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Review

Towards a Renewable Energy Source Cadastre—A Review of Examples from around the World

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Abstract: In the age of the impending climate crisis, and further forecast ecological catastrophes, humankind has begun to think with growing interest about replacing existing energy sources with renewable ones. An increasing number of people have begun to discuss the need to implement registries that collect information about the energy potential of specific parts of the environment we live in. Additionally, the simultaneous registration of installations used for obtaining energy from alternative sources is desirable. In addition to quantitative attributes, such databases should also contain comprehensive spatial information. Since, in the era of globalization, the creation of such databases ought to be standardized, the purpose of this study is to indicate the directions in which the cadastre of renewable energy sources should be developed by: (i) reviewing the solutions of renewable energy sources that have been described in the scientific literature; (ii) analyzing the content of selected geoportals containing data on renewable energy sources. The literature review was preceded by a detailed bio-metric analysis, whereas the content analysis of the geoportals led to the creation of a flow chart containing a proposal for a renewable energy source cadastre, and a ranking of the analyzed portals. Nevertheless, the conceptual work was limited to the solar cadastre only.

Keywords: biomass; cadastre; database; energy potential; green energy; geoportal; geothermal; hydropower; map; renewable energy sources; solar; sun; waste heat; water; wind

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1. Introduction

Global trends, as well as climate and energy policy targets, influence the efforts of countries to promote renewable energy sources as an alternative to fossil energy. As part of the sustainable development strategy, in 2007, the European Union (EU) member states agreed on the following so-called "3 × 20", or "20-20-20", targets for 2020 [1]: (i) to reduce greenhouse gas emissions by 20% compared with 1990; (ii) obtain 20% of primary energy from renewable sources; and (iii) reduce primary energy demand by 20% through energy efficiency. The relevant regulations were enacted in 2009 and then amended in 2014. The change that took place caused the previously set values to be raised to the levels of 40%, 32% and 32.5%. They are expected to be achieved throughout the EU in 2030 [2]. In addition, in 2015, during the United Nations Conference in Paris, nearly 200 countries stood committed to reducing greenhouse gas emissions to limit global warming [3]. An obvious consequence of the above initiatives is the implementation of tools to achieve their goals and increase public awareness of the opportunities of renewable energy sources.

There is a growing interest in renewable energy source installations worldwide, both among individual households and in the public sector. In connection with that, and with the development of modern methods of acquiring and sharing spatial data, there are many opportunities to create databases related to alternative energy resources [4].

In 2010, it was pointed out that the lack of a complete real estate cadastre and urban spatial development plans, with which renewable energy installations could be located, could be an obstacle to the promotion of renewable energy sources (RES) and the obtainment of green energy [5]. Although the authors of this observation did not have in mind the construction of a separate cadastre of renewable energy sources, the conclusion posed by them can be treated as an introduction to consider it. Such a cadastre could be useful not only for determining the potential of renewable energy by monitoring environmental factors, but it could also help in the design of smart homes and constitute a real-time decision-making instrument for local, national or regional authorities and business entities [6]. It would also be extremely useful in the face of climate change, which is causing an increase in demand for the collection, management and use of reliable spatial information technologies to ensure the integrated sustainability of policies used to address environmental issues [7]. Creating such a cadastre could especially help the operation of cities with high degrees of energy consumption [8]. However, there is also a growing recognition for the need for broad changes in the energy sectors of entire countries [9–11].

Although the matter of registering already-constructed RES installations in public registers or indicating areas suitable for new RES installations is not yet common in the world, such analyses are increasingly performed, and their results are widely available. There are numerous maps or cadastres of renewable energy sources, which contain data on the location of RES installations, as well as the potential and opportunities for new installations. These are mainly studies dedicated to a selected source, but a few of them contain data on the potential for more than one source. Therefore, the aim of the following study is an indication of the directions in which the renewable energy source cadastres should be developed by (i) reviewing the solutions of renewable energy sources that have been described in the scientific literature and (ii) analyzing the content of selected geoportals containing data on renewable energy sources.

2. Materials and Methods

The present review of global renewable energy source cadastre (RES cadastre) solutions was carried out in four steps: (i) search of scientific databases; (ii) bibliometric analysis of retrieved scientific publications; (iii) literature review of the subject; (iv) analysis of functioning RES cadastres. These activities led to the determination of what information should be collected and made available within the RES cadastre and what functions should be provided by the spatial information infrastructure necessary to support it. A diagram of the research methodology is presented in Figure 1.

Figure 1. Scheme of the research methodology. Source: own study.

Data necessary for the bibliometric analysis and literature review were collected from the Web of Science Core Collection [12] and Scopus [13]. These databases were chosen because (i) they have excellent reputations in the scientific community for indexing high-quality peer-reviewed publications and (ii) they provide detailed information that enables researchers to receive accurate results, using a variety of bibliometric analysis software. In order to collect data for analysis, a query was entered into the Web of Science and Scopus search engines, consisting of phrases formed by pairing (each with each) keywords from two sets: (i) *renewable energy, renewable sources, green energy, solar, wind energy, biomass energy* and *water energy*; and (ii) *cadastral map*, *cadaster* and *cadastre*.

The elements of the sets were selected after many attempts of searching through databases with many different and sometimes complicated combinations of keywords. The first set consisted of the most popular words describing renewable energy sources. Introducing keywords related to geothermal, tidal, rain or waste, changed almost nothing in the results, and even if additional (single) publications appeared in the search results, they were in no way related to the RES cadastre. The second set consisted of the title *cadastre* and its synonyms.

Additionally, the search results were narrowed by document type. The Web of Science database excluded the correction-type document, whereas the Scopus database excluded the *conference review* and *errata* type.

The final Web of Science query looked as follows: *((((((((((((((((((((TS = (renewable energy cadastre)) OR TS = (renewable energy cadaster)) OR TS = (renewable energy cadastral map)) OR TS = (renewable sources cadastre)) OR TS = (renewable sources cadaster)) OR TS = (renewable sources cadastral map)) OR TS = (green energy cadastre)) OR TS = (green energy cadaster)) OR TS = (green energy cadastral map)) OR TS = (solar cadastre)) OR TS = (solar cadaster)) OR TS = (solar cadastral map)) OR TS = (wind energy cadastre)) OR TS = (wind energy cadaster)) OR TS = (wind energy cadastral map)) OR TS = (biomass energy cadastre)) OR TS = (biomass energy cadaster)) OR TS = (biomass energy cadastral map)) OR TS = (water energy cadastre)) OR TS = (water energy cadaster)) OR TS = (water energy cadastral map)) NOT DT = (Correction)*. The Scopus query was as follows: *(TITLE-ABS-KEY(renewable energy cadastre) OR TITLE-ABS-KEY(renewable energy cadaster) OR TITLE-ABS-KEY(renewable energy cadastral map) OR TITLE-ABS-KEY(renewable source cadastre) OR TITLE-ABS-KEY(renewable source cadaster) OR TITLE-ABS-KEY(renewable source cadastral map) OR TITLE-ABS-KEY(solar cadastre) OR TITLE-ABS-KEY(solar cadaster) OR TITLE-ABS-KEY(solar cadastral map) OR TITLE-ABS-KEY(green energy cadastre) OR TITLE-ABS-KEY(green energy cadaster) OR TITLE-ABS-KEY(green energy cadastral map) OR TITLE-ABS-KEY(wind energy cadastre) OR TITLE-ABS-KEY(wind energy cadaster) OR TITLE-ABS-KEY(wind energy cadastral map) OR TITLE-ABS-KEY(biomass energy cadastre) OR TITLE-ABS-KEY(biomass energy cadaster) OR TITLE-ABS-KEY(biomass energy cadastral map) OR TITLE-ABS-KEY(water energy cadastre) OR TITLE-ABS-KEY(water energy cadaster) OR TITLE-ABS-KEY(water energy cadastral map)) AND (EXCLUDE (DOCTYPE, "er")) AND (EXCLUDE (DOCTYPE, "cr"))*. Importantly, search engines in both databases treat phrases in brackets as a conjunction of all the words within them. However, they do not have to occur in the recorded order, or next to each other.

The 1 October 2021 search yielded 61 records from the Web of Science database and 82 from the Scopus database. The collections were not disjointed. A significant number of publications were indexed in both Web of Science and Scopus. However, about 20% of the publications indexed in the Web of Science were not available in Scopus, and about 40% of the publications indexed in Scopus could not be found in Web of Science. Therefore, we decided to analyze them separately, in terms of bibliometrics.

The bibliometric analysis consisted of two parts: (i) quantitative analysis of publications and their citations, and (ii) keyword analysis (links and time of appearance). The keyword analysis, similar to other researchers who based their reviews on Web of Science [14–17] and Scopus [18–21], was performed using the program VOSviewer [22].

The publications were not analyzed together until the actual literature review [23]. On this basis, using a simple Google search for web pages [24], the actual functioning and online available cadastres of renewable energy sources were searched. We then decided what parameters should be included in the RES cadastre and what functions should be provided by the infrastructure necessary to make these data available.

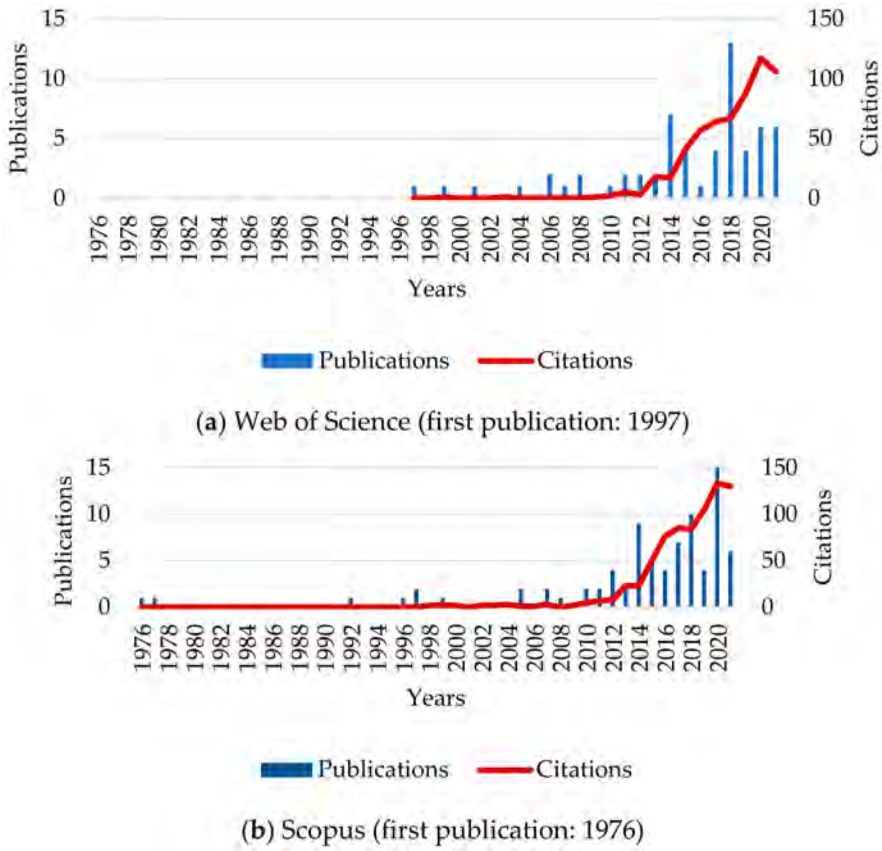
3. Results

Despite modest search results, we decided to carry out a separate bibliometric analysis of the datasets obtained from Web of Science and Scopus [25], and check whether only one of them could be used to obtain a satisfactory background for the research. The datasets were described together only during the literature review.

3.1. Quantitative Analysis

The quantitative analysis began by determining what kind of publications appeared, in which languages they were written, and which research areas they concerned. Thus, in the Web of Science database, there were articles (35), proceedings papers (22), review articles (4) and book chapters (1). They were published mainly in English (57), but there were also single articles in Croatian, Czech, Lithuanian and Spanish. These publications were most often assigned to research areas related to energy fuels, environmental sciences ecology and engineering. The Scopus database contained articles (47), conference papers (24), book chapters (6) and reviews (5). They were also published mainly in English (73), but there were also papers in German (5), Russian (2), Spanish (2) and Czech (1). Most were assigned to research areas such as energy, engineering and environmental science, but also to social sciences, or Earth and planetary sciences.

Afterwards, we checked how the number of publications on the cadastre of renewable energy sources had evolved in particular years, whether the publications evoked any reactions in the scientific community, and if they were cited by researchers dealing with similar topics. The first paper from the analyzed collections was published in 1976, and therefore this was considered as the beginning of the research period. This was an article indexed in the Scopus database. Graphs showing the number of publications and citations by Web of Science and Scopus are presented in Figure 2.



(**a**) Web of Science (first publication: 1997)

(**b**) Scopus (first publication: 1976)

Figure 2. Publications and citations over the years in (**a**) Web of Science; (**b**) Scopus. Source: own study.

As illustrated, the analyzed research topic has only become popular in the past decade. A significant increase in the number of publications on renewable energy cadastres occurred around 2014. Immediately afterwards, an intensification of citations of publications in this field began. However, not all of the papers were cited equally readily. Publications cited most frequently are presented in Table 1. Moreover, it should be noted that of all the papers found in Scopus, 56 were cited at least once in publications also indexed in this database.

In total, they were cited 749 times. The corresponding figures for Web of Science were 40 and 588. At the time of analysis, the h-index of publications was 13, in both databases.

Table 1. Most cited articles.

No.	Title	Year	Web of Science			Scopus		
			Location	Citation per Year	Citation	Location	Citation per Year	Citation
1	A high-resolution determination of the technical potential for residential-roof-mounted photovoltaic systems in Germany [26].	2014	1	7.25	58	3	7.63	61
2	Photovoltaic techno-economical potential on roofs in regions and islands: the case of the Canary Islands. Methodological review and methodology proposal [27].	2013	2	6.44	58	4	6.78	61
3	Smart microgrids as a solution for rural electrification: ensuring long-term sustainability through cadastre and business models [28].	2014	3	6.75	54	2	8.38	67
4	Solid waste as renewable source of energy: current and future possibility in Algeria [29].	2012	4	5.20	52	5	5.60	56
5	Spatio-temporal modeling of roof-top photovoltaic panels for improved technical potential assessment and electricity peak load offsetting at the municipal scale [30].	2015	5	7.00	49	1	10.14	71
6	The solar map as a knowledge base for solar energy use [31].	2014	6	5.63	45	6	6.25	50

Source: own study.

In addition to the most-cited publications, it is also worth mentioning those that may not have been cited as many times in other scientific texts because they were published relatively recently (Table 2). However, their number of citations per year was similar to the most-cited ones.

Table 2. New most-cited articles per year.

No.	Title	Year	Web of Science			Scopus		
			Location	Citation per Year	Citation	Location	Citation per Year	Citation
1	Solar energy potential assessment on rooftops and facades in large built environments based on LIDAR Data, Image Processing, and Cloud Computing. Methodological background, application, and validation in Geneva (Solar Cadaster) [32].	2018	8	5.50	22	10	6.50	26
2	A calculation method for the BIPV potential of Swiss facades at LOD2.5 in urban areas: a case from Ticino region [33].	2020	12	6.50	13	13	8.00	16
3	Multicriteria roof sorting for the integration of photovoltaic systems in urban environments [34].	2020	15	5.50	11	18	5.50	11

Source: own study.

The authors of the analyzed publications were mainly affiliated with institutions located in Western European countries. As shown in Table 3, they were mainly researchers from Germany, Italy, Spain and Switzerland.

Table 3. Countries where the most authors were affiliated.

Location	Web of Science (Number of Publications)	Scopus (Number of Publications)
1	Italy (10) Switzerland (10)	Germany (12) Italy (12)
2	Spain (8)	Spain (10) Switzerland (10)
3	France (6)	Russian Federation (7)
4	Czech Republic (5) Germany (5)	United States (6)
5	Austria (4) United States (4)	France (5)

Source: own study.

To summarize: (i) the most-cited publications were related to solar energy; (ii) the topic of cadastres related to renewable energy sources was of interest mainly among scientists from Europe, which may be related to the provisions of the EU Directive 2009/28/EC [35], which stipulated that by 2020, the share of renewable energy in total energy consumption in the European Union should be at least 20%; (iii) all the most-cited publications could be found in both the Web of Science and Scopus databases. The last partial conclusion can of course be reversed, and it can be stated that the publications were cited so readily because they were published in journals indexed in the two most highly regarded databases.

3.2. Keywords

The next step in the bibliometric analysis was keyword analysis. It was based on all the words with which the publications were described. This means that in addition to *Author Keywords*, *Keywords Plus* for publications from the Web of Science database and *Indexed Keywords* for publications from the Scopus database were used. *Keywords Plus* were determined by a special algorithm when an article was entered into Web of Science on the basis of its bibliography (references). *Indexed Keywords* were determined by the publication's publisher. They were standardized on the basis of publicly available dictionaries, and took into account synonyms, different spellings and plural forms.

Keyword analysis in VOSviewer involved creating a network of links between keywords. The aim was to show how often a word occurred in the analyzed set (frequency of occurrence was indicated by the size of the description of a point in the network) and how often the same pairs of words described publications (by means of links, but the strength of the link also influenced the size of the description of a point).

The authors of the publications found on Web of Science described them using 254 different keywords. After taking *Keywords Plus* into account, it transpired that the analysis could be based on 358 words. Due to the small number of analyzed words, we decided to build a network of words that occurred in at least two publications. There were 52 such words; therefore, in order to increase the network readability, 17 words with the lowest weight (depending on the number of occurrences of the word and the number of its connections with other keywords) were excluded from the analysis. Keywords excluded from the study were *barriers* (total link strength—5; occurrences—2), *information* (3; 5), *integration* (2; 5), *photogrammetry* (2; 5), *cadastre* (4; 4), *cloud computing* (2; 4), *energy efficiency* (4; 4), *energy management* (2; 4), *shadow casting* (2; 4), *spatial analysis* (2; 4), *solar* (2; 3), *solar potential* (2; 3), *citygml* (2; 2), *topography* (2; 2) and *waste management* (2; 1). The treatment did significantly affect the network, as the entries described in detail were mainly the indicators, tools and methods used in the analyzed papers. The final shape of the generated network is shown in Figure 3.

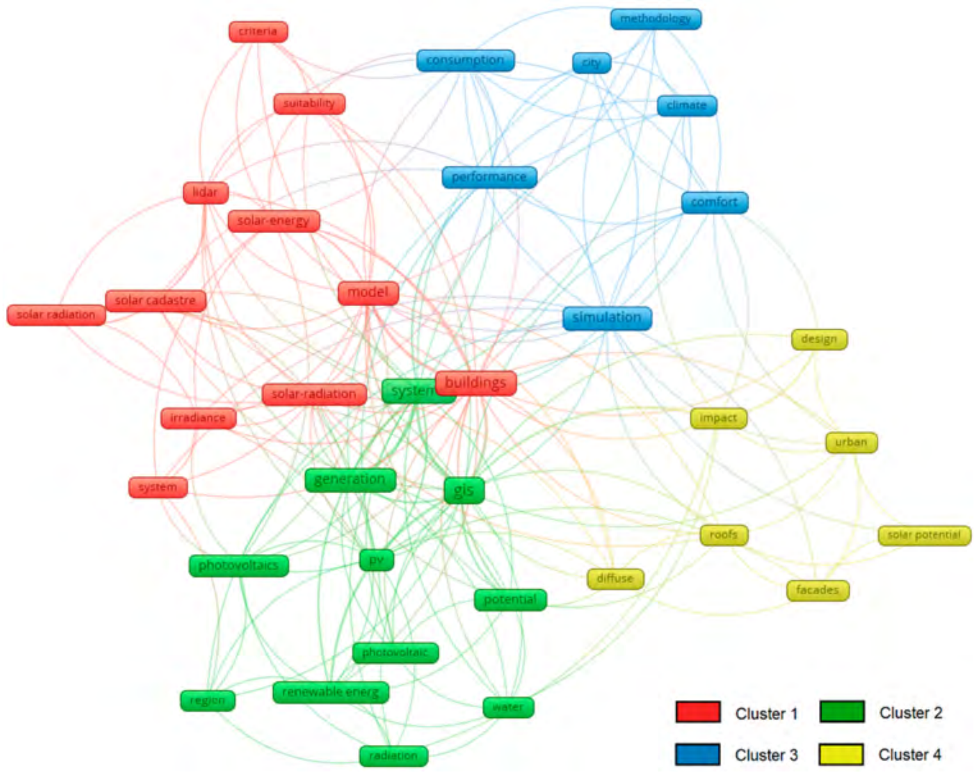


Figure 3. Keyword network from Web of Science. Source: own study.

The analyzed words were divided into four thematic clusters, which are color-coded in Figure 3. With the help of such a network of keywords, it is easy to point out the issues that are most often discussed in the literature on renewable energy sources in the Web of Science database: cluster 1—the development of a ***solar cadastre model***on ***buildings*** using ***LIDAR***; cluster 2—the development of a ***system***, also using ***GIS*** tools, to show the **potential of renewable energy** (generally **photovoltaic**); cluster 3—the **comfort** of life in a **city**; cluster 4—the **design** and use of **roofs** and **facades** in the **solar cadastre**. It is also clearly visible that the words forming cluster 1, i.e., *GIS* (total link strength—42; occurrences—13), *systems* (37; 7) and *buildings* (34; 6), have the highest weight in the generated network of keywords. This means that in the publications indexed in the Web of Science database, information on the construction of a solar cadastre using GIS tools was most frequently found.

In order to determine which topic appeared in the publications indexed on Web of Science the earliest, the generated keyword network was colored in such a way that individual keywords were marked depending on the average year of occurrence in the analyzed publications (Figure 4).

The words that appeared earliest were *climate* and *solar-radiation* (mid-2014). The ones cited currently, on the other hand, are *urban* (early 2021), *solar potential* and *system* (mid-2020), *solar-energy* and *facades* (early 2020).

Publications retrieved from the Scopus database were described with 288 words. However, the number of *Indexed Keywords* was so large compared with *Keywords Plus* that the analysis was based on 837 words. The size of the analyzed set resulted in the decision to build a network of words that occurred in at least four publications. There were 35 such words, all of which were used for further analyses, as the number was similar to the number of words used previously to create a keyword network from Web of Science (37). The generated network is shown in Figure 5.

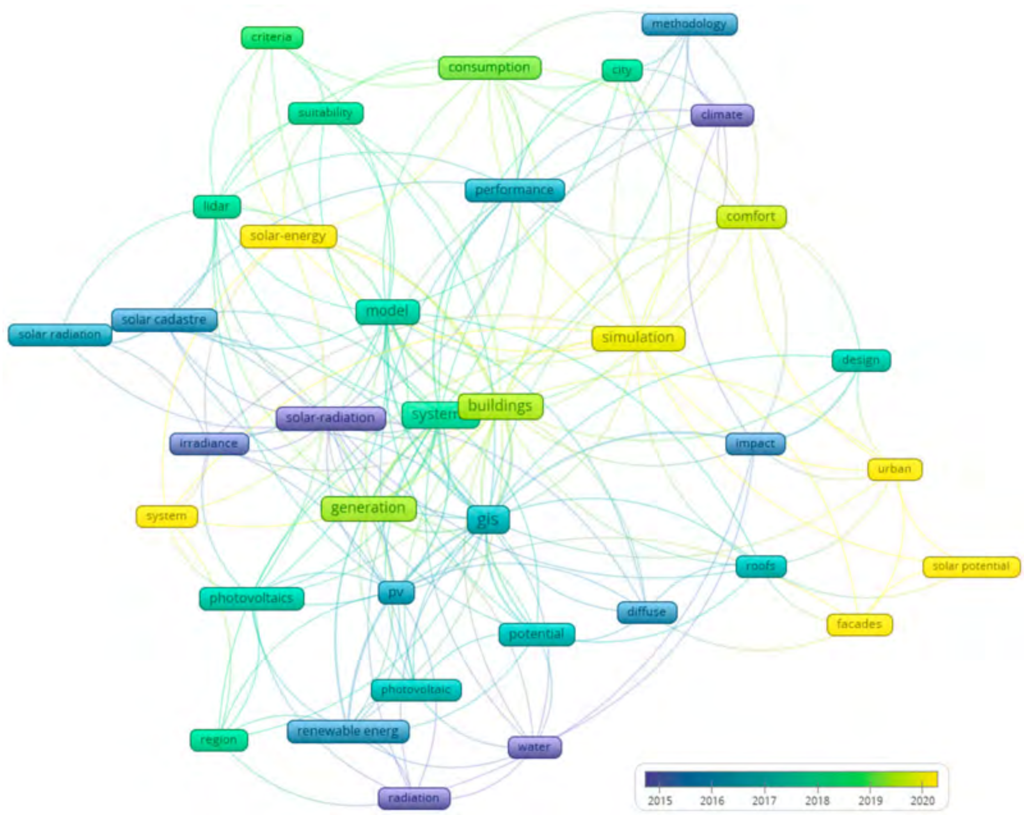


Figure 4. The average publication year of the documents from Web of Science in which a keyword occurs. Source: own study.

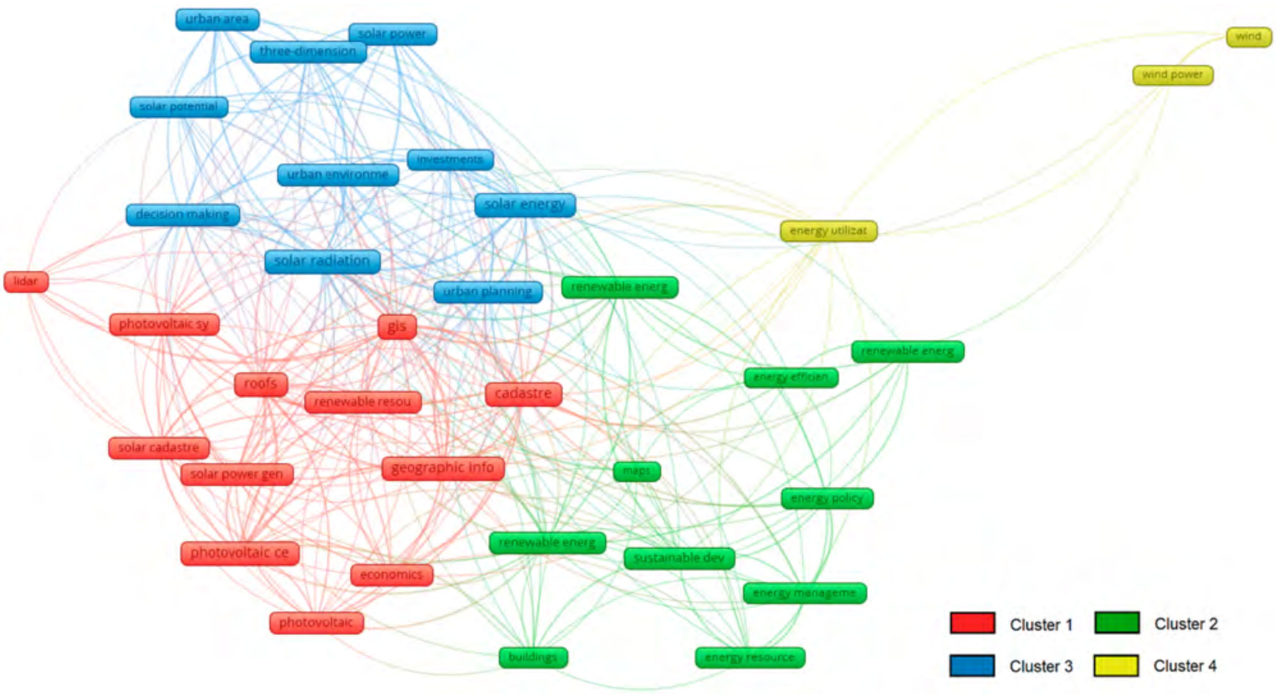


Figure 5. Keyword network from Scopus. Source: own study.

Similarly to the Web of Science keyword network, the words describing publications found in the Scopus database were divided into four thematic clusters, which are color-coded in Figure 5. With the help of such a network of keywords, it is easy to indicate the issues that are most often discussed in the literature on the cadastre of renewable energy sources, indexed in the Scopus database: cluster 1—***GIS*** tools for ***decision making*** related to ***solar power*** in ***urban planning***; cluster 2—**cadastre** for (**renewable**) **energy management**; cluster 3—use of **geographic information systems** for **solar cadastre** on **roofs**; cluster 4—**wind power**.

In the network generated from the Scopus database, it is more difficult to indicate which cluster had the greatest importance. The words *GIS* (total link strength—57; occurrences—13), *solar energy* (51; 13), *solar radiation* (48; 11), *cadastre* (46; 11) and *roofs* (46; 9) had the highest weight, but they were assigned to three different clusters. Additionally, it is noteworthy that the words *wind power* (total link strength—7; occurrences—8) and *wind* (5; 4), which have the least weight, were given a separate cluster.

The set of keywords from the Scopus database was also analyzed to determine the order of their appearance over time (Figure 6).

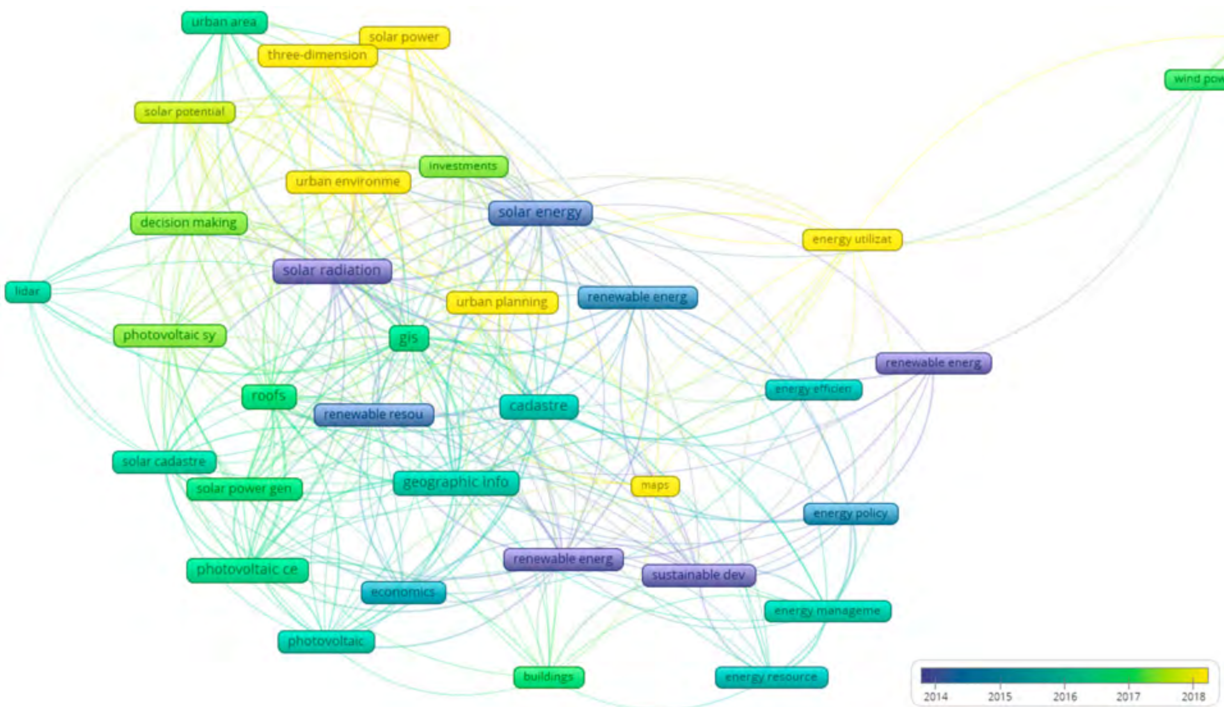


Figure 6. The average publication year of the documents from Scopus in which a keyword occurs. Source: own study.

In this case, the earliest keywords assigned as keywords were *renewable energy source* (second half of 2011) and *solar radiation* (mid-2012). The most recent keywords were *three-dimension* (mid-2018) and *wind* (early 2019).

Summarizing the keyword analysis, it can be stated that both databases mostly contained publications on solar cadastres. The articles mainly focused on (i) the use of solar energy in urban areas and (ii) the creation of tools to determine the solar potential of selected sites. Evolution of the topics over time could also be observed, which was generally in one direction in both databases—from interest in solar radiation as an energy source to 3D solar cadastres. However, in the Scopus database, much more information could be found. The network of keywords in the database was created on the basis of passwords which must have occurred in more articles, yet wind energy also appeared in it. This means that it is an important topic for the authors of the articles indexed in Scopus.

3.3. Review of the Literature

The bibliometric analysis showed that the scrutinized papers were mostly concerned with the solar cadastre. Therefore, we started the literature analysis with this. Then, we examined a wind cadastre, a biomass cadastre, a water-energy cadastre and a geo-thermal cadastre. We devoted a separate section to the description of each of these.

Importantly, most of the text in this section was based on publications indexed in Scopus. This is because only one important publication was actually published exclusively in Web of Science. It concerned the update of the solar cadastre in Geneva (Switzerland) [36].

3.3.1. Solar Cadastre

The main problem connected with the development of the solar cadastre is finding a fast but accurate method to calculate the global annual irradiance of each plane, taking into account its inclination and possible shading [37]. As mentioned earlier, the first publications on this topic indexed in Scopus or Web of Science date back to the 1970s. In the first [38], the basis for the development of a solar cadastre was presented. It was to be based on a mathematical model, which would make it possible to determine the production capacity of a photovoltaic installation of any design and justify the effectiveness and desirability of its application. However, the second publication [39], written by the same author affiliated in Uzbekistan, contained tables of solar radiation repeatability data that could be used to assess the cost-effectiveness of a photovoltaic installation of any design. According to the data contained in the searched databases, similar studies were carried out only after 30 years. Indeed, in 2007, calculations were published on the frequency of repetition and the delivery of daily solar radiation totals over the meteorological stations of the Apsheron Peninsula (Azerbaijan) [40]. Five years later, researchers from Switzerland presented their method for calculating photovoltaic potential using meteorological data [37], generating an insolation map with a resolution of one meter. Meanwhile, Schallenberg-Rodríguez also developed a methodology for determining the techno-economic potential of photovoltaics on rooftops [27], carrying out calculations for the Canary Islands (seven islands belonging to Spain, located off the northwest coast of Africa). A detailed analysis of the actual photovoltaic potential (as complex and effectively exploitable) of the South Tyrol area was carried out by a team from Bolzano (northern Italy) [41]. Later, the calculation algorithm for all of Italy was also presented [42]. In contrast, a paper by researchers from Delft (the Netherlands) presented a simplified model for the direct estimation of surface irradiance and performance of a photovoltaic system in urban areas [43].

Parallel to the development of computational algorithms, Geographic Information Systems (GIS) have started to be included in solar cadastre research. GIS tools have been used to determine the photovoltaic solar energy potential of roofs and building facades. The first mention of this topic in the publications analyzed was found in a study that was carried out in Spain, and related to three-dimensional information on the insolation of building walls [44]. The analyses were based on integrated property cadastre data and solar irradiance data recorded by the State Meteorological Agency (AEMET), considering potential shading. The proposed method was tested using data for Recoletos, a district of Madrid (Spain). A similar study was also carried out in Germany (Frankfurt am Main) [45] and Switzerland (Geneva) [46]. Similar considerations guided a research team from Trento (northern Italy), which published a study in 2012 on the estimation of solar irradiance of building roofs in complex alpine landscapes [47]. A year later, in a slightly expanded composition, the team published their idea to introduce a third dimension into the calculation [48]. The analyses were carried out in and around the city of Transacqua (Trento province, northern Italy). Parallel with the 3D work in Italy, similar work was carried out in Germany [49].

Another type of analysis based on GIS tools was concerned with estimating the amount of electricity that can be obtained from photovoltaic cells installed on the roof. The first example of such work concerned the area of the German municipality Waldthurn (north-eastern part of Bavaria) [30]. A detailed GIS analysis of the solar potential of residential roofs was also performed for the cities of Hamburg (Germany) [50], M'diq (Morocco) [51], Komárno (Slovakia) [52] and Zaragoza (Spain) [53]. Total analysis on roofs and facades was carried out in Geneva (Switzerland) [32,54]. For Austria, the photovoltaic potential of rooftops in addition to ground-mounted installations were tested [55]. In Poland, areas suitable for the installation of photovoltaic farms were identified for rural municipalities [56].

In Spain, a web-based tool with proprietary algorithms was developed to automatically calculate the photovoltaic potential on rooftops and on undeveloped plots [57].

The authors of the subject analyses often used LIDAR data and automatically built 3D city models to calculate the solar potential. However, the studies were also performed using other photogrammetric techniques. A research team from Torino (northwestern Italy) tested the possibility to generate the data necessary for solar radiation analysis using measurements taken with a digital camera [58].

Over the years, it has been increasingly considered that all studies may be burdened by various external conditions. Thus, in a paper published in 2018, which concerned the development of a map of the actual solar radiation distribution for a part of Wroclaw (Poland) [59], attention was drawn to the need to take cloud cover into account. Meanwhile, a Swiss–British team of authors presented a method for incorporating uncertainty in solar potential assessment using multiple simulation scenarios, providing information on confidence intervals of summary energy production statistics based on vegetation and weather variability [60]. The method was tested for a fragment of Neuchâtel (Switzerland). However, research teams from Geneva (Switzerland) [61] and Valencia (Spain) [62], almost in parallel, proposed their methods for including shading in the calculations. In addition, it was considered important to classify roofs according to their suitability for the installation of photovoltaic systems [34]. The study area was once again Geneva. Additional criteria analyzed (apart from the energy potential of the roof) were related to economy, aesthetic and heritage, superstructure constraints and roof structure robustness.

Aesthetics also proved to be important for the authors involved in the broader solar cadastre. In a case study of the design of a photovoltaic installation on a church in Switzerland [63], a method for assessing the visual perception of panels was presented. With the aid of this method, it is possible to indicate where to install the panels in order to disturb space users as little as possible. The authors suggest introducing their method into solar cadastre tools, especially in urban areas.

Economic considerations have not been forgotten. Researchers from Canobbio (Switzerland) [33] have proposed a computational method capable of extending the existing insolation analyses, which are based on models at the LOD2 level of detail, by building typological indicators. Their aim is to perform more accurate analyses without the need for costly LOD3 models. The accuracy of the input data used was also important in such studies. The aspect was investigated in the Turin area (Italy) [64] during acquisition of digital surface models from satellite stereo pairs taken by three different satellites (Deimos-2, Pléiades-1 and WorldView-3).

Around the same time, when the construction of models to estimate energy potential returned after 30 years, work began on the solar cadastre as we know it today (a multifunctional geoportal). In 2010, a team of authors from Germany [65] proposed the realization of an interactive online solar roof cadastre in Lage (a city in Germany, located in the state of North Rhine-Westphalia, in the region of Detmold, in the district of Lippe). Its aim was to show the energy potential of roofs. It was based on airborne laser-scanning data. Moreover, in Germany, the SUN-AREA project was implemented, which is described in [66]. Its aim was to create a WebGIS application with which solar potential maps were generated based on high-resolution LIDAR data. The calculations took into account factors such as shape, slope, exposure and shading for each roof. In addition, ecological factors were taken into account, such as determining the amount of carbon dioxide that would not be generated into the atmosphere by using the energy potential of a specific area. The implementation of solar cadastres in Germany were verified by calculations [26].

Over the years, such online applications have been developed in many countries. The first major summary of work on online solar maps was conducted by researchers from Sweden in 2014 [31]. They collected information on the contents of 19 such studies available online: two from Austria (Graz and Vienna), one from England (Bristol), six from Germany (Aachen, Berlin, Dusseldorf, Marburg, Osnabrück and Solingen), two from the Netherlands (Amersfoort and Arnhem), one from Portugal (Lisbon), one from Sweden (Gothenburg), three from Switzerland (Basel, Geneva and Porrentruy) and three from the USA (Boston, Los Angeles and New York City). Then, they classified these studies into three groups: basic (showing irradiation levels), medium (additionally showing the output of solar systems, categorization of suitable areas for production, and system effective PV) and advanced (additionally showing monthly output, financial considerations, information regarding installers and solar energy). It must be acknowledged that the solar cadastre initiative is increasingly being developed. In Switzerland, studies have been carried out on the concept that a solar cadastre could serve as a tool for urban planning and monitoring [67]. In Spain, the analysis of solar potential was contrasted with energy consumption; calculations were carried out at the building level for the city of Irun [68].

It should also be noted that the developers of solar cadastres are keen to keep them up to date. For example, [36] carried out a project in Geneva that will make it easier to periodically update its existing solar cadastre. The aim was to design and develop a cloud-based decision support system with high computational performance that uses high-resolution 3D digital urban data to perform environmental analyses over large built-up areas, such as assessing solar energy potential.

3.3.2. Wind Cadastre

In the analyzed publications, the wind cadastre was mentioned for the first time in 2005, when the production and distribution of electric energy in the Baltic countries was assessed [69]. This study presents the results of wind parameter measurements made for Latvia. The measurements were carried out at a height of 50 m in the years 2004–2005. The average annual wind speed was determined and the use of GSM mobile phone masts and radio beacon tops for wind speed cadastre for the Baltic Sea coast was proposed for deployment at a height of 50–100 m. At the same time, the existence of a wind cadastre in Moldova was also signaled [70].

As of 2018, the basic elements of the wind energy cadastre of the western sector of the Russian Arctic have begun to be presented. Publications in that area [71,72] present the distribution of multi-annual mean wind speeds across the region, as well as the areas with the highest wind strength and the frequency of occurrence of specific wind speeds at exemplary meteorological stations. In addition, they describe research on wind energy resources in the analyzed part of the Arctic and describe conditions favorable for the successful use of wind energy. In the course of the research, promising locations for the construction of large wind farms were selected on the northern coast of the Kolsk Peninsula, in the area of the Serebryanskaya and Teriberskaya power plants. These papers also indicate the main directions of possible practical applications of wind power plants. One of them was proposed to support heat supply systems for Arctic consumers. Presumably, this is the reason that in the following publications [73,74], the same authors considered this problem. In their studies, they identified the areas with increased wind power that were most promising for district heating. In addition, the main features of the wind energy cadastre in the Chechen Republic can also be found in the literature [10]. However, the latest research on wind cadastre comes from Ukraine [75] and concerns a mathematical model for determining the amount of energy that a wind turbine can produce.

It should also be noted that much wind energy is contained in offshore areas. Being aware of the economic and legal issues related to the use of marine areas, some countries (the United States, Australia and New Zealand) have built multi-purpose maritime cadastres, which contain information necessary for the use of renewable energy sources, especially wind [76].

The U.S. government began mapping U.S. coastal areas as early as 1954 to support the development of oil and gas resources [77,78]. Upgrading the produced elaborations would allow the creation of the mapping primers needed to exploit the energy resources found there, including those from which renewable energy can be received. In this regard, the National Oceanic and Atmospheric Administration (NOAA) and the Bureau of Ocean Energy Management (BOEM) have been working together since 2007 to develop an integrated marine information system that provides access to jurisdictional, legal, physical, ecological and ocean-use data using GIS tools [79]. The project was developed specifically to support site selection for renewable energy installations on the U.S. outer continental shelf. Many other countries (the Netherlands, Belgium, the United Kingdom, Germany, Sweden, Poland, Israel and Greece) are exploring this concept as a complement to maritime spatial planning [76].

3.3.3. Biomass Cadastre

Biomass cadastre surveys are not very popular if they do not concern the green areas register—the so-called green cadastre [80–84]. Only one publication was found in this field [85]; however, this publication is quite unique. The author states that there is a need for a reed inventory and cadastre system in Latvia. According to the author, reed is a long-term renewable energy source covering more and more of the country every year. Therefore, this study contains information on the basic principles of creating a reed cadastre. It is intended to be an inventory of reedbeds, including information on reedbed areas, their size and location, legal status and exploitation possibilities, as well as the quality of biomass in individual water bodies. For each water body included in the reedbed cadastre, a certificate and a map are produced. The map shows information on the distribution of reeds in each specific lake, the boundaries of the water body, the boundaries of the plant and reed areas, the boundaries of the protected habitat area, the administrative boundaries and the access boundaries to the lake. Data on reed characteristics and available volume are compiled in the certificate issued for the water body.

3.3.4. Water Energy Cadastre

The production of energy from water takes place during the movement of large volumes of water. The amount of energy depends on the speed and amount of water being moved. This movement can involve water flowing in riverbeds and water moved by tides in seas and oceans. In both cases, studies are carried out to help locate the facilities necessary for extracting energy from water.

The first cadastre of Lithuanian rivers was created in the middle of the 20th century [86], and is constantly supplemented and updated. Especially important is the development of a new method of calculating flowing water parameters. Moreover, intensive research of water resources in Lithuania has led to the identification of a location for the construction of a pumped-storage power plant.

Researchers from Russia have also addressed a similar issue [87], developing an algorithm for finding the optimal location of a hydropower plant and the necessary number of hydropower plants in a river channel network. In the paper, they took into account the energy, economic, social, ecological, water energy and resource characteristics of the region involved in the calculations. This helped them to justify the main parameters of the hydropower plant for each of the many localization options.

In an article from Poland [88], the application of curves representing the water flow parameters (forecasted and used in the development of the hydropower cadastre) to determine the installation flow of small hydropower plants was presented. As already mentioned, wave and tidal flows of sea and ocean water can also be a source of hydropower. The aforementioned information (Section 3.3.2) regarding offshore wind energy is the same for energy from those sources.

3.3.5. Geothermal Cadastre

The cadastre of areas from which geothermal energy can be extracted was described even less frequently in the reviewed publications than that of biomass. Nevertheless, it is worth mentioning that a platform has been developed for the Asturias region (the Cantabrian coast in Spain), which calculates the energy savings that can be achieved using geothermal technologies [89]. The geothermal resources were estimated on the basis of the National Geological Map (MAGNA), prepared by the Geological and Mining Institute of

Spain (IGME) between 1972 and 2003. The calculation took advantage of the fact that each rock material was assigned a certain conductivity according to tabular data prepared by the Institute for the Diversification and Saving of Energy of Spain. This has resulted in a map showing the average thermal conductivity in the postal districts of the Principality of Asturias.

3.4. Examples of RES Cadastres from the World

Based on the literature review, a search was performed for both functioning and online renewable energy cadastres. The most interesting were selected and described. Internationally, this name is simply assigned to geoportals containing information on energy potential, heat potential and renewable energy installations. As in the case of previous analyses—also in the subject case—the solar cadastre, which was given a separate section, was analyzed first. The cadastres of the other sources are presented separately.

3.4.1. Solar Cadastre

Among the cadastres of renewable energy sources, the solar cadastre is the most common. On the basis of the analysis of exemplary world solutions, a model concept of a cadastre of renewable energy sources can be developed. In the literature [26], emphasis is put on the importance of efficient political control over newly projected installations, by providing the proper division of subsidy schemes that can be achieved on the basis of data from the regional remaining potentials, and individual local abilities of electricity usage. The first solar potential map was created in 2008 for the city of Osnabrück (Germany). As indicated in the literature [90], Germany and the United States are the countries that have developed the most in this field. The number of solar cadastres has consequently increased in the past decade, providing different levels of detail about the urban solar potential in different cities [91]. As indicated in [31], solar maps or solar cadastres have been developed to provide information about the local urban solar resource. The authors emphasized that a solar map is a GIS system providing the annual solar irradiation on building surfaces, mostly accompanied by information of the output of solar thermal or photovoltaic systems. As indicated in [92], built on the basis of a numerical model of land cover and a database of topographic objects, the solar cadastre enables users to obtain information on the better distribution of collectors and photovoltaic cells on the roofs of buildings, and allows a more accurate forecasting of their efficiency. In addition, according to the authors, the application of insolation analysis for the use of renewable energy sources in the economy raises public awareness of the need for new solutions, and their application in practice. The creation of the geoinformation portals enables the user to check whether the planned investment in a solar installation is possible and profitable in a given location, and what savings it could bring. Recording the location of existing installations allows identification of the already installed, as well as the remaining capacity for newly planned photovoltaic investments [26]. There have been cases [93,94] when the extensive installation of solar plants has caused the failure of the electricity grid (Italy—2003, Northern Germany—2006), so prevention should be applied. In turn, one can find the view that solar maps also serve as a back-end tool for city administrations to base energy decisions on [31].

Geomatic tools are applied to answer questions such as which roofs have proper solar orientation, on which roofs solar panels are already located, or how many panels can a roof accommodate. These tools are mainly aerial photos, numerical land cover models (NMPT), data extracted from airborne laser scanning, databases of topographical objects, etc. In simple terms, the creation of a solar cadastre also requires meteorological data, an algorithm to calculate solar potential, a server and access to the internet [95]. The simplest solar geoportals, such as the PVGIS portal, use low-resolution climate data and a numerical terrain model [92]. As affirmed in [31], the basic solar map is a solar map with elementary information on the irradiation level, preferably categorized. The medium solar map provides the energy output of the suitable areas as PV/ST, whereas the most advanced provides quantitative data, as well as information about what to do next when people want to install PV or ST. The authors indicate that a growing number of cities are obtaining LIDAR data, making it possible in theory to produce a solar map. It is from high-resolution data, acquired by laser scanning, that 3D geometry is obtained, along with more detailed and practical information as a result. As emphasized in [47], establishing roof surface models involves gathering data on the height of buildings, which can be obtained through three different procedures: field measurement, photogrammetry/photo matching and LIDAR measurement. According to [67], the appellation of "solar cadastre" may be more relevant for a solar map of a city which is coupled with the local land register, i.e., the local ownership of the house/building part. The authors emphasized that such a cadastre takes the form of an open-access Geographic Information System (GIS) tool, and is often managed by the local collective. Furthermore, to establish the roof cadastre, the LOD2 level must be reached, as this level of detail makes possible the observance/calculation of the shape of the roof structure, the exposure and the extent of leaning, as well as further calculations on the basis of the model [4]. As indicated in [47], high-resolution geometric models of the building roofs are generated by means of advanced automated image-matching methods. The authors emphasized how crucial it is that predictive models provide credible results; however, most of the systems available online emphasize that the interfaces provide an invaluable first estimate for rooftops, and there is ultimately a need for a more detailed assessment of suitability, when planning an installation.

For the purpose of this publication, the functionality of selected solar cadastres, as well as maps and portals containing data on solar potential, were analyzed and the optimal solutions and functionalities were specified. The research included 15 portals containing solar energy data (Table 4). These were realized at different levels of detail. Two of them presented data for the whole world [96,97], one for the area of the whole country, i.e., Switzerland [98,99], whereas the others concerned the following cities, regions or agglomerations: (i) Metropolitan area of Geneva (Switzerland) [100]; (ii) Graz (Austria) [101]; (iii) Vienna (Austria) [102]; (iv) Calgary (Canada) [103]; (v) Hannover (Germany) [104]; (vi) Hessen (Germany) [105]; (vii) Munich (Germany) [106]; (viii) London (Great Britain) [107]; (ix) Amsterdam (the Netherlands) [108]; (x) Wroclaw (Poland) [109]; (xi); Boston (USA) [110]; (xii) San Francisco (USA) [111]. Obviously, only the portals at the level of cities, agglomerations or regions, which presented data for non-real estate cadastre objects (buildings or parcels), can be treated as solar cadastres.

Table 4. Characteristics of selected solar cadastres.

Name/Area	Characteristics
Global Solar Atlas [96]/the whole Earth	– Calculates potential electricity production from the PV power, providing reliable in-formation only for preliminary analysis. – Methods used in the solar radiation model consider the attenuation factors of solar radiation through the atmosphere, until it reaches the ground surface. – In most situations, the expected uncertainty for annual values will be within ±4% for GHI and ±9% for DNI (there may be exceptions in the case of countries in humid tropical climates and coastal zones, high mountains regions with regular snow and ice coverage, high-reflectance deserts, etc.). – To calculate solar resource parameters data, inputs from geostationary satellites and meteorological models are used.

Table 4. *Cont.*

Name/Area	Characteristics
Photovoltaic Geographical Information System (PVGIS) [97]/the whole Earth	– A web application that gathers data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world (in Europe and Africa, as well as large parts of Asia and America). – Available in English, French, Italian and Spanish. – Provides free and open access to: (i) data of PV potential for different technologies and configurations of grid-connected and standalone systems; (ii) daily profiles of solar radiation and air temperature, as well as averages for a given month; (iii) hourly values of both solar radiation and PV performance; (iv) typical meteorological year data for nine climatic variables; (v) maps, by country or region, of solar resource and PV potential; (vi) PVMAPS software includes all the estimation models used in PVGIS. – No restrictions on what the results can be used for, and no registration is necessary. – Can use information about the local horizon to estimate the effects of shadows from nearby hills or mountains.
Sonnendach.ch [98] Sonnenfassade.ch [100]/all of Switzerland	– The map shows the degree of suitability of roofs, as well as façades for the use of solar energy, together with the potential yield on the basis of the simulation of the course of the sun throughout the year and the calculation of the level of solar radiation reaching the roof. – Possibility of a 3D view of buildings. – Indication of the entire surface of a façade, without deducting the space occupied by windows, door, etc. – Calculations are based on the data provided by the federal office of meteorology and climatology (meteoswiss) and the 3D building data (swissbuildings3d 2.0) of the federal office of topography (swisstopo). – One of the available tools is a solar calculator, which provides the opportunity to determine the investment costs and potential benefits, including the amount of energy to be produced, tax savings, etc.
Le cadastre solaire du Grand Genève [100]/metropolitan area of Geneva (Switzerland)	– Estimates the monthly and annual solar energy production potential (heat and electricity) of a property's roof. – Identifies the roofs that have the best exposure to the sun, assesses the potential of the roof and indicates the area of panels that can be installed on the roof. – It is based on the position of the sun, meteorological statistics (from measurements taken between 1990 and 2010), latitude, slope and orientation of surface parts and near and far shadows. – The meteo-norm tool offers extrapolation of weather data to any point in the territory from the analysis of satellite images of cloud cover. – The shadowing analysis is derived from a digital surface model (0.5 m resolution) that has been constructed from airborne LIDAR height readings. – It indicates, among other things, the total electricity that can be produced per year, the costs of installation and its operation and maintenance. – In a future version, it will also provide information on the ability to consume its own produced energy according to framework conditions and economic models, as well as the ability of electricity grids to inject currently produced energy, etc.
Solar roof cadastre Grazer Solardachkataster [101]/Graz (Austria)	– Assessment whether solar installations are worthwhile for their specific property in Graz—for hot water preparation, for heating, or for generating electricity, and of course for the environment. – The roof surfaces, due to their slope and orientation, were classified as "very suitable" or "well suited". – Due to the strict regulations for the preservation of the Old Town in Graz, roofs within the area can only be altered to a limited extent, hence the comment "roofscapes worth preserving" is shown in the roof application and the colors representing the potential are faded out.

Table 4. *Cont.*

Name/Area	Characteristics
Solarpotenzial3D [102]/Vienna (Austria)	– Shows which roofs and façades in Vienna are potentially suitable for using solar energy to generate heat (solar thermal generation) or electricity (photovoltaics). – Evaluates the orientation and slope of the roof surface, the shading induced by vegetation and buildings, as well as relief. – Remote shading was performed based on a digital terrain model of the Vienna area. – Based on a model that considers the actual shape of the roof. – Determined based on CityGML LOD2 detail, indicating which part of the roof is most suitable for installations (suitability detailed in colors). – The structural and static properties of the roof areas are not included in the calculations. – Potential for the façades of buildings is also assessed.
Solar Potential Map [103]/Calgary (Canada)	– The map shows varying degrees of a roof's solar exposure in generalized optimal conditions. – The data model considers the shape of the terrain and the relative position of building rooftops and structures, existing infrastructure and tree canopies. – Weather conditions are not taken into consideration. – It may not reflect new adjacent structures built after 2012 that may obstruct solar exposure. – Information on the yield levels of solar potential are shown in the solar potential map in color (low yield, low moderate yield, high moderate yield, high yield). – Gives the opportunity to select a base map, among others in aerial image—aerial image BW, light-grey basemap.
Solarkataster [104]/Hannover (Germany)	– Provides verification of roof areas for their suitability for installation of a photovoltaic or solar-thermal system. – Developed using 3D laser-scanning data. – Yield calculator, integrated with the cadastre, uses existing information and individual input data on energy consumption and usage behavior to estimate possible production and savings. – Determines possible module area, system output, potential energy/heat yield, possible CO_2 savings, annual savings, indicative costs, etc. – Provides an efficiency calculator and a solar-yield calculator (possibility to enter own expectations and data on the existing state).
Solar Cadastre Hessen [105]/Hessen (Germany)	– One of the winners of the eGovernment competition—it was awarded as the best digitalization project of 2017. – Indicates the optimal location for photovoltaic and solar-thermal systems. – Provides detailed calculations of the solar potential of both rooftop and open areas. – Indicates the suitability of each square meter, follows classification and color coding. – Takes shading losses into account. – Possibility to optimize own requirements, consumption, etc. – Provides a solar-thermal computer that gives a forecast of possible savings and a profitability calculator that determines rates of return, payback period, etc.
Geoportal München [106]/Munich (Germany)	– Provides information on the intensity of solar radiation on roof surfaces and its potential suitability for solar energy use or solar heat generation. – Class division and differentiation by color have been applied. – Provides information on the possible efficiency of the system, the expected annual output, the size of the photovoltaic installation, etc. – Considers the shading of the roof surface by neighboring buildings and trees (during the year) depending on the respective position of the sun. – For the calculation of the solar potential, an installation parallel to the roof is assumed: an angled mounting variant. In the case of solar energy, flat roofs are assumed to be oriented to the south, and are raised at an angle of 45 degrees. – The information to be extracted from them is only preliminary, the sub-basis is 2017 flight data (source: lhm geodata service).

Table 4. *Cont.*

Name/Area	Characteristics
The London Solar Opportunity Map [107]/London (Great Britain)	– An interactive online solar mapping tool that estimates the potential for both photovoltaic solar panels and solar-thermal installations on buildings and open land around the capital. – Provides an invaluable first estimate of site-specific suitability. – Based on the interpretation of LIDAR data collected and made available by the U.K. Environment Agency to create a 3D model of all buildings, trees, hills and open space in and around London. – Provides an initial estimate of the amount of electricity that could be generated from panels at both rooftop and ground level, and shows, among others, annual output, estimated installed potential, average potential per m^2, estimated viable area, carbon savings, potential by surface orientation, etc. – Possibility of specification of a custom output ratio/utilization factor. – Gaps within the LIDAR coverage may impact the shown figures. – The areas marked as unsuitable are based on land-use classifications and known planning restrictions.
Interactive maps of the City of Amsterdam [108]/Amsterdam (The Netherlands)	– Enables verification of whether a given roof, and which part of it, is suitable for mounting solar panels and generating solar energy, and how much energy can be generated (indicated by color). – Provides a calculation module to indicate the benefits of investing in solar panels in a given case, and the payback period of the investment. – It is possible to adapt the standard calculation to a given situation and energy consumption to create an individual installation design. – Indicates the recommended size of the installation. – Available maps include "Solar panels—increase in number and power" and "Solar panels and heritage—roof inventory" (the specification for the possibilities of solar panels for historic buildings and non-historic buildings with indication of those with wide possibilities and limited possibilities).
Mapa potencjału solarnego [109]/Wrocław (Poland)	– Presents data on the amount of solar energy falling on the roofs of buildings in annual and monthly terms, divided into direct radiation (IDH), diffuse radiation (ISH), and total radiation, i.e., the sum of the above (ITH). – Provides the possibility of simulating the solar potential of a drawn area (e.g., a sample panel). – The analysis excludes areas with slopes greater than 60 degrees and those located outside the contours of buildings. – The calculations do not consider the limitations related to the efficiency of the equipment or the physical possibility of their installation on the building.
Solar SystemTM Boston [110]/Boston (USA)	– Estimates rooftop solar–electric potential (PV panels) for almost every building. – Based on topographical surveys, information models, and simulation methodologies, three-dimensional elevation data serve to create a surface model of the sample terrain. – Shape of building rooftops and structures, existing infrastructure and tree foliage are taken into consideration. – Data may be unavailable or inaccurate due to partial sample obsolescence, excess of vegetation or non-modelled obstructions, incomplete or corrupted databases or GIS layers, undetectable partial obstructions based on survey resolution, etc. – Has the possibility to input the amount users want to save monthly. – Provides information on financials, (e.g., federal tax credit, monthly revenue, payback period) on system specs, (e.g., number of panels, total roof area, system size, electricity output, panel efficiency, etc.) and on carbon offsets, (e.g., carbon capture—trees). – Has the possibility to draw over the roof to select desired system areas. – Has the possibility to provide data on your system to share with others.

Table 4. *Cont.*

Name/Area	Characteristics
Solar Energy in San Francisco [111]/San Francisco (USA)	– The map shows the average annual solar energy received by every square meter in San Francisco, California, USA. – Shows the information compiled by using data from the SFPUC solar monitoring stations, combined with the sun's position, building shapes and general topography. – The urban features were derived from LIDAR data made publicly available by USGS. – Presents estimated annual solar irradiation (in color).

Source: own study.

The results of the analyses confirmed that the available solar maps and cadastres are characterised by different levels of advancement, providing a scope of data from different model details and graphic designs. They provide solar irradiance maps, either to a global extent or covering the area of a selected country, region or city (Berlin, Vienna, Tokyo, Amsterdam, San Francisco, London, etc.). Generally, their aims are the same: to promote the use of renewable energy from the sun and to determine the efficiency of future installations. Within the available solar maps and solar cadastres, there are some original, ingenious solutions, undoubtedly worthy of replication. Some portals, such as the Hannover Solarkataster, provide additional tools such as a yield calculator integrated into the cadastre, using existing individual input data on energy consumption and usage behavior to estimate possible production and savings. Others, such as the London Solar Opportunity Map (London), highlight limitations due to land-use classifications and known planning restrictions. As not all planning restrictions are recorded in the system, and land uses are subject to frequent change, the areas marked as unsuitable are noted purely for information. It is mentioned that final opinion of the suitability should be given based on a full search of statutory restrictions for the site. Interestingly, the aforementioned London Solar Opportunity Map gives the opportunity to recognize the theoretical potential for not only photovoltaic solar panels or solar-thermal installations on buildings, but also on open land around the capital (Figure 7).

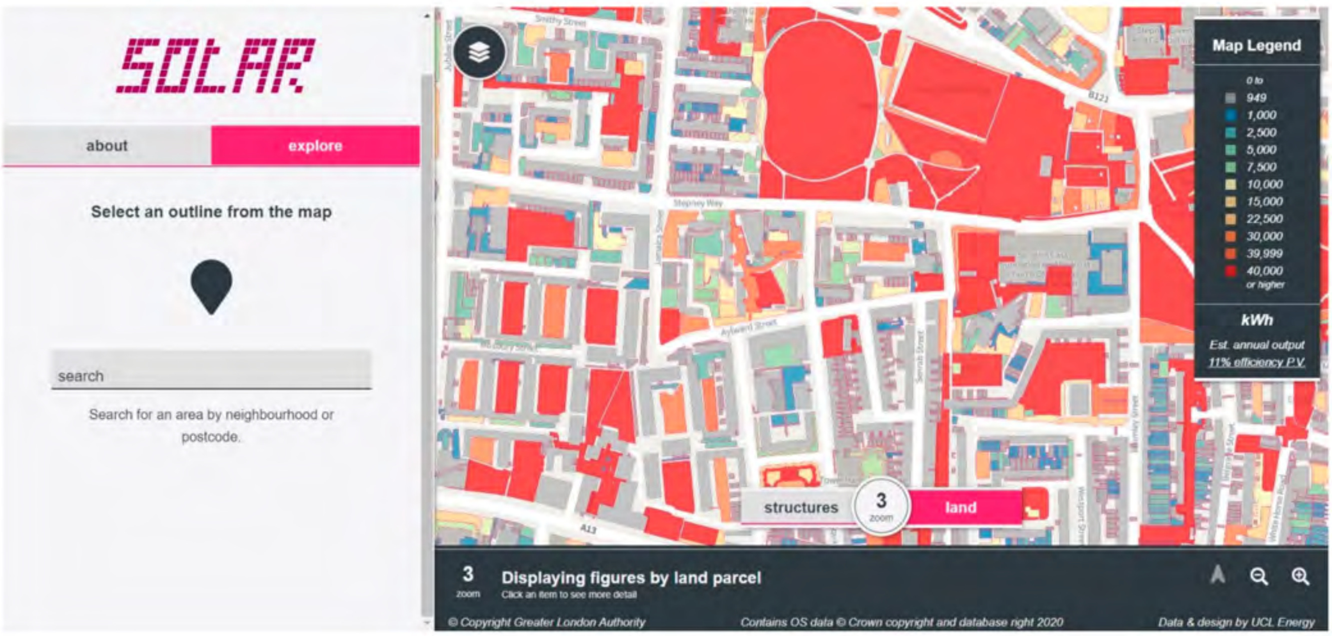


Figure 7. Solar cadastre in London—structures mode: buildings or land can be selected. Source: own study based on [107].

Some of the currently available solar cadastres use 3D visualization (e.g., Vienna, Berlin, Switzerland, etc.), whereas others use only 2D visualization (e.g., Hannover, Hessen, Wroclaw, etc.). Some of them do not consider the structural and static properties of the roof areas (e.g., Vienna), although in practice, only 10% to 50% of the roof area is technically usable. In the solar cadastre of the Hanover Region (Figure 8), it is possible to obtain a listing of roof areas suitable for photovoltaics, but it is also possible to display areas where no suitable partial roof areas are available. On the other hand, the interactive map "Solar panels and heritage—roof inventory" of Amsterdam indicates possibilities for solar panels with a distinction of special objects such as historic buildings and non-historic buildings and other properties with a division into those of wide possibilities and limited possibilities.

Urban solar maps providing the BIPV potential of both roofs and façades are also an interesting solution. Vienna (Figure 9) and Switzerland can serve as examples.

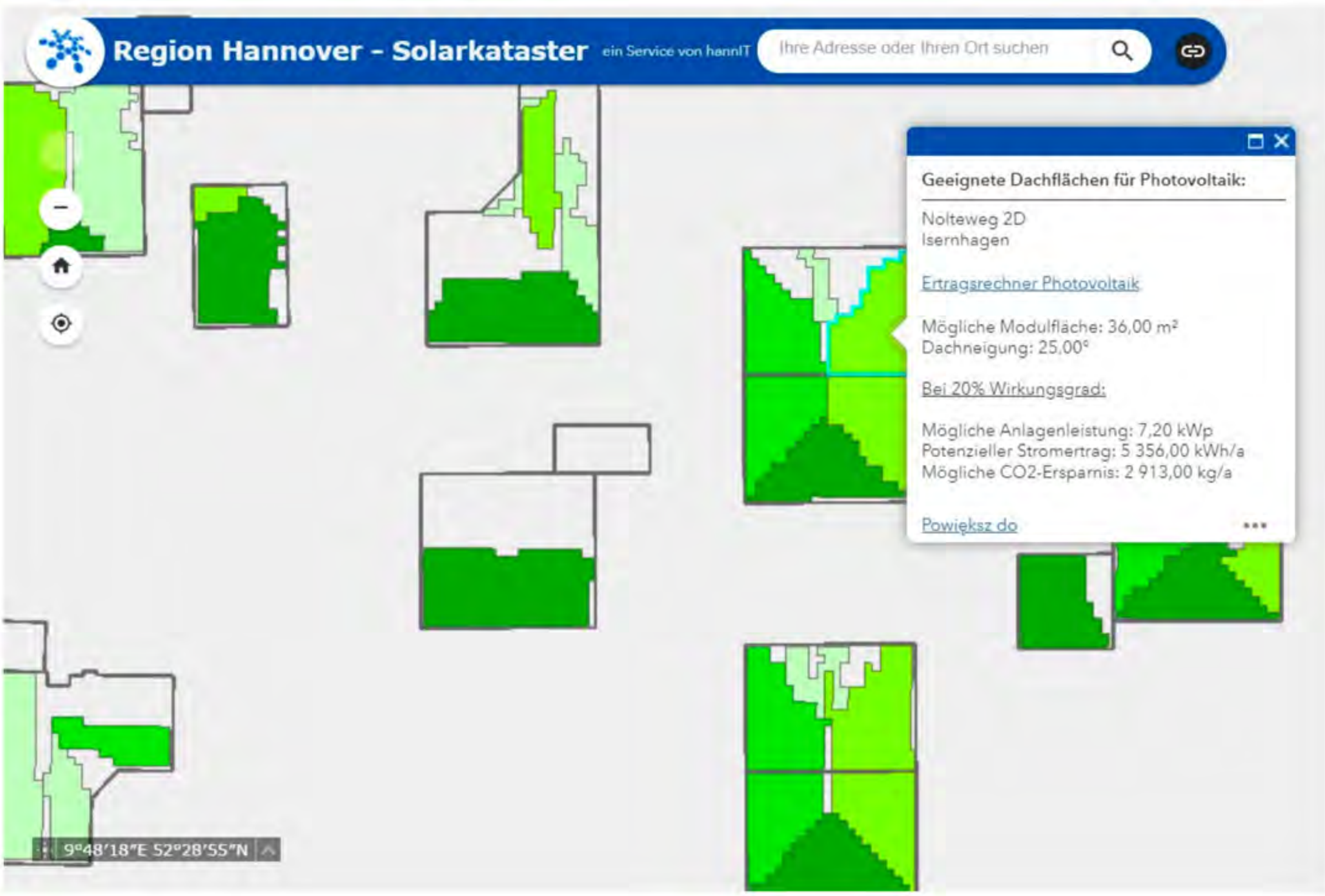


Figure 8. Solar cadastre of the Hanover Region—specification of roof areas suitable for photovoltaics. Source: own study based on [104].

As indicated in the literature [33,112–114], there are situations where roof surfaces are not sufficient enough to provide the expected solar energy, or due to a high-density of urban areas, the façades of buildings provide more space to locate installations (for example, multi-storey buildings). Thus, the potential of façades is garnering more and more attention. In such cases, to properly determine the real BIPV exploitability, not only solar radiation algorithms are required, but also the identification of construction façade characteristics. However, as confirmed by [33], the majority of the current urban BIPV façade cadastres are based on 3D city models at LOD2, so the influence of architectural elements (such as windows, balconies, etc.) is not evaluated. In their work, the authors proposed a calculation method to match existing solar radiation analysis at LOD2 with architectural characteristics of façades, to better estimate their urban BIPV potential (LOD2.5) without the need for LOD3 models. An excellent tool is the simulation of the installation project available at Zonatlas Amsterdam (Figure 10). The calculation module allows one to estimate the benefits and payback period of an investment in solar panels. Importantly, it is possible to adapt the standard calculation to the specific situation and energy consumption to create an individual installation design. In addition, the user is shown the recommended installation size.

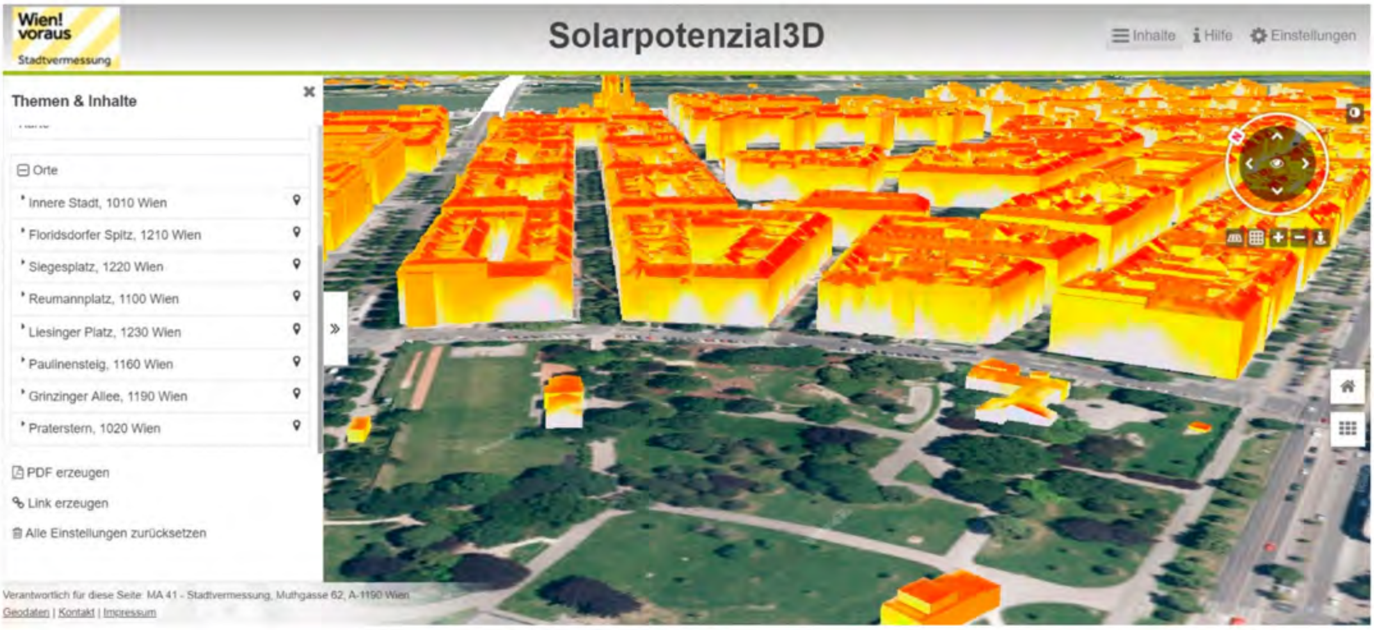


Figure 9. Example of the solar cadastre for both roofs and façades of buildings—The Wien Solarpotenzial3D. Source: own study based on [102].

Figure 10. Simulation of individual installation project in Zonatlas Amsterdam. Source: own study based on [108].

3.4.2. Cadastres of Others Renewable Energy Sources

As noted earlier, there are not many portals for renewable energy sources other than sunlight. Moreover, it should be mentioned that the sources that exist often concern the same areas as the solar cadastre. However, not every location is suitable for solar installations, which do not always provide satisfactory savings. As indicated in [115], in Utrecht (the Netherlands), it is not possible to cover the whole electricity demand of the area with only PV power. In order to make the region energy-neutral, other renewable sources of energy such as (urban) wind energy and offsite solar parks or Bio-CHPs may have to be applied. Other technologies may also be applied, including renewable energy from wind, waste, biomass heating, cooling, etc. According to [4], available tools such as remote sensing and geographic information methods, as well as the gaining ground of renewable energy sources, facilitate innovatory, utilizable databases. The importance of the availability of a cadastre of renewable energy sources should be emphasized in such a situation. It would be possible to identify for which applications the location of a property is suitable, and what energy potential it has. Only a few systems contain data on the possibilities of more than one source. One of the examples of a renewable energy source cadastre [116] is a system created in Belarus, in which all operating and scheduled renewable energy installations are presented. Similarly, the State Cadastre of Renewable Energy Sources of the Republic of Tajikistan contains a system of necessary information and documents on the quantity and location of renewable energy sources, as well as on their use in the republic [117]. Moreover, an example of a collective system is the Global Solar Atlas, provided by The World Bank Group, including information on: biomass, small hydro, solar and wind power (part of a global ESMAP initiative on Renewable Energy Resource Mapping); interactive maps of the City of Amsterdam (solar, wind); maps of the Swiss Federal Office of Energy for Switzerland (solar, wind, hydropower, biomass); Red Electrica De Espana (solar, wind, biomass). They mainly contain information that aims towards the preliminary identification of favorable areas for the exploitation of a given energy source, and an estimation of actual usable potential based on empirical data. Table 5 summarizes examples of other RES potential maps/RES cadastres, including maps of wind potential/wind cadastres, maps of hydropower production potential, maps of geothermal energy potential, biomass potential, etc.

Table 5. Characteristics of selected RES cadastres (except solar cadastre).

Source	Area	Name
Wind	The whole world	Global Wind Atlas [118]
	All of Switzerland	The Wind Atlas of Switzerland [119]
	All of Spain and all cities	Wind Installations Map [120] Wind Installations by Town Map [121]
	Amsterdam (the Netherlands)	Wind energy [122]
Biomass	All of Switzerland	Biogas plants and biomass potential [123]
	All of Spain	Cogeneration, Wastes and Biomass/Biogas Installations Map [124]
Water	All of Switzerland	Potential of small hydropower plants map [125]
Geothermal	Munich (Germany)	GeoPortal of Munich—Energy and Climate [126]
	Vienna (Austria)	Vienna City Map [127]
Waste heat	Munich (Germany)	GeoPortal of Munich—Energy and Climate [126]
	Vienna (Austria)	Vienna City Map [127]

Source: own study.

Apart from solar energy, wind power constitutes an important source of energy and is a fast-growing renewable energy technology. According to [128], in ten years since 2009, the worldwide capacity for wind power increased by 276%, whereas the U.S. capacity increased by 175%. There are portals presenting the location of already existing wind installations, such as the Wind Installations Map and Wind Installations by Town Map for Spain, which indicate wind energy's suggested search areas, etc. As indicated in [129], the results of wind research in different places, registered in the energy cadastre, constitute the basis for the building of wind generators. The authors emphasized that the main defect of wind energy is its long-term and seasonal changeability, as well as its changing activity during the day. For the needs of the above-mentioned cadastre, wind characteristics, such as average long-term wind speeds, seasonal distribution in average monthly speeds, wind speed frequency, etc., should be analyzed [73]. Using databases obtained from meteorological stations over several years, calculations of wind energy resources by region are carried out [130] to determine the wind energy resources in the area where the wind farm installation is planned. The Wind Atlas of Switzerland, for example, provides information about the annual averages of the modelled wind speed and direction at five different heights above the ground, areas with wind power potential and federal government interests (Swiss Federal Office of Energy). The aim is to identify areas with the largest wind potential. Meanwhile, the website maps.amsterdam.nl (Figure 11) provides information on existing wind turbines, as well as preferred areas for the location of new facilities, reserve areas and sound sensitive facilities, etc. Planning the location of such plants involves specification of the areas where their construction is not permitted (exclusion and reservation zones) as well as connections to the road network and electricity grid.

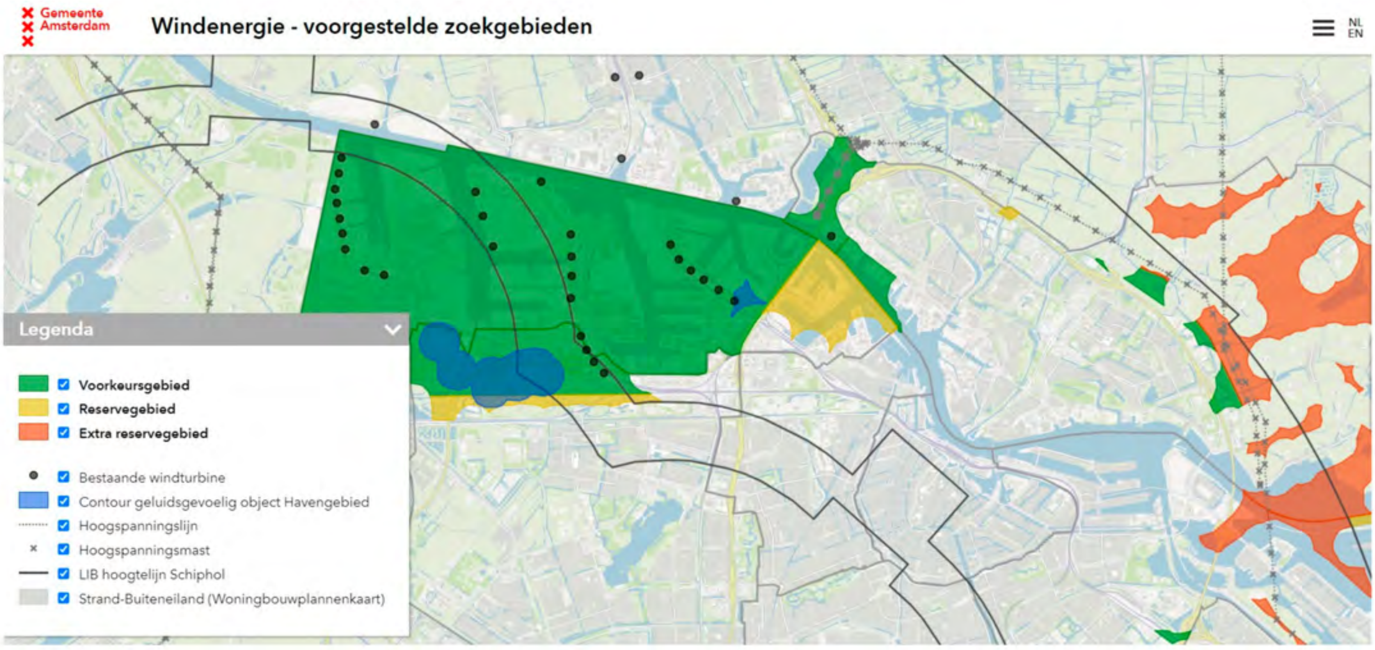


Figure 11. Wind energy of Amsterdam. Source: own study based on [122].

Another important energy source is hydropower, which is considered to be responsible for generating around 57% of electricity in Switzerland. The Swiss Federal Office of Energy provides the geodata product—"potential of small hydropower plants in Switzerland"—estimating the hydropower production potential of all natural flowing bodies of water in Switzerland. It also facilitates technical data on power output and expected levels of production. Furthermore, there are other important renewable energy sources, such as biomass, which can be transformed into several forms of energy, including heat, electricity, biogas or liquid fuels, and may also contribute to the security of the energy supply and reduction of carbon dioxide emissions. It is emphasized in the literature of the subject that energy generated from waste provides a particularly significant opportunity. As indicated in [129], in the United States, biomass accounted for 1.5% of electricity generation, and about 9% of electricity from renewables. The author emphasizes that two-thirds of the electricity from biomass comes from wood and wood waste, so there is a need for land area for growing and harvesting biomass fuel. Interestingly, the total forest biomass in Lithuania amounts to 150 million tonnes, as the biomass from small diameter trees is 89 thousand tonnes, the biomass from felling residuals is 760 thousand tonnes and the stumps potentially available from final felling is 610 thousand tonnes [73,131]. An excellent tool for indicating the biomass potential of an area are maps showing the sustainable potential of woody and non-woody biomass for bioenergy. An example is the map of woody biomass for energy popularized by the Swiss Federal Institute for Forest, Snow and Landscape Research, which presents a 3D view of the situation. It shows geodata on the current status of energy production biogas plants in Switzerland, as well as the locations of the potential of important woody and non-woody biomass resources in Switzerland at the communal level (Figure 12).

Figure 12. Woody biomass for energy in Switzerland. Source: own study based on [125].

Research on the methods proposed for the estimation of biomass potential for energetic needs in Lithuanian forests was described in [73,131]. The authors indicated that two approaches were used to obtain the figures from the data of conventional forest inventories: (i) total above- and below-ground biomass and biomass of dead wood, according to the FAO Global Forest Resource Assessment; (ii) forest biomass potentially available for fuel consisting of small diameter trees from thinning cuttings, felling residuals and stumps from final felling, derived using conventional cutting budget calculation methods.

An equally important heat source is groundwater, which is used in practice when the hydrogeological situation permits. A great deal of the world's potential for geothermal energy exists in the so-called Ring of Fire, a ring of volcanoes around the Pacific Ocean [128]. Geothermal energy is heat taken from below the surface of the Earth in the form of steam or hot water, that can be used to generate electricity, but can be used in heating and cooling homes and for other direct uses. Recently, maps/cadastres showing potential for groundwater and geothermal energy are becoming more and more popular. They contain information aimed at the preliminary identification of favorable areas for the possible use of surface geothermal energy, and the estimation of actual usable potential based on empirical data. Examples are, among others, Potenzial der oberflächennahen Geothermie in München or the register of geothermal potential in Vienna (Figure 13).

There are also other maps/cadastres showing the potential of renewable energy sources, such as the waste–heat potential cadastre, showing the locations of usable waste heat across the city, as exemplified in the information portal on the potential use of waste heat for Vienna or Munich (Figure 14).

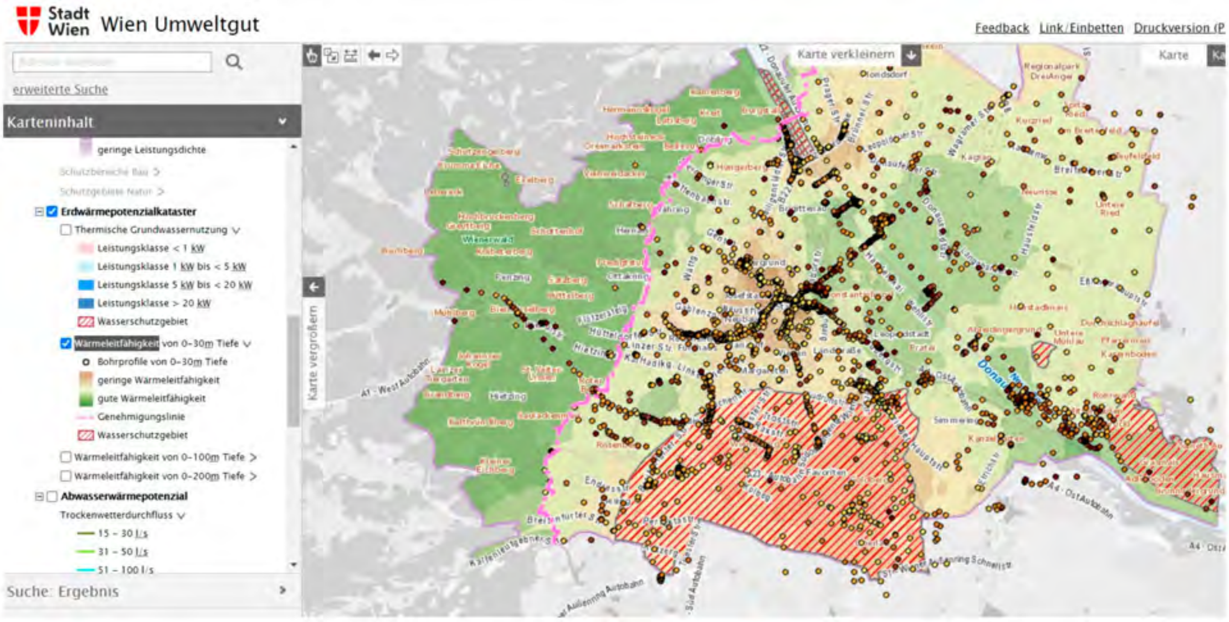


Figure 13. Environmental asset in Vienna, layer geothermal potential cadastre, areas with thermal conductivity from 0–30 m depth. Source: own study based on [127].

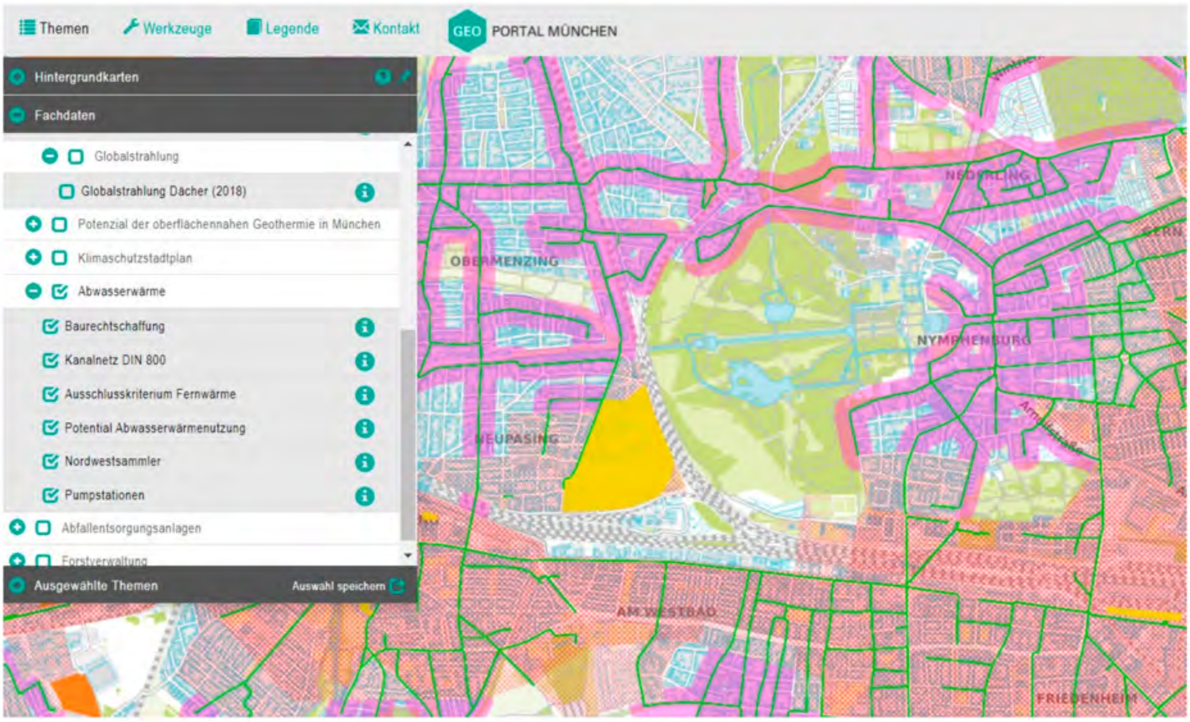


Figure 14. Wastewater heat in Munich. Source: own study based on [126].

4. Discussion

The implementation of cadastres including data on the location of renewable energy sources requires advanced GIS tools. As emphasized in [132], the construction of a GIS database ought to be preceded by detailed familiarization with the spatial and functional structure of the analyzed terrain. Taking some inspiration from a comparative analysis of the 2014 solar maps [31], we decided to list the features and functions of selected sustainable energy source cadastres (Figure 15), on the basis of which their ranking was developed (Table 6, Figure 16). However, due to the fact that so far, solar radiation as a source of renewable energy has been the most frequently studied and solar cadastres have been the most often realized, the comparison concerns selected existing studies related to solar energy. For the needs of the paper, thirteen cadastres for cities, agglomerations and regions were described in Section 3.4.1. The analysis determined the information that should be made available in such portals and the features that they should have. In total, 19 features and functions were selected for comparison.

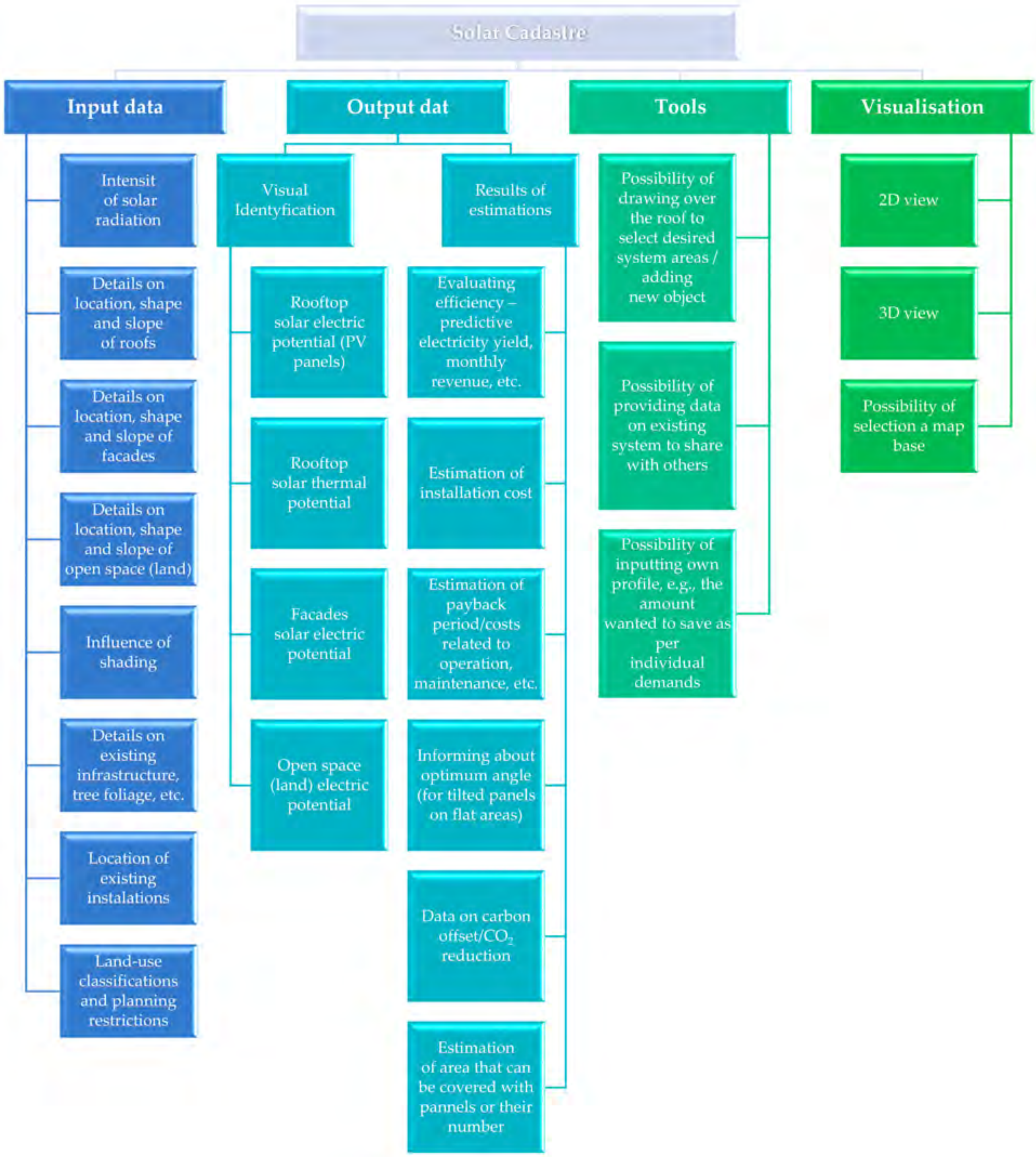


Figure 15. Scheme of the solar cadastre. Source: own study.

Table 6. Comparison of selected solar cadastres.

Feature	All of Switzerland	Metropolitan Area of Geneva (Switzerland)	Graz (Austria)	Vienna (Austria)	Calgary (Canada)	Hannover (Germany)	Hessen (Germany)	Munich (Germany)	London (Great Britain)	Amsterdam (The Netherlands)	Wroclaw (Poland)	Boston (U.S.A.)	San Francisco (U.S.A.)
Estimation of rooftop solar electric potential (PV panels)	1	1	1	1	1	1	1	1	1	1	1	1	1
Estimation of rooftop solar-thermal potential	1	1	1	1	1	1	1	1	1	1	0	0	0
Estimation of façades' solar electric potential	1	0	0	1	0	0	0	0	0	0	0	0	0
Estimation of open space (land) potential	0	0	0	0	0	0	1	0	1	0	0	0	1
Including land use classifications and known planning restrictions	0	0	1	0	0	0	0	0	1	0	0	0	0
2D view	1	1	1	1	1	1	1	1	1	1	1	1	1
3D view	0	0	0	1	0	0	0	0	0	0	0	0	0
Estimation of area that can be covered with panels or their number	1	1	0	0	0	1	0	1	1	1	0	0	0
Estimation of installation cost	1	1	0	0	0	1	0	0	0	1	0	1	0
Including some of the details such as slope or shape of rooftops/façade/open space (land), existing infrastructure, tree foliage, etc.	1	1	1	1	1	1	1	0	1	1	1	1	1
Including the influence of shading	n/a	1	1	1	1	1	1	1	1	1	1	1	n/a
Evaluating efficiency (e.g., predictive electric yield, monthly revenue, etc.)	1	1	1	0	0	1	1	1	1	1	1	1	0
Estimating payback period/costs related to operation, maintenance, etc.	1	1	0	0	0	1	1	0	0	1	0	1	0
Informing about optimum angle (for tilted panels on flat areas)	0	0	0	0	0	0	0	0	0	0	0	1	0
Data on carbon offset/CO_2 reduction	1	0	0	0	0	1	1	1	1	1	0	1	0
Possibility of inputting own profile, e.g., the amount wanted to save, as per individual demands	1	0	0	0	0	1	1	0	1	1	0	1	0
Possibility of drawing over the roof to select desired system areas/adding new objects	0	n/a	0	1	0	0	1	0	0	1	1	1	0
Possibility of providing data on existing system to share with others	0	0	0	0	0	0	0	0	0	0	0	1	0
Possibility to select a map base or to change its properties	1	0	1	0	1	1	0	0	0	0	1	0	0
Summary	12	9	8	6.5	6	12	11	7	11	12	7	12	4

Table marks: 1—available; 0—unavailable; n/a—data not available. Source: own study.

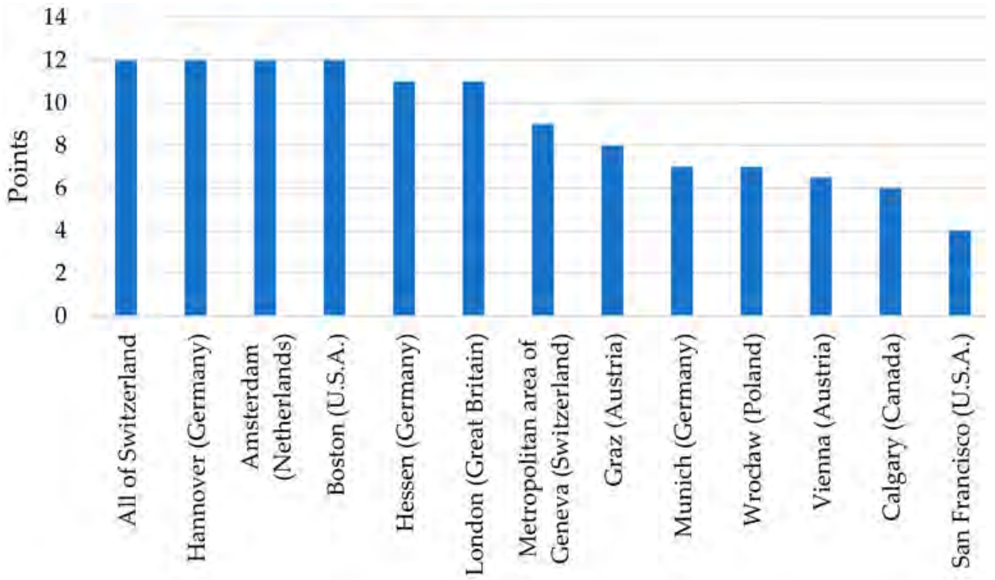


Figure 16. Ranking of evaluated solar cadastres. Source: own study.

If a given map/cadastre had a selected functionality, it was referenced with a "1". The mark "n/a" was assigned when we found insufficient data to verify the availability of an analyzed option. The results of the study indicated that among the analyzed solar cadastres/solar potential maps, the widest range of tools was provided by portals maintained in Boston (U.S.A.), Hannover (Germany), Amsterdam (the Netherlands) and Switzerland.

Based on the listed features of the analysis, a ranking of the reviewed portals was created (Figure 15).

The high-ranking positions for some portals from Switzerland or Germany constituted a confirmation of the validity of solar cadastre studies, as described in the literature review (Section 3.3.1), which have been conducted in the mentioned countries over the years. However, it should be noted that even studies carried out in one country often contain different information and have different functions. More than half of the points (i.e., a minimum of 10) were scored by six of the analyzed cadastres: for the whole country of Switzerland and for the cities of Amsterdam, Boston, Hanover, Hesse and London. However, none have all the mentioned functionalities. This does not mean, however, that the rest do not fulfil their basic role. All analyzed portals inform their users, at least at a basic level, about the energy potential of roofs in a 2D view. Most also contain information about the shape of the roof and the existing infrastructure and shading. Thus, they could be the basis for a framework of a multifunctional solar cadastre and, in the future, for a framework of a multifunctional cadastre of renewable energy sources (RES cadastre).

5. Conclusions

Renewable energy source cadastres (RES cadastre) are an issue relatively rarely discussed in scientific publications. However, the bibliometric analyses carried out allowed us to notice that this topic aroused interest mainly among researchers from Europe, who were primarily concerned with one source of renewable energy: sunlight. The first observation may be related to the provisions of the EU Directive 2009/28/EC [35], which stipulates that by 2020, the share of renewable energy in the EU's total energy consumption should be at least 20%. In addition, it is probably not without significance that the literature review was based mainly on publications indexed in Scopus, which belongs to the European economic entity, and is therefore more widespread in Europe. The second observation is related to the fact that the sun is the most abundant source of renewable energy. It reaches the Earth's surface with about 86 PW (0.086 EJ) per second, which is about 4500 times more than humanity's demand (about 600 EJ/year).

However, an analysis based solely on the literature could be misleading. Many of the projects carried out so far presenting the online potential of renewable energy sources have not been mentioned in reputable scientific journals. Various maps and geoportals with information on renewable energy exist all over the world, and despite the lack of information in Web of Science and Scopus, they are thriving and gaining popularity. Although, admittedly, portals presenting the energy potential of sunlight still lead among them. Nevertheless, in our opinion, the extended bibliometric analysis was necessary, as it indicates where to start looking for realized RES cadastres.

The performed literature review, and the examples described, prove unequivocally that it would be premature to apply the name "cadastre" to maps with the energy potential for some renewable energy sources. The solutions described in Section 3.4 showed that even studies created in the same country were not based on a uniform basis. In our opinion, however, this is the direction that countries investing heavily in the development of this energy sector should take.

The well-known and widespread real-estate cadastre can serve as a model, indicating the canon of conditions that any register should fulfil. The cadastre should constitute an interoperable database system containing fair and reasonable information about objects [133], as the reliability of the data gathered in the cadastre affects decisions concerning specific real estate, or decisions taken within the sphere of economic management [134]. In our opinion, the renewable energy cadastre, like the real-estate cadastre [135] and spatial planning [136], will someday be systematized and globally evolved to have more than two dimensions, and maps based on 3D analysis containing information on average wind speed or conditions for the location of photovoltaic cells on roofs will be helpful to identify areas favorable for the location of wind or solar installations. Such a cadastre could thus, in the future, form part of a newly integrated Land Administration System (LAS) [137]. This will require the continuous development of the technologies used to build renewable energy installations [138] and the costs involved in setting up any kind of geographical information system [139]. Now, it seems that the forerunners of including the RES cadastre in the LAS will be European countries. However, in order for this to happen, a framework for the cadastre of renewable energy sources must first be created, which will be the basis for the creation of such studies around the world. That is why, on the basis of the conducted analyses, we have created our own specified world solutions, which will be helpful in establishing the rough framework of a solar cadastre. We plan to develop this by making adding detail, and by checking the real possibilities of obtaining the data necessary for creating such a cadastre.

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