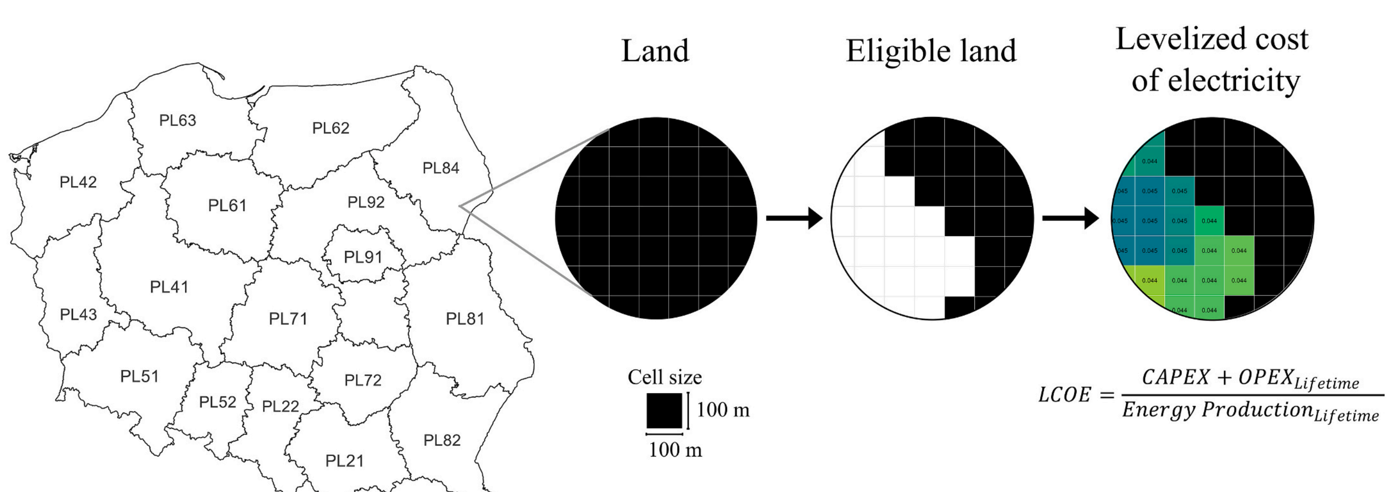

Fig. 1. Scheme of the method.

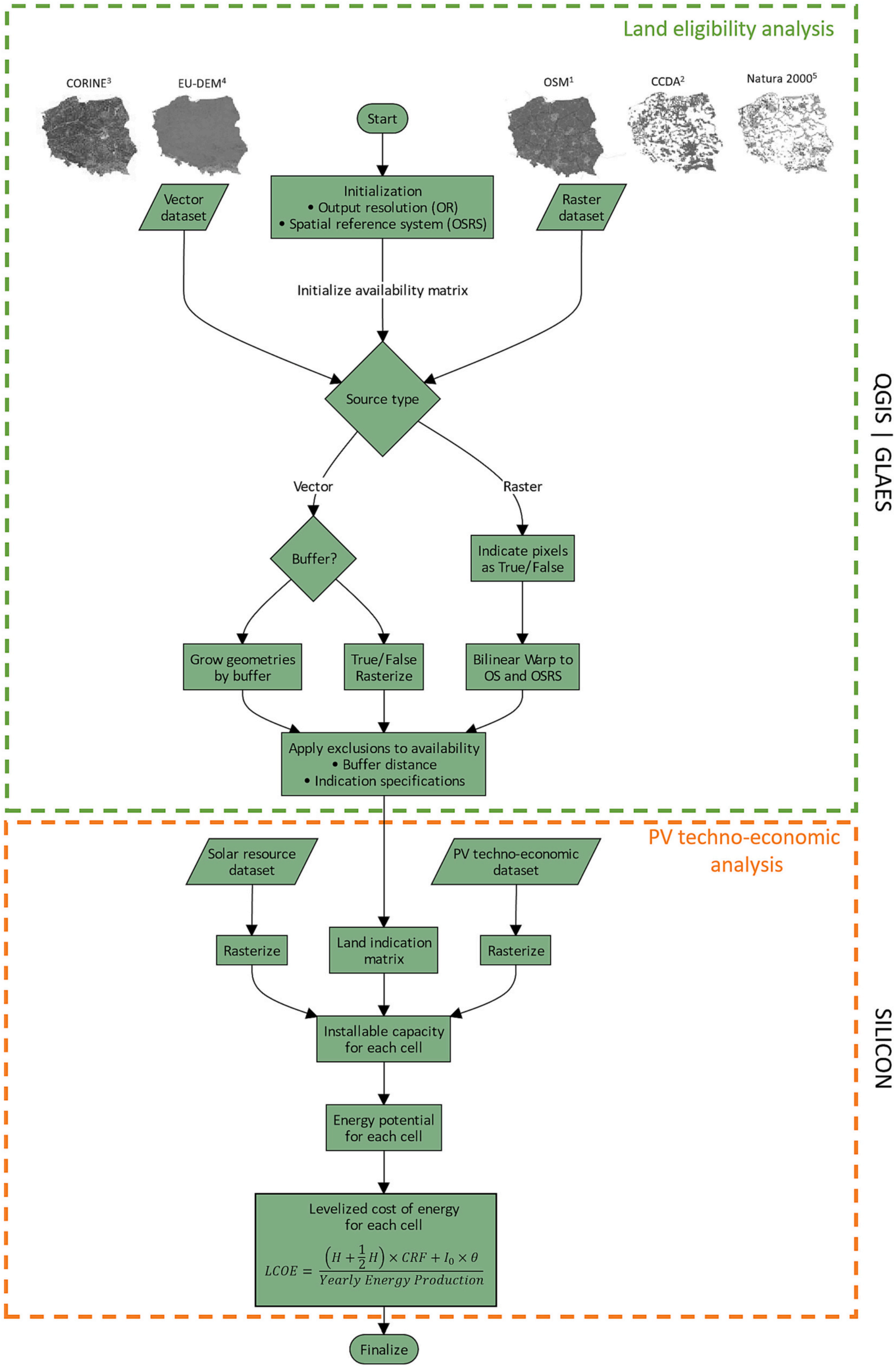

Fig. 2. Overview of the method. Maps data from: [35,36], [37,38], [39].

economy. In response, researchers have begun to utilize advanced computational tools to evaluate criteria and uncertainties that significantly affect the distribution of large-scale renewable-based power generation systems. Recent studies suggest that to ensure the successful implementation of large-scale RES projects, the spatial characteristics of the region/area, as well as the application of sociotechnical criteria, must be thoroughly investigated [17,40].

Consequently, various land eligibility (LE) analyses have been conducted for countries that are at the forefront of the global solar market (i.e., Germany, the United States, China, and others) [28,41]. Nonetheless, the literature review indicates a research gap regarding land eligibility analyses and solar energy potential assessments with a detailed breakdown of factors that drive the levelized cost of electricity (LCOE) in utility-scale solar photovoltaic projects. To overcome this deficit in the literature, this study develops a GIS-based approach that integrates an LCOE breakdown commonly used by governmental and intergovernmental organizations —since such institutions often prioritize simplicity and ease of access to pertinent data. Although the proposed method can be applied in various contexts and regions, this study exhibits its versatility by evaluating the Polish territory at the NUTS-2 level.

To determine the land area available for utility-scale solar installations within the 17 Polish NUTS-2 regions, several vector and raster-based geodatabases were preprocessed and transformed using the open-source software QGIS (Quantum Geographic Information System). The land eligibility analysis consists of several key steps: initialization and region definition, data processing, exclusion indication, application, and finalization. In the initial step, the spatial reference system (SRS), output resolution (OR) and geographical area of interest are defined. The GLAES model divides the geographical space into discrete spatial units creating a Boolean map (also known as a raster dataset or region mask) with the specified spatial reference system and pixel resolution. In the second step, the exclusions datasets (either in vector or raster format) are clipped and processed to ensure that they match the resolution and spatial reference system of the region mask. In the third and fourth steps, the exclusion datasets are converted to Boolean matrices, and then the exclusion procedure is applied to the region mask. The Boolean matrices indicate whether a pixel is available or excluded, essentially filtering the pixels based on the exclusion criteria. This process generates an intermediate Boolean raster. The procedure is applied iteratively until the final availability matrix is populated with 1 and 0 values, indicating the exclusion or availability of the geographical area. In the final step, the matrix is stored in a raster-type file format that can be displayed or rendered as a map. A comprehensive description of this process can be found in [34].

The operations for determining land eligibility, considering sociotechnical criteria (exclusion constraints), were carried out using the Python programming language and the library GDAL (Geospatial Data Abstraction Library) [42], along with an adapted version of the open-source software GLAES (Geospatial Land Availability for Energy Systems) [17].

In recent years, a significant number of publications conducting land eligibility analyses have proposed and adopted numerous exclusion constraints based on local and international social, political, technical, economic, and conservation considerations [43–46]. However, results from the works of [17,47–49] have demonstrated that the selection and application of various socio-technical constraints related to the deployment of renewable energy technologies can have a substantial impact on the eligible area, leading to significantly different assessments. Furthermore, the recent scientific debate between Enevoldsen et al. ([50,51]) and McKenna et al. ([52]) has highlighted the critical need for comprehensive evaluations of land eligibility constraints at local, regional, and international levels. Such evaluations should enable the replication of studies and facilitate the relative comparison of results. Therefore, the land constraints adopted in this study were derived from peer-reviewed works conducted by Ryberg et al. [17], Risch et al. [53], and Welder et al. [28]. These studies indicate a consensus on the most impactful constraints found in literature, corresponding to four criteria (i.e., sociopolitical, physical, conservation and economical) that can be uniformly imposed across the European landscape. It is worth noting that the study by Ryberg et al. [17] reviewed 53 publications centered on land eligibility analyses to determine the most commonly used constraints. As a result, the present study incorporates 20 of the most frequent and impactful constraints indicated by [17] from the review of 53 land eligibility analyses, as shown in Table 1. For additional information on the methodology for criteria identification, readers are directed to the comprehensive studies presented in [17,28,40].

2.1.2. *Techno-economic assessment*

The land availability analysis yields valuable insights into the potential of utility-scale solar PV projects while considering sociotechnical criteria that may limit their implementation in certain areas. The derived findings can subsequently be used to assess the economic viability of these installations across various regions, taking into account local infrastructure, meteorological characteristics, and land attributes [55]. For this purpose, the levelized cost of electricity (LCOE) is a metric commonly used to examine and compare the cost-effectiveness of renewable energy projects [56,57]. The LCOE is defined as the selling price of electricity required to achieve the economic break-even of the project [58]. Additionally, the LCOE is a standard metric used for analyzing power generation projects and represents the ratio of total lifetime costs and total lifetime energy production [59]. The LCOE is also utilized to compare the economic viability of projects and facilitate the decision-making process of policymakers, businesses, and other

Table 1
Exclusion criteria applied.

	Criterion	Distance (m)	Reference
(1)	Power transmission lines	120	Open Street Map [35]
(2)	Roads	100	Open Street Map
(3)	Railways	100	Open Street Map
(4)	Airports	5000	Corine Land Cover [36]
(5)	Urban areas	500	Corine Land Cover
(6)	Industrial areas	500	Corine Land Cover
(7)	Lakes	0	Corine Land Cover
(8)	River and streams	0	Corine Land Cover
(9)	Marine waters	0	Corine Land Cover
(10)	Bird protection areas	200	Natura2000 [37,38]
(11)	Flora, fauna, and habitat-protected areas	300	Natura2000
(12)	Designated areas of national and international importance	300	CDDA [54]
(13)	Mixed forests	0	Corine Land Cover
(14)	Deciduous forest	0	Corine Land Cover
(15)	Coniferous forests	0	Corine Land Cover
(16)	Elevations above 2000 m	0	EuroDEM [39]
(17)	Slopes above 30°	0	EuroDEM
(18)	Mineral extraction sites, dump sites, construction sites	0	Corine Land Cover
(19)	Non-irrigated arable land	0	Corine Land Cover
(20)	Permanently irrigated land	0	Corine Land Cover

stakeholders [60].

Considering the above, the present study aims to analyze the LCOE of utility-scale solar PV systems by utilizing the land eligibility results obtained from the first module of the SILICON model (described in Section 2.1.1). Unlike previous studies that have estimated the LCOE of a particular region based only on the assessment of resource potential, this study integrates an innovative approach that addresses the problem of country-dependent cost elements by breaking down the lifetime cost of production into installation, soft and hardware costs. This approach allows for the incorporation of different parameter settings for utility-scale solar investments in a specific region or country, enabling the comparison of the competitiveness of such installations with a high spatial resolution (100 m). Consequently, the computational method developed in this paper accounts for the variation in the levelized cost of electricity due to labor-related costs like PV system installation, mechanical and electrical installation, and other expenditures.

The calculations of the LCOE for utility-scale solar systems rely on the approach developed by Lugo-Laguna et al. [61], which allows for the allocation of labor-related costs linked to site inspection, type of solar tracking system technology, electrical and mechanical installation, to the levelized cost of electricity. As indicated in Eq. (1), the LCOE of a project is composed of two cost components: capital expenditures (CAPEX) and operational expenditures (OPEX). These two components are known to differ substantially over the world due to economic, demographic, and technological factors [62].

$$\mathrm{LCOE} = \frac{CAPEX + OPEX}{Lifetime\ Energy\ Production} \tag{1}$$

Although various studies have indicated that solar PV is one of the most cost-competitive renewable technologies commercially, capital expenditures in utility-scale solar installations exhibit significant variations [63]. Some of these variations have been attributed to PV cell and panel production costs [64] and the manufacturing costs of inverters [61]. However, a substantial share of the cost variation in solar PV projects is also due to changes in installation and soft costs [61].

In Eq. (2), capital expenditures are decomposed into (a) hardware costs (H) (which include modules, inverters, racking and mounting, cabling/wiring, safety and security, monitoring and control installation costs), (b) soft costs (SC) (which include margin, financing costs, system design, permitting, incentive application, customer acquisition costs), (c) installation costs (I_0) (which include mechanical installation, electrical installation, and inspection costs) [63]. Taking into account that hardware costs often account for 66% of the total CAPEX [65], in Eq. (2), soft development and installation costs are expressed as a function of hardware costs and the Capital Recovery Factor (*CRF*).

The annual operation expenditures of the project are defined as a fraction of the installation costs, as shown in Eq. (3), where θ is the fraction that represents the yearly operating and maintenance costs and I_0 stands for the installation costs [61].

$$CAPEX = H + SC + I_0 = \left(H + \frac{1}{2}H\right) \times CRF \tag{2}$$

$$OPEX = \theta \times I_0 \tag{3}$$

The Capital Recovery Factor (*CRF*) is a common economic metric for estimating the recovery of capital as a series of payments. The *CRF*, given by Eq. (4), is used to convert capital expenses into a series of annual payments [66], where i stands for the discount rate, and N is the investment period or lifetime of the project.

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{4}$$

Subsequently, the levelized cost of electricity for a utility-scale PV system can be expressed as a function of hardware costs and installation costs, as shown in Eq. (5), where H stands for hardware costs, *CRF* is the capital recovery factor, I_0 stands for the installation costs, and θ is the fraction that represents the yearly operating and maintenance costs.

It is important to note that the concept of the levelized cost of electricity is widely used to evaluate and compare the economic feasibility of investments in power systems and assess the cost effectiveness of different energy sources and technologies. It reflects the "minimum price at which energy must be sold for an energy project to break even" [67,68]. In utility-scale PV projects, the LCOE typically excludes factors such as land costs, tax reliefs, and other parameters related to the local context. This aspect is particularly important for utility-scale PV projects because investors often do not own the land where the installations are situated. Instead, they lease the land, creating a complex ownership structure with a lack of uniform accounting standards. This complex ownership structure makes it challenging to directly factor these costs into the LCOE and compare them across projects or regions [69]. Consequently, the inclusion of these parameters into the LCOE is typically done for specific investments with available ownership and cost data, rather than for evaluating the overall capacity and generation potential of a region of interest [70].

$$LCOE = \frac{\left(H + \frac{1}{2}H\right) \times CRF + I_0 \times \theta}{Yearly\ Energy\ Production} \tag{5}$$

The long-term yearly power potential of a generic 1 kW-peak grid photovoltaic system with crystalline silicon modules optimally titled towards the equator was estimated using Eq. (6). In the present study, the solar resource and photovoltaic power potential were estimated using the data layer developed by the company Solargis s.r.o. on behalf of the World Bank Group [71].

$$Longterm\ yearly\ PV\ power\ potential = Longterm\ average\ of\ daily\ totals \times 365.25 \tag{6}$$

The proposed computational framework has a wide range of applications and can be adapted to examine and assess various geographical areas. As previously indicated, the method comprises two key components. The first component entails a land eligibility analysis using a GIS-based tool, whereas the second component focuses on the techno-economic analysis of electricity generation in utility-scale solar PV systems. The universality and versatility of the first component stems from its reliance on publicly available datasets, which are detailed in Tables 1 and 2. This allows for customization when applying the method to different case studies. Consequently, researchers and practitioners interested in utilizing the method in other regions can adjust or replace the vector datasets, raster datasets and exclusion criteria to better align with the local context, resources, and policies.

The second component, which focuses on the techno-economic assessment of utility-scale solar PV systems, relies on established financial concepts, such as capital investment costs, operational and maintenance costs, and the levelized cost of electricity. These concepts are widely used in academic studies and analyses conducted by governmental and intergovernmental organizations. They can be transformed into formulas that are adaptable to various case studies by modifying factors like investment and operational costs, interest rates, and capacity factors to align with local conditions. It is important to note that this study does not take into account land costs, lease costs, tax reliefs, and other local parameters. This exclusion is made to maintain the universality of the proposed method and facilitate the comparative analysis across the administrative divisions of the investigated area.

Table 2
Techno-economic parameters adopted in the study.

Parameter	H[€/kW]	N[yrs]	i[%]	θ [%]
Value	545.6	25	5.92	1.0
Reference	[63]	[69]	[61]	[61]

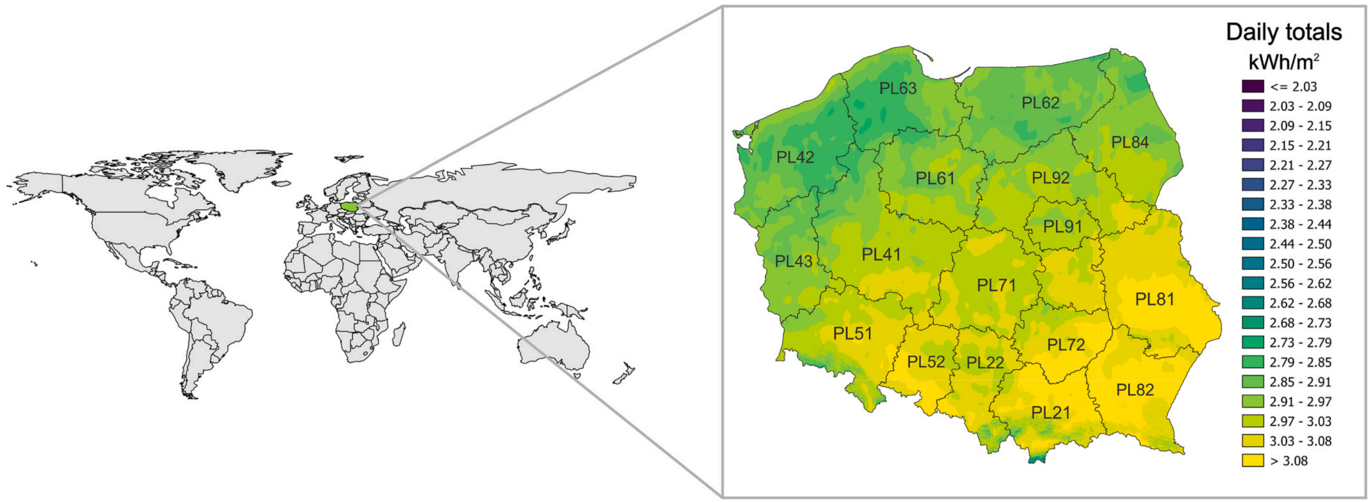

Fig. 3. Global Horizontal Irradiation in Poland. Map data from [71].

The computations were executed on the Ares supercomputer hosted at the Academic Computer Centre Cyfronet AGH. The Ares supercomputer is one of the fastest high-performance computing (HPC) clusters in Poland, with a peak performance of 3.51 PFlops, 37,824 computing cores, and 147.7 TB of RAM [72]. The execution times on multiple worker nodes ranged from 900 s to 3600 s, depending on the exclusion criteria applied, spatial resolution, and size of the NUTS-2 region.

3. Case study

The applicability of the method is demonstrated through the case study of Poland, situated in Central Europe, as shown in Fig. 3. Depending on the region, the country experiences a daily total global horizontal irradiation ranging from 2.03 to 3.08 kWh/m^2 [73]. Based on data spanning over 40 years, the average yearly irradiation ranges from 1017 to 1124 kWh/m^2, with a significant difference between southern and northern regions [74]. The highest solar potential is observed in the southern regions, while this potential gradually decreases towards the north. According to the Köppen-Geiger-Photovoltaic climate classification system, Poland is categorized under the Cfb class, which denotes a warm temperate climate (C) that is fully humid (f) with warm summers (b) [75]. It is important to note that in previous years, Poland was classified as having a warm summer humid continental climate (Dfb). However, due to climate changes, the primary climate is now classified as warm temperate instead of continental [76,77].

Poland serves as an example to examine the viability of utility-scale photovoltaics in areas with average insolation and historical reliance on fossil fuels, where solar PV systems would play a key role in the energy transition towards the zero-emission power system in the long term [78]. Currently, nearly 75% of the total installed photovoltaic capacity comprises small-scale systems or rooftop micro-installation. Nonetheless, the Polish PV market is expected to shift from micro-installations to utility-scale systems in the upcoming years [79]. As a result, there is a need for advanced tools and comprehensive technical analyses that focus on land eligibility and the spatial distribution of solar energy installations, which can assist in decision-making processes at governmental and intergovernmental levels.

The evolution of solar photovoltaic capacity in Poland is shown in Fig. 4. Substantial growth in solar PV capacity has been observed in the last four years, reaching over 11 GW and accounting for approximately 18% of the country's total installed capacity [80]. In 2022, it was estimated that nearly 8.2 GW corresponds to small-scale installations, which accounts for 75% of the total solar power capacity [81]. This significant increase in small-scale installations has been primarily driven by the governmental support mechanism "My Electricity" and tax reliefs offered to private owners of PV systems. Another crucial support mechanism for larger PV investments has been the Renewable Energy Source (RES) auctions, which establish reference prices of electricity for

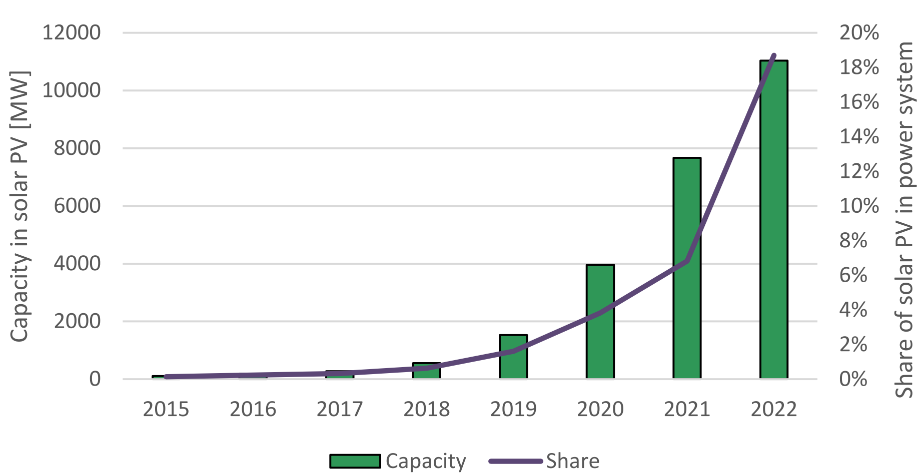

Fig. 4. Capacity of solar PV installations in Poland and their share in the power system.
Based on: ARE (2015–2022) [81].

upcoming years. Under this system, auctions are held for each source individually, with separate auctions conducted for capacities below and above 1 MW. The current reference prices were set at around $90/MWh for solar PV installations below 1 MW and at $85/MWh for others. Note that in recent years, the auctions have cleared at higher prices than the average wholesale electricity sold in the day-ahead market. The installation capacity that benefited from this mechanism was 5329 MW as of 2021 [82].

These incentives have provided additional funding and accelerated the development of the local photovoltaic market, surpassing the policy objectives set by 2040. The Polish Energy Policy projects a rise in solar capacity to 5.1 GW by 2035 and 9.8 GW by 2040 [83], which was already achieved in 2021 and 2022, respectively.

Poland is also one of the largest providers of solar photovoltaic employment in Europe. In 2021, the solar sector provided 113,000 jobs, which accounted for 24% of all solar jobs in the European Union [84]. Over 90% of these jobs came from small-scale rooftop installations built within the abovementioned support mechanisms. In the coming years, Poland is expected to maintain its position among European PV market leaders through jobs provided by utility-scale PV systems. However, the share of jobs in rooftop installations is expected to decrease by around 45% in 2026 [84].

Globally, the average levelized cost of electricity generated from solar PV installations was around $0.048/kWh in 2021, with the 5th and 95th percentiles of all projects ranging from $0.029 to $0.120/kWh [63]. Recent studies in Poland indicate that the levelized cost of electricity produced by small-scale solar photovoltaic systems varies from €0.14–0.18/kWh [85], which ranks Poland among the countries with the highest levelized cost of electricity from solar PV. Due to the early development stage of utility-scale installation in Poland, accurate and available data about the levelized costs of electricity in those facilities are not yet publicly available. However, a study analyzing the case of Germany, which experiences comparable insolation levels, revealed that the levelized cost of electricity of solar PV utility-scale systems ranged from around €0.03 to €0.06/kWh [86].

In this context, the data employed to estimate the LCOE of utility-scale PV installations in Poland were acquired from multiple sources (Table 2). Hardware costs (H) of the systems were assumed to be €545.6/kW. These costs were calculated using the detailed breakdown of utility-scale solar PV installed costs reported for Poland in [63] and the average cost difference between fixed-tilt and one-axis tracking on ground-mounted racking systems (approximately 8.4%) reported by the U.S. National Renewable Energy Laboratory (NREL) [9]. The detailed breakdown of installed costs and cost difference between racking systems can be found in Tables A1-A2, presented in Appendix A. The discount rate (i) was set at 5.92% based on the estimates reported for Poland in [61,87]. A conservative lifetime expectation (N) of twenty-five years was adopted, taking into account the results from a survey of U.S. Solar industry professionals [69]. Additionally, the fraction that represents the yearly operating and maintenance costs (θ) was set at 1%, based on a recent study focused on solar energy costs in over twenty European Countries [61].

4. Results

This section provides an overview of the outcomes obtained using the proposed computational method for conducting a geospatial assessment of utility-scale photovoltaic installations in Poland. First, the section shows the results of the land eligibility assessment at the national and NUTS-2 level. Second, it describes the country's installable capacity and solar energy potential while accounting for different land use efficiency factors. Finally, it compares the levelized cost of electricity of utility-scale solar systems throughout the seventeen Polish NUTS-2 regions.

4.1. Land eligibility for utility-scale photovoltaic systems

The utilization of the SILICON model, which integrates twenty exclusion constraints (detailed in Section 2), facilitates the computation and derivation of the land eligibility outcomes for utility-scale PV installations in Poland. These calculations were executed at a spatial resolution of 100 m across the seventeen Polish NUTS-2 regions (the names of regions are listed in Appendix C). The computations were carried out iteratively, using raster datasets obtained from overlaying land exclusion constraints. Figs. 5a-h illustrate the results, which vary depending on the specific land exclusion criteria applied.

Firstly, power lines and other transmission elements were excluded, which resulted in 4.33% of the total territory being ineligible for utility-scale PV systems (Fig. 5a). These outcomes are consistent with the locations of electricity transmission and distribution lines, power plants, and heating power plants. The most significant exclusions are in regions PL22 and PL51, where the largest number of power grid components and elements are situated. Secondly, areas with elevations above 2000 m and slopes above 30° were designated as unsuitable. This, combined with the power lines and other transmission elements, increased the ineligible land to 4.73% (Fig. 5b). This step primarily excluded the southern part of the country, where mountainous terrain is prevalent. Thirdly, continuous and discontinuous urban fabrics were set as ineligible areas, resulting in 27.75% of the land being excluded (Fig. 5c). This exclusion is particularly pronounced around major urban centers, where the availability of space for utility-scale solar PV systems diminishes significantly. Fourthly, constraints associated with commercial areas, industrial zones, port areas, dump sites, construction sites, sport and leisure facilities, green urban areas, and buffer distances to roads, rails, and airports were employed. This expanded the total ineligible area in Poland to 30.49% (Fig. 5d). The exclusions of these areas resulted in the removal of urban centers as viable locations for the potential deployment of utility-scale solar PV installations.

In the subsequent step, regions characterized by broad-leaved, coniferous, and mixed forests were designated as ineligible, resulting in the exclusion of 72.84% of the total land (Fig. 5e). It is important to emphasize that the exclusions of forested areas represent the most substantial reduction in potential sites for utility-scale PV installations. These findings arise from the extensive coverage of forested regions in Poland, a characteristic influenced by the climatic conditions of the country. When water courses, water bodies, coastal lagoons, estuaries, sea, non-irrigated arable land, and permanently irrigated land are excluded, 93.34% of the total land is classified as ineligible (Fig. 5f). These exclusions further reduce the available land for utility-scale solar PV systems, primarily due to the considerable presence of water bodies in Poland. Constraints related to bird and habitat-protected areas increase excluded land to 95.00% (Fig. 5g). This environmental constraint is of paramount importance, given that environmental clearance is often not granted in regions inhabited by protected species. Lastly, the areas of national and international importance designated by the European Environment Agency result in the exclusion of 96.39% of the land (Fig. 5h).

As a result, only 3.61% of the total area is eligible for the potential deployment of utility-scale PV systems, equivalent to 11,277.70 km^2 (please refer to Table B.1 in Appendix B for detailed outcomes of each NUTS-2 region). These outcomes are consistent with the findings of Ryberg et al. [34], who investigated the land eligibility of pan-European countries. Note that Ryberg et al. estimated the total available land for open-field PV in Poland at 11,478 km^2 but did not provide specific land eligibility values at the NUTS-2 level. This represents a 1.75% difference between the results in this study and those reported by Ryberg et al. In contrast, the computations performed using the SILICON model provide detailed results at both the national and administrative subdivision levels.

Figs. 6 and 7 present the area of land available and excluded in each NUTS-2 region (the detailed model outcomes are provided in Table B.2

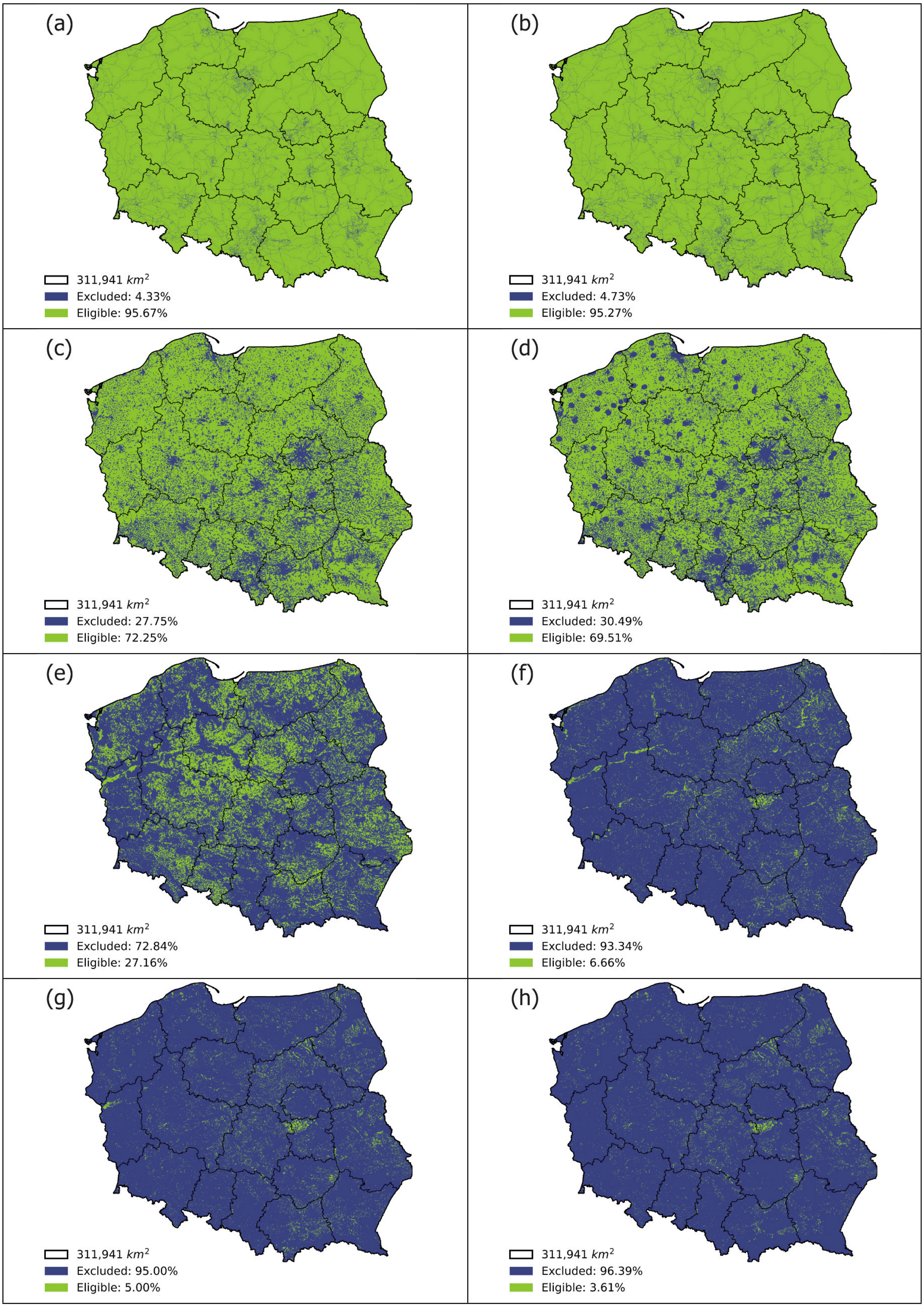

Fig. 5. Land available for solar photovoltaic installations in Poland.

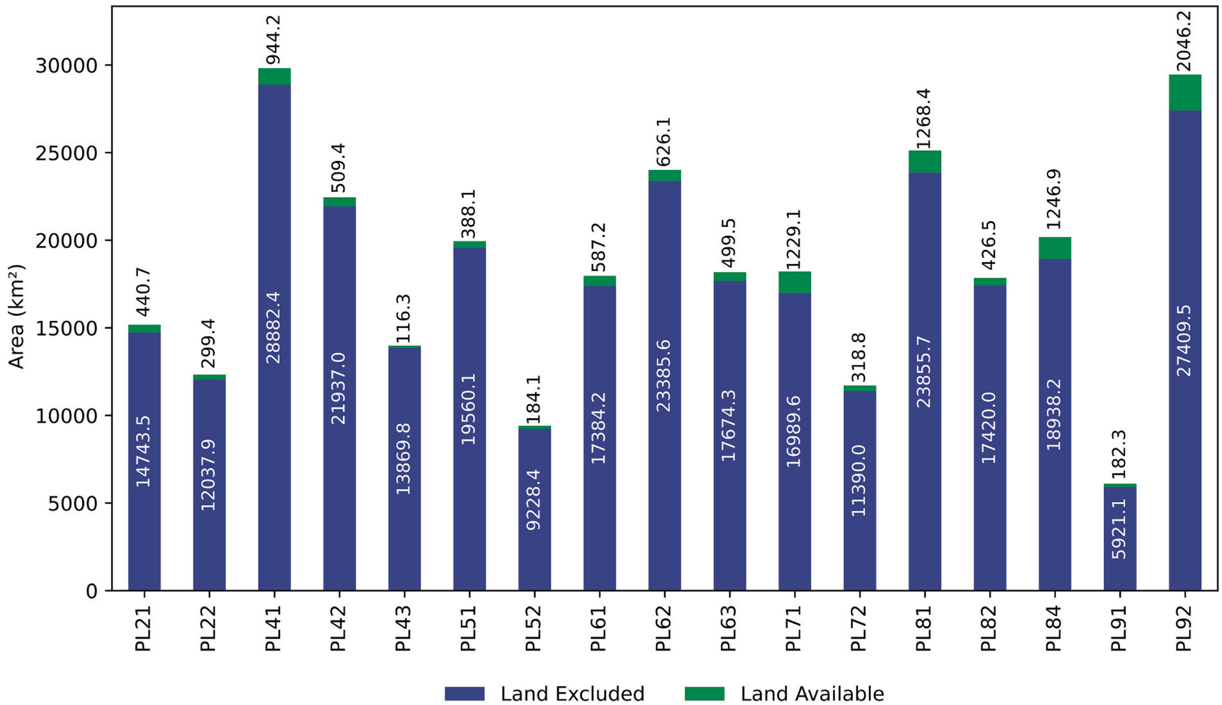

Fig. 6. Area of land available and excluded in each NUTS-2 region in Poland.

in Appendix B). The results show that more than half of the eligible land is concentrated in four regions. The largest available land is in PL92, covering 2046.2 km^2, which represents 6.95% of the total region area and approximately 18.1% of all eligible land in Poland. The NUTS-2 regions PL71, PL81, and PL84 each have around 1200 km^2 of land eligible for solar utility-scale installations, constituting approximately around 11% of the total available land in the country. In terms of each region's area, the eligible land areas make up 6.75%, 6.18%, and 5.05% in PL71, PL84, and PL81, respectively. Despite the southern regions having the highest global horizontal irradiation, the results indicate that the most favorable areas, considering land constraints, are primarily located in the central and western parts of the country. This is due to significant exclusions in the south, associated with the presence of mountains and forests.

4.2. Installable potential of utility-scale solar PV

In addition to investigating the different aspects of land eligibility limitations in Poland, this study also estimates the installable capacity and electricity generation potential of utility-scale solar photovoltaics in

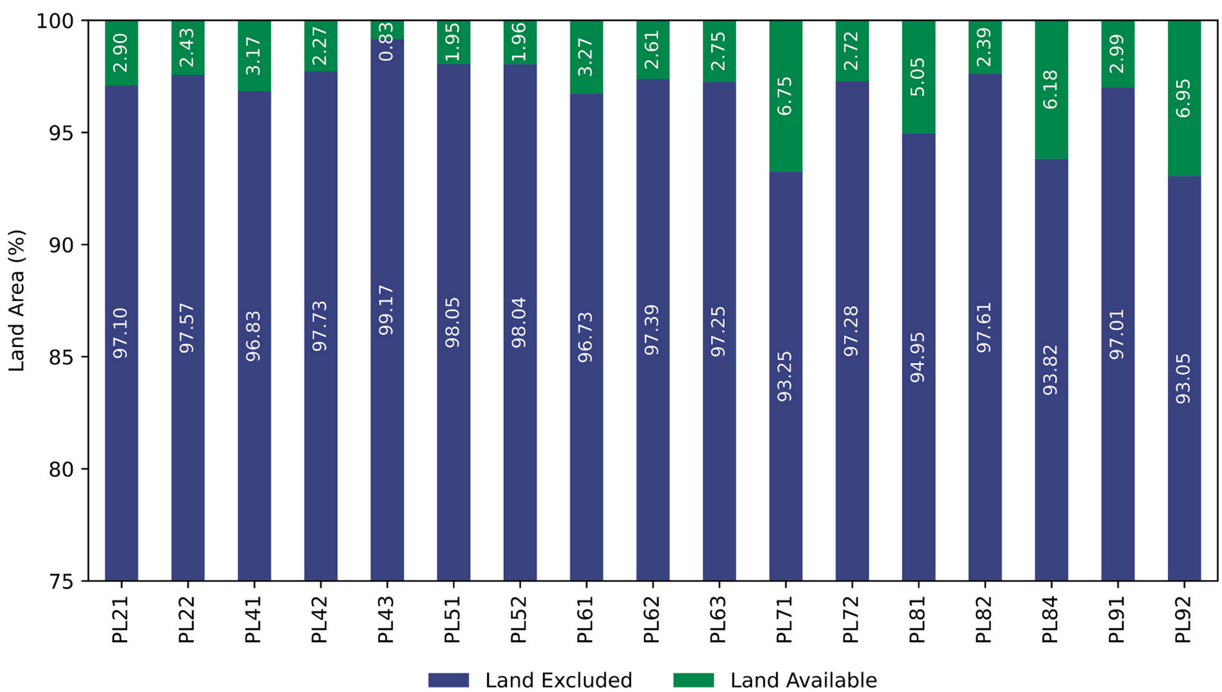

Fig. 7. Percentage of land available and excluded in each NUTS-2 region in Poland.

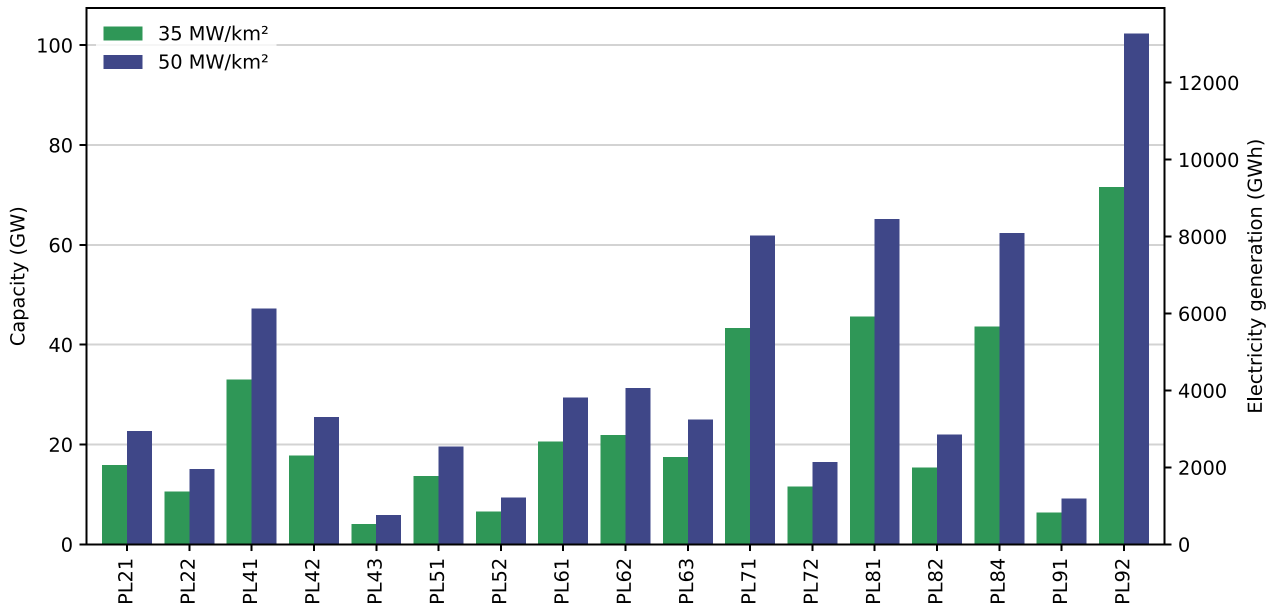

Fig. 8. Capacity and electricity generation potential of utility-scale solar photovoltaic systems in Poland.

Poland. To do this, two factors of land use efficiency were adopted. First, the study examined the land-use efficiency of 35 MW per square kilometer, which is a conservative assumption for practical implementation and corresponds to the 95th percentile of the global average land-use efficiency of utility-scale photovoltaic systems [63,88]. Second, the analysis assumed an increase in land use efficiency to 50 MW per square kilometer [89]. This value reflects the average land-use efficiency of existing and ongoing utility-scale PV installations in Poland [90–92] and is close to the global average land use reported in the literature [63].

The potential installable capacity of utility-scale solar PV systems across the entire country ranges from 394.64 to 563.77 GW, depending on the land use efficiency factor employed in the calculations. Taking into account the capacity factors and technical characteristics of PV installations, these values can be translated into 51.4 to 73.4 TWh/year. Fig. 8 shows the potential installable capacity and electricity generation for each region. Of the total installable capacity in the country, 51.35% can be allocated to four central-western regions (PL71, PL81, PL84, and PL92), of which almost 20% is located in one region (PL92). Even in the region with the smallest area of land available (PL43), the potential installable capacity ranges from 4.07 to 5.82 GW, which translates to 0.52–0.74 TWh of renewable electricity, depending on the land use efficiency factor.

Cameron and van der Zwaan investigated the employment factors for solar energy technologies and indicated that the number of jobs created from operation and maintenance costs in solar photovoltaic installations ranges from 0.1 to 1.65 jobs/MW, with an average number of 0.3 jobs/MW [93]. When these values are taken into account, the development of utility-scale solar systems could create approximately 118,416 to

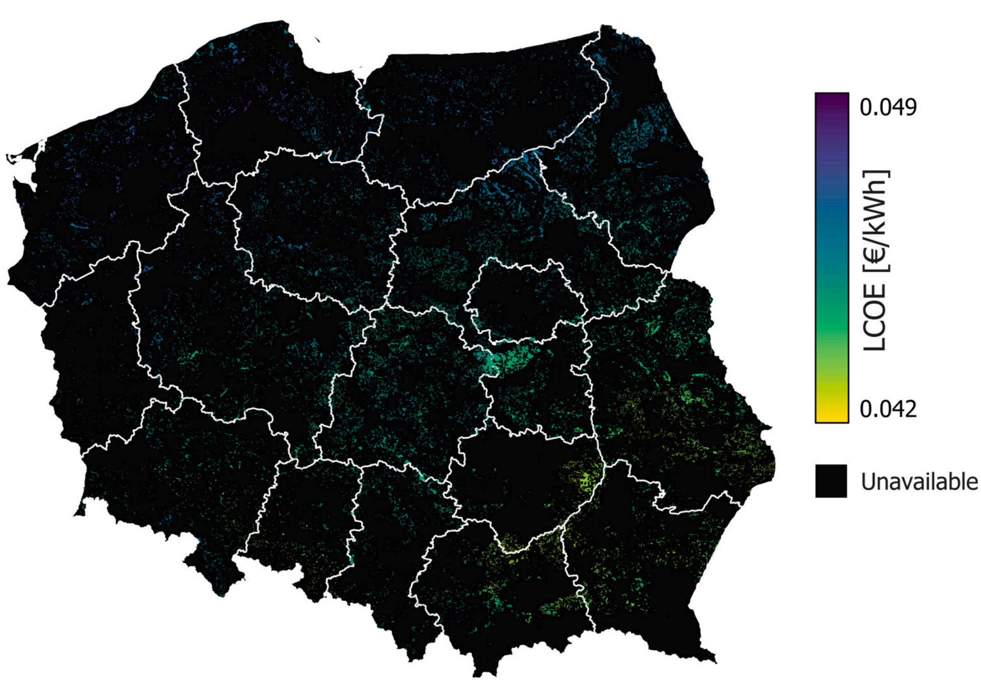

Fig. 9. LCOE for utility-scale solar photovoltaic installations in Poland.

169,167 jobs in Poland. The region with the greatest potential for job creation is PL92, where employment associated with utility-scale solar installations may amount to 21,486–30,693 jobs.

4.3. Levelized cost of electricity

In addition to assessing the capacity and electricity generation potential of solar PV systems, the SILICON model allows for the computation of the levelized cost of electricity in each cell representing the area with a resolution of 100 m within the analyzed country or region. The formulas given in Section 2.1.2 incorporate various techno-economic parameters that aid in analyzing the levelized cost of electricity generated by utility-scale solar PV installations. The LCOE is calculated by considering capital (CAPEX) and operating (OPEX) expenditures, as well as the long-term yearly power potential of a cell eligible for the deployment of utility-scale PV systems. By leveraging widely accepted financial concepts, the SILICON model can be adapted for application in diverse countries and regions.

The developed model was applied to a case study focused on Poland. The results, depicted in Fig. 9, indicate that the LCOE is higher in the northern regions and gradually decreases in the southern areas of Poland. This observed pattern aligns with the distribution of solar resources and the corresponding fluctuations in renewable capacity factors across the country.

The LCOE values range from €0.043/kWh to €0.049/kWh, which are comparable to those found in previous studies. Out of the seventeen NUTS-2 regions that were analyzed, the lowest LCOE values are observed in seven regions: PL21, PL22, PL51, PL52, PL72, PL81, and PL82.

According to the International Renewable Energy Agency (IRENA), the global weighted average LCOE of utility-scale solar PV projects is $0.048/kWh, with the 5th percentile at $0.029/kWh and the 95th percentile at $0.120/kWh. However, it is expected that the LCOE will decrease to $0.02–0.08/kWh by 2030, depending on the isolation and geographic position of the system [94]. Considering Poland's insolation and location in the northern hemisphere, the LCOE throughout the country (€0.043–0.049/kWh) falls within reasonable ranges with countries that experience similar levels of insolation. However, the recent decrease in investment costs has led to a global reduction in the LCOE, which is taken into account in this study and reflected in the slightly lower LCOE values.

Furthermore, the results of this study are consistent with the levelized cost of electricity of utility-scale photovoltaic systems in Germany ($0.031 to $0.057/kWh) —which received comparable levels of solar insolation [63]. Kost et al. [86] estimated that the LCOE of utility-scale PV installations is less than €0.06/kWh in northern Germany and below €0.045/kWh in the southern part of the country.

Fig. 10 displays the ranges of the LCOE in each NUTS-2 region of Poland. The results are presented in the form of boxplots, which provide information on the minimum, maximum, median, first, and third quartiles of the LCOE. Crucial insight can be derived from the median, first, and third quartiles of the LCOE values. The median values range from €0.043/kWh in PL72 to €0.047/kWh in PL42, with an average of €0.045/kWh. The first quartile of the LCOE ranges from €0.043/kWh to €0.046/kWh, while the third quartile ranges from €0.044/kWh to €0.047/kWh. It is worth noting that the differences within the regions of Poland are minimal. This is consistent with the capacity factors observed at this latitude and geographical location.

The lowest values are observed in the southeastern part of the country, specifically PL21, PL72, PL81, and PL82. These results are consistent with the higher insolation in the aforementioned regions, resulting in higher capacity factors for utility-scale solar PV. Conversely, the highest LCOE values are observed in PL42 and PL63, corresponding to the northwestern part of Poland, where the insolation is the lowest.

Although the ranges between the regions vary, the difference between the maximum and minimum LCOE values is only €0.006/kWh.

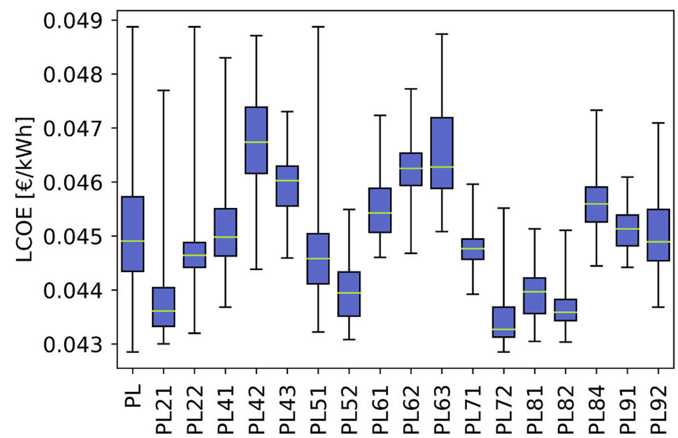

Fig. 10. Boxplot of LCOE values for utility-scale solar photovoltaic installations in NUTS-2 regions in Poland.

Therefore, taking into account the marginal difference in the LCOE, it is advisable that land exclusion criteria and cost of financing should be prioritized during the planning and investment decision-making processes of utility-scale photovoltaic systems in Poland.

Fig. 11 presents a histogram that shows the range of LCOE values for utility-scale solar photovoltaic installations in Poland. The histogram provides a visual representation of the dispersion of the LCOE values across the country. As previously mentioned, the levelized cost of electricity can differ significantly by region, spanning from €0.042 to €0.049/kWh. The tails of the distribution are thin, suggesting that the values are concentrated around the mode. Most observations cluster within the €0.044–0.045/kWh range, indicating that in regions with suitable land for utility-scale solar, one may generally expect these levels of LCOE. Moreover, the shape and skewness of the histogram suggest relatively low variability in the plausible values of the LCOE across all seventeen NUTS-2 regions.

5. Conclusions

This paper addresses the significant problem of spatio-temporal land use and cost distribution of solar technologies. It proposes an innovative method for analyzing land eligibility and conducting techno-economic assessments of utility-scale photovoltaic systems. The effectiveness of the method was tested through the geospatial analysis of the Polish territory and its seventeen NUTS-2 regions, a country heavily reliant on coal. The method contributes to the literature by proposing a GIS-based model that accounts for variations in the levelized cost of electricity due to labor-related costs such as PV system installation, mechanical and

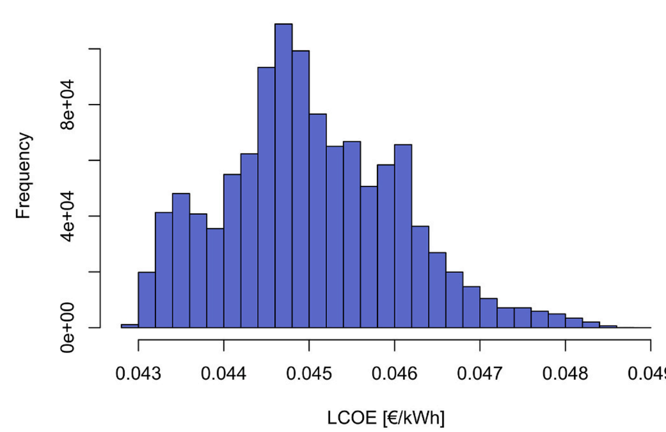

Fig. 11. Histogram of LCOE values for utility-scale solar photovoltaic installations in Poland.

electrical installation, and other expenditures.

The developed model was able to estimate that 3.61% of the total area of Poland is available for installing utility-scale solar PV systems, corresponding to 11,277.70 km^2. The deployment of PV installations in these areas would facilitate the achievement of solar capacities ranging from 394.64 to 563.77 GW, depending on the land use efficiency. By taking into account the irradiation in Poland and the technical parameters of current PV technologies, these capacities can be translated into 51.4–73.4 TWh of renewable electricity. Considering the electricity consumption in Poland, which was 174 TWh in 2021, utility-scale PV installation could cover a significant share of this demand. Furthermore, it was found that most of the suitable sites for the deployment of utility-scale PV systems are concentrated in four regions located in the central and western parts of Poland (Łódzkie (PL71), Lubelskie (PL81), Podlaskie (PL84), and Mazowiecki (PL92)). These regions account for more than 50% of the total capacity and electricity production potential. Additionally, region PL92 represents around 20% of the installable capacity potential. Consequently, investments in these four regions may substantially benefit the development of solar capacities and the fulfillment of Poland's renewable goals. This study is significant as it is the first that offers a comprehensive assessment of the installable capacity and electricity generation potential of utility-scale solar photovoltaics in the 17 Polish NUTS-2 regions, considering different land use efficiencies.

The results of this study indicate that the levelized cost of electricity in Poland ranges from €0.043/kWh (PL72) to €0.049/kWh (PL22), with a national average of €0.045/kWh. The highest values are observed in the northern regions, whereas the lowest are in the southern regions. The southern regions have the highest irradiation levels and capacity factors, which may enable utility-scale systems to achieve higher annual electricity production compared to regions located in the central and northern parts of the country. However, despite the lower cost, the southern regions exhibit lower land eligibility values than the central regions. Some paths for future research include assessing other renewable energy technologies in Poland and investigating the impact of large-scale battery energy storage on the competitiveness of renewable technologies.

Overall, this study provides an advancement towards the development of GIS-based tools for planning and modeling renewable energy systems. Although the approach was tested for the case of Poland, the computational method is versatile and could be used for the development of national and regional strategies focused on large-scale PV installations and to fulfill renewable energy goals at the lowest cost in other countries, regions, and locations.

Future research will aim to enhance the capabilities of this tool to facilitate the techno-economic assessment of rooftop utility-scale installations and wind farms. This will involve accommodating adjusted land constraints and integrating new geospatial datasets. Additionally, the GIS-based method is planned to support spatio-temporal analyses of potential green hydrogen installations.

This study primarily focuses on the evaluation and comparison of techno-economic aspects associated with utility-scale solar photovoltaic systems. However, it is important to acknowledge certain limitations. Firstly, the study does not take into account the variable land costs in specific geographic locations, tax reliefs schemes, and other factors closely tied to the local context. Consequently, a comprehensive understanding of the total costs of electricity generation in diverse regions may necessitate further analyses that incorporate all relevant cost components unique to some locations. Secondly, it is also worth noting that investment projects are susceptible to risks related to social acceptance. Therefore, for a more holistic assessment of solar PV potential, it is advisable to supplement the GIS-based tool employed in this study with decision-making methods such as the Analytic Hierarchy Process or similar techniques. These additional methods can provide valuable insights into the broader spectrum of factors influencing the deployment and sustainability of utility-scale solar PV projects.

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CRediT authorship contribution statement

Pablo Benalcazar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aleksandra Komorowska:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacek Kamiński:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The author declares no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.122044.

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