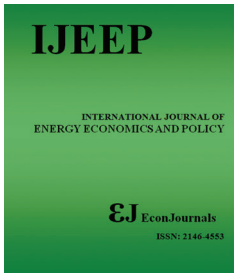
Vanegas-Chamorro, Marley; Cely-Bautista, María Mercedes; Villicaña-Ortiz, Eunice et al.

Article

Current status of solar-thermal and solar-photovoltaic technology development at the international level

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Vanegas-Chamorro, Marley/Cely-Bautista, María Mercedes et. al. (2022). Current status of solar-thermal and solar-photovoltaic technology development at the international level. In: International Journal of Energy Economics and Policy 12 (6), S. 112 - 122. https://econjournals.com/index.php/ijeep/article/download/13699/6996/31587. doi:10.32479/ijeep.13699.



International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(6), 112-122.

Current Status of Solar-Thermal and Solar-Photovoltaic Technology Development at the International Level

Marley Vanegas-Chamorro[1]*, María Mercedes Cely-Bautista[1], Eunice Villicaña-Ortiz[2], Daniel Mendoza-Cáceres[3], Valeria Visbal-Vanegas[4]

[1]Research Group KAÍ, Department of Chemical Engineering, Universidad del Atlántico, Puerto Colombia, Barranquilla Metropolitan Area-081007, Atlántico, Colombia, [2]Universidad de Ingeniería y Tecnología, Departamento de Ingeniería Mecánica e Ingeniería de la Energía, (511) 230 5000 anexo 4212, Jr. Medrano Silva 165, Barranco, Lima-Perú, [3]Universidad del Atlántico, Department of Industrial Engineering, Universidad del Atlántico, Puerto Colombia, Barranquilla Metropolitan Area-081007, Atlántico, Colombia, [4]Universidad del Norte, Department of International Business, Kilómetro 5 Vía, Puerto Colombia, Metropolitan Area of Barranquilla, Colombia. *Email: marleyvanegas@mail.uniatlantico.edu.co

Received: 28 July 2022 **Accepted:** 23 October 2022 **DOI:** https://doi.org/10.32479/ijeep.13699

ABSTRACT

This article shows the trend in the development of solar thermal and solar photovoltaic technologies and their impact on developing more efficient and sustainable systems based on a bibliometric and scientometric study from 2000 to 2022. By conducting a bibliometric analysis, the incidence of publications related to the topic was determined, concerning the countries with the highest production, institutions, most representative authors, and keyword analysis, among others; in addition, the study of patents related to the topic was analyzed. The databases Scopus, Journal citation report, Espacenet software, and different computer tools were used for the analysis. The results showed that the countries with the most significant impact and production of technologies are the United States, India, China, Spain, and Brazil, which account for more than 50% of the total. The United States is the country that produces the most patents.

Keywords: Solar-Thermal Energy, Solar-Photovoltaic Energy, Emerging Technologies, Bibliometric Studies, Scientometric Research
JEL Classifications: Q16, Q20, Q42

1. INTRODUCTION

The high global demand and increasing needs of industries in the energy sector in their different sectors have shown the use of solar photovoltaic (PSE) and solar thermal energy (TSE) as renewable technologies with great potential for cleaner, more reliable, and affordable power systems for the near future (Gul et al., 2016).

After the 70 s energy crisis, the industry and the energy market began a search for alternatives that would meet the market needs, especially with solar thermal and solar photovoltaic technologies for cooling processes, such as refrigeration and air-conditioning (Lazzarin, 2014). However, their high costs, especially in the solar photovoltaic system, did not allow further development. In the case of solar thermal energy, applications have been considered in single and double-effect absorption chillers, water-condensed, and low-temperature adsorption machines future (Gul et al., 2016).

Conventional energy sources such as fossil fuels affect climate change, global warming, air pollution, and acid rain. On the other hand, solar photovoltaic energy, because it does not need to be refined, extracted, or transported to the generation site, minimizes damages, unlike fossil fuels. Only in some cases, due to the process of photovoltaic energy, can it emit some greenhouse gases, mainly in the manufacturing processes of solar cells or photovoltaic modules (Sampaio and González, 2017).

According to Bortoluzzi et al. (Bortoluzzi et al., 2021), renewable and sustainable energies are alternatives that for decades have been essential for the future of societies, and that today need to be addressed to minimize environmental damage, with lower costs to satisfy the social values of consumers.

Solar thermal and photovoltaic solar energy are alternatives that continue to be researched with increasing growth. A search in the Scopus database for keywords such as "photovoltaic solar energy" found almost 28476 documents, while with the keyword "thermal solar energy" we obtained 923. Therefore, photovoltaic solar energy has been generating publications since the 1950 s, with a more significant increase since the 1990 s -with more than 100 documents per year. On the other hand, in the case of solar thermal energy began to generate documents in the 70 s, but only in 2010 there is an increase with more than 20-30 publications per year.

One of the themes in these searches is based on the development of new technologies which have generated important contributions in the environmental aspect, in addition to a remarkable social and economic value over time.

1.1. Emerging Technologies

The demand for energy worldwide is growing exponentially, as well as the impact of non-renewable fuels or materials used. The search for options, such as renewable energies, solar thermal, and solar photovoltaic energy, continues to be viable and sustainable alternatives for the demand required at this time.

According to Chandrasekar and Senthilkumar (Chandrasekar and Senthilkumar, 2021), the growth of natural energy resources is projected to supply 67% of total energy requirements in applications such as power generation, heating, and transportation by the year 2050. Solar water heating systems are widely used to harness solar energy to generate hot water or steam for different applications, such as drying, heating, preheating, and sterilization systems.

Solar photovoltaic energy (PSE) is applied for electricity generation. This type of energy has grown substantially in recent years, using first, second, and third-generation photovoltaic panels. These panels use different technologies such as thin films, innovative semiconductors with nanocrystalline polymers, solar cells, and systems with semiconductor materials (polycrystalline and monocrystalline silicon). Each of these systems has different degrees of efficiency. The problem with some solar photovoltaic electricity generation systems is the amount of energy dissipated as heat, which increases the temperature in the environment (Awasthi et al., 2020).

The improvement techniques in solar photovoltaic systems improve their efficiency, useful life, and environmental factors. In that sense, Rajmati et al. (Rajmati et al., 2021) analyzed four systems that show significant improvements; firstly, the use of textured and reflective surfaces in the solar PV cell using hydrogenated amorphous silicon (SiH), varying period sizes and heights increasing the efficiency of the system. A second system uses indium tin oxide as front contact in the solar cell, in this case using layers of molybdenum, CIGS and CdS sandwiched layers, which improve efficiency. Another alternative to improve efficiency is using gold nanoparticles (Sajid, 2022). Due to their small size and high surface density, they boost the physicochemical properties, allowing their location between semiconductors to increase their spectral efficiency. Finally, a fourth system is related to the development of nano-imprinted gratings; in this case, the increase in efficiency is enhanced by lateral gratings that improve light capture and trajectory. Although these last two systems improve the efficiency of PV systems, they do not lower their costs since they are technologies that still require high investment for their development.

For the case of solar thermal energy, Chandrasekar et al. (Chandrasekar and Senthilkumar, 2021), show a summary of technologies developed in the last decade. These techniques are based on heat extraction systems using nanofluids and phase change materials, energy augmentation such as CPVT systems, and air space heating systems, Figure 1 (Chandrasekar and Senthilkumar, 2021).

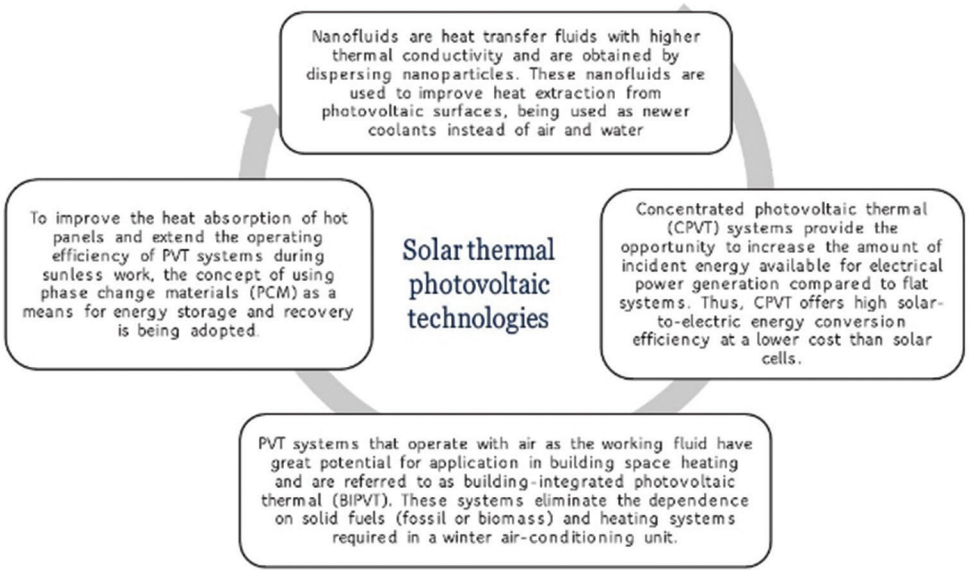
On the other hand, in TSE systems, Kumar et al. (Kumar et al., 2021) showed a classification of the system according to their operating temperature: Low-temperature systems (30-150°C); medium-temperature systems (150-400°C); and high-temperature systems (>400°C). Each system presents different efficiencies. Low-temperature systems such as flat plate collectors (FPC), evacuated tube collectors (ETC), solar ponds (SP), and solar chimney (SC) are in the order of 15-40%. Medium temperature systems are linear Fresnel reflectors (LFR) and parabolic trough collectors (PTC), which are in the order of 50-60%. Finally, for high-temperature systems such as central receiver (CR) and parabolic dish collector (PDC) is in the order of 60-80% (Kumar et al., 2021).

Another emerging technology that has continued to grow in the last decade is Artificial Intelligence, according to (Lyu and Liu, 2021). Artificial intelligence (AI) is defined as "a collection of all kinds of technology and methods that are used to execute tasks related to the human brain, especially cognitive tasks such as learning and problem solving." This new and growing technology enables the use of digital machines and devices at all levels of the energy system, from demand forecasting, generation, and conservation of energy, to the use of artificial intelligence in energy management (Lyu and Liu, 2021).

Emerging digital technologies such as artificial intelligence, Big Data, IoT, robotics, and cloud computing, among others, are necessary technologies in the energy sector not only for the prediction of markets and systems with better efficiencies and conditions but also for the impact that can be generated in modern society and the economy, developing a series of technical skills that can change the future of employment in our society.

This article aims to review the most recently published information on solar thermal and solar photovoltaic energy in terms of new technologies and their impact on the development of more efficient and sustainable systems based on a bibliometric and scientometric study during the period 2000-2022.

Figure 1: Technologies used for photovoltaic solar thermal systems



2. METHODOLOGY

The methodology for developing this research was based on bibliometric studies of some authors (Bautista et al., 2020; Chamorro and Cecilia, 2012). The data were collected from the Scopus software on July 09, 2022. For the development of the bibliometric study, a combination of keywords using logical operators AND, OR, NOT, including title, abstract, author, and keywords, among others, was used to develop the equation that covers all relevant publications related to solar thermal and solar photovoltaic energy technologies.

The databases used were Scopus, web of science, and software such as Openrefine, VOSviewer, advanced Excel, and Espacenet software. The VOSviewer software was used to develop the analysis of keywords based on their frequency and co-occurrence among authors or countries.

For the research, the following equation was used for the bibliometric study: ((TITLE-ABS-KEY ("thermal solar")) OR (TITLE-ABS-KEY ("photovoltaic solar")) AND (emerging AND technology*) AND (PUBYEAR >2000)). A total of 321 documents were obtained and analyzed in their entirety.

To complement the information, a patent analysis was developed using Esp@cenet software to determine the incidence of patent production, timeline, most representative countries, application areas, and most representative applicants. In the case of patents, the following equation was used: (nftxt = "thermal solar" OR nftxt = "photovoltaic solar") AND (nftxt = "emerging" AND nftxt = "technology*") AND pd = "2000-2022"; where 1000 patents related to the topic were reported.

2.1. Indicators of Research Results

The indicators of the impact measures of this research are based on the sources of origin, authors, institutions, countries, h-index, and the correlations present. The impact factor of the publications was taken from JCR (Journal citation reports), where the number of current citations of the source in the last 2 years is related. On the other hand, the h-index indicates a ratio of the number of citations with respect to the number of publications presented by the author, institution, country, or journal concerning solar thermal and photovoltaic technologies in the last 20 years.

For the analysis of journals, institutions, or countries, the equivalent percentage of articles or citations is considered to analyze their contribution and influence. This index is calculated with the number of articles or citations concerning the total of each one, as shown in Equations 1 and 2, respectively.

$$\%=\frac{\text{Articles}}{\text{üüüüüüüü}} \quad (1)$$

$$\%=\frac{\text{citations received}}{\text{Total citations}} \quad (2)$$

In the case of the author's performance, the productivity index (PI) was used, where different levels are presented to indicate how much productivity the author presents. When PI is equal to zero, it is considered a small producer (1 single work). If PI is between 0 and 1, it is considered a medium producer. When PI is equal to one, it is considered a large producer (10 or more works) and is defined as the decimal logarithm of the number of articles published, Equation 3.

$$PI = Log\ N$$

Authors were analyzed on the basis of the total number of articles (TA), the total number of citations (TC), key articles (AC), subject h-index, overall author h-index, and the personal productivity indicator for each author (PI). The prestige in the production of an author is based on a limited number of citations; thus, the term "key article" is taken for those articles with more than 50 citations. On the other hand, the number of authors per publication and year and their impact is analyzed with the number of citations per year.

For the scientometric study, which is based on the search and analysis of patent databases, the Espacenet software was used to study the number of patents per country, year, area of application, and the most representative applicants.

3. RESULTS AND DISCUSSION

3.1. Bibliometric Study

3.1.1. Article and patent analysis

Table 1 summarizes the most relevant data on the search for publications related to solar thermal and solar photovoltaic technologies over the last 20 years; it is worth noting that the average growth of publications is 32% over the 20 years. This is generating new expectations in the development of renewable energy technologies.

Figure 2 shows the results obtained for the number of publications and patents between 2000 and 2022 in the solar thermal and photovoltaic energy field. It shows upward growth, especially since 2011, and in general, an average growth rate of 32%.

From a preliminary study related to the review of keywords of solar thermal and photovoltaic solar energy technologies independently, the following was found: For the keywords: "thermal solar energy" AND technology* -766 publications were found, while with the keyword: "photovoltaic solar energy" AND technology* -20602 publications were found, this analysis showed significant growth of publications in photovoltaic solar energy (PSE), which was evident since the 80s, where the number of publications exceeded 25-30 documents per year, by the year 2000 it reached 200 documents and currently exceeds 1000 documents per year. In the case of solar thermal energy, its growth was evident around 2009-2010, with 15 papers. By 2019 it had significant growth with 91 papers; however, it currently does not reach more than 100 papers per year, as shown in Figure 3.

3.1.2. Country statistics

The analysis of solar photovoltaic and thermal energy-related technologies has an essential presence in different countries worldwide, as shown in Figure 4.

Table 1: Summary table of information on solar thermal and photovoltaic technologies

Description	Results
Documents analyzed	321
Time period	2000-2022
Average growth rate publications	32%
Keywords	1764
Average citations per document	26,34
Total citations	8548
Authors	1282
Countries	66
Single-authored documents	29
Types of documents	
Article	172
Conference paper	69
Review	50
Book chapters	25
Book	4
Paper data	1

The top 5 countries, the United States, India, China, Spain, and Brazil, account for more than 50% of the total number of publications and 46.9% of the total number of citations. Table 2 shows the analysis of documents and citations of the ten countries with the highest production in the area concerning the 63 countries found.

From the point of view of solar thermal energy, China shows the highest number of publications, making it a leader in the field of solar energy. This is due to its long-term government policies, the rapid economic growth, and the increasing demand for space cooling with sustainable and clean systems (Saikia et al., 2020). On the other hand, photovoltaic solar energy has been developing and growing since the 80s. It is noteworthy that the United States and Germany show high productivity, specifically in devices for nanometer-level systems using photovoltaic systems to improve solar cell design approaches (Strupeit and Palm, 2016; Atwater and Polman, 2010). This is to understand the reason for the incidence of the countries in our case study. Table 2 shows the analysis of documents and citations of the ten countries with the highest production in the area. It is observed that the United States has the highest number of publications, with 13.8% of the total number of citations. This aspect is corroborated by the fact that in the study of patents, it is the United States that in 2000-2022 study period has developed the most significant number of patents from the point of view of solar thermal energy, solar photovoltaic energy, and hybrid systems, followed by China and Australia.

Figure 2: Evolution of the articles and patents from 2000 to 2021

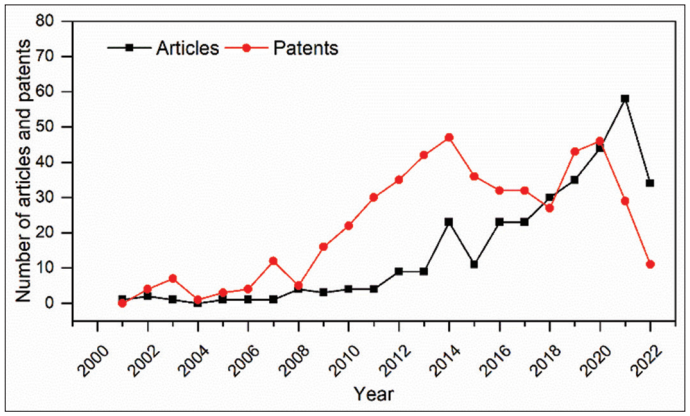


Figure 3: Timeline of publications related to TES and PSE technologies independently

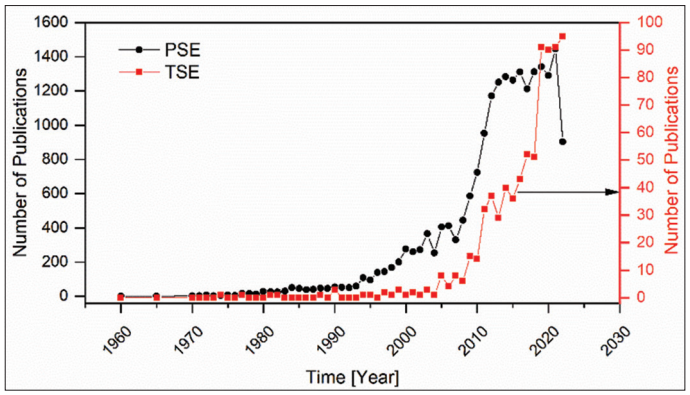


Figure 4: Geographical distribution of publications related to technologies in TSE and PSE

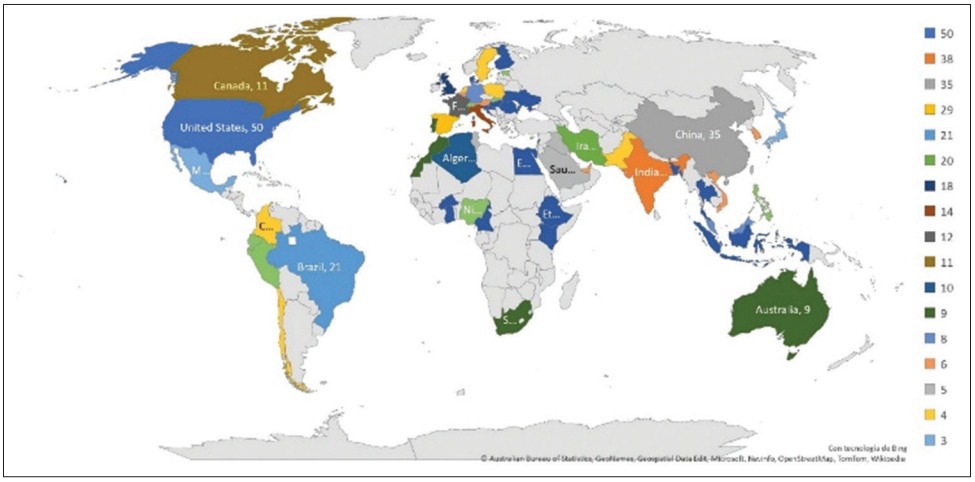


Table 2: Analysis of documents and citations from the ten countries with the highest production in the field

Country	Total		Number of productive		Hot articles		h-index
	Papers	Citations	Authors	Institutions	No. of Art.	Citations	
United states	50	1156	158	103	6	665	16
India	38	528	122	84	4	379	9
China	35	912	160	92	7	543	16
Spain	29	857	118	55	5	589	13
Brazil	21	471	89	39	1	324	8
Iran	20	650	72	48	5	464	11
United Kingdom	18	400	67	44	2	157	11
Italy	14	157	65	32	1	65	6
France	12	218	60	45	2	153	6
Turkey	12	61	41	28	0	0	4

It should be noted that India and Spain entered with an important contribution to these issues. Due to the problems of global warming and the energy crisis in Spain, alternatives are being explored from different sources that allow more efficient thermal or photovoltaic systems for cooling or heating systems.

In the case of India, the second most populated country in the world and the seventh largest in terms of area, its primary energy resource is solar energy. In order to make the best use of this resource, it is crucial to develop interdisciplinary studies that consider different cultural, economic, social, and environmental elements necessary for implementing systems such as photovoltaic solar energy. This technology would benefit society, which has been developed slowly and with many complexities. However, it should be noted that the growth of installations in recent years of photovoltaic solar energy systems exceeds almost twenty times the solar thermal systems (Padmanathan et al., 2019). On the other hand, the high degree of solar insolation present in this region is an important reason for generating electricity from this renewable energy. A decade ago, electricity was generated by hydro, coal, and gas mainly; while renewable energy only represented only 8% (Kumar, 2016). All these aspects led to the growth in publications in this country.

Taking into account the h-index and the number of citations of key articles, the United States, China, and Spain are the countries with the highest index; however, the number of publications does not fully demonstrate the degree of impact of these countries.

Figure 5 shows the collaborative networks of 26 countries in the field of TSE and PSE technologies. The size of the spheres indicates the number of papers published by each country, and the color indicates the most active period in the last ten years. The connecting lines between them indicate the present cooperation. In Figure 5, it is significant to see the strong collaboration between the United States and the United Kingdom in 2016 and China and Spain in 2018 and 2019, forming a small cluster. Further ahead, towards 2020, India appears with a considerable number of publications and a strong collaboration network with the United States.

3.1.3. Institutional production

Table 3 shows the distribution of the most productive institutions in the area of solar photovoltaic and solar thermal energy. There, the "National Renewable Energy Laboratory" is the institution with more documents. This institution is located in Denver-USA, has 39 patents, and works mainly in engineering, materials science, and energy, among others. On the other hand, the "CNRS Centre National de la Recherche Scientifique," located in Paris-France, has 25481 patents and works in physics and astronomy, biochemistry, and engineering, among others. The five main institutions have 29.2% of the total citations.

3.1.4. Journal analysis

Table 4 presents the list of journals with the most publications in the area of Solar Thermal Energy and Photovoltaic Solar Energy

in 2000–2022. The journal "Renewable and Sustainable Energy Reviews" presents the highest number of documents with a citation percentage of 20.48% with respect to the total number of citations. The ten journals with the most documents represent 30.5% of the total citations; however, the table shows in the final part the journals with the highest number of citations represented in a single article and 26.9% of total citations. Another point to highlight is the publishing country of the journals, as the United Kingdom is the publishing country with seven of the ten journals that publish the most in the area. The most cited article is "Solar-energy conversion and light emission in an atomic monolayer p-n diode" with 1000 citations, published by Pospischil et al. in the journal Nature Nanotechnology.

Table 3: Distribution of the most productive institutions

Journal	Countries	TA	TC	h-index
National renewable energy laboratory	United States	8	133	5
CNRS centre national de la recherche scientifique	France	6	96	3
University of tehran	Iran	5	243	4
Universidad de Castilla-La mancha	Spain	4	13	2
Technische universitat wien	Austria	4	2079	4
Chinese academy of sciences	China	4	70	3
UNSW Sydney	Australia	4	65	2
Tarbiat Modares University	Iran	4	243	3
UM-SJTU Joint Institute	China	4	238	4
University of Johannesburg	South Africa	3	72	2

TA: Total articles, TC: Total citations

3.1.5. Distribution by topic

When talking about solar thermal and solar photovoltaic energy, there are many representative areas that, in one way or another, require this technology. However, from the bibliometric study, it was found that the areas of Engineering (21%), energy (20%), Materials Science (12%), and Computer Science (9%) are the most representative, with 61.6% of the total (Figure 6).

3.1.6. Authors statistics

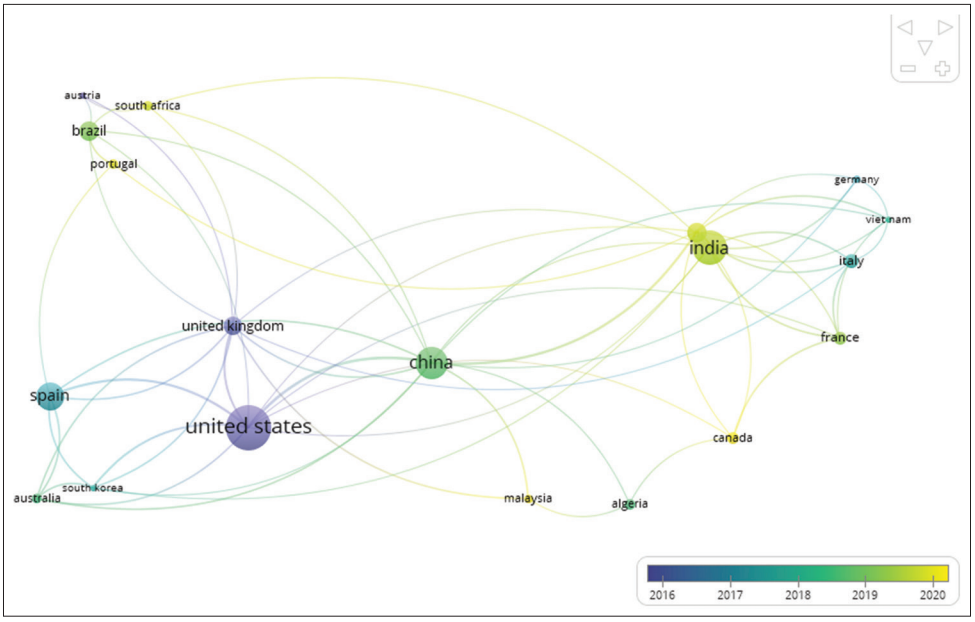
According to Table 1, the 321 articles on solar thermal and solar photovoltaic technology were published by 1282 authors from 66

Table 4: Most productive journals in the field of solar thermal energy and solar photovoltaic energy in the period 2000-2022

Countries	Institute	TA	TC	TA (%)	TC (%)	h-index	SJR	1Cites
United Kingdom	Renewable and sustainable energy reviews	13	1712	4.05	20.03	337	3.68	16.95
United Kingdom	Solar energy	10	190	3.12	2.22	194	1.42	7.12
United Kingdom	Renewable energy	6	107	1.87	1.25	210	1.88	8.65
United Kingdom	Energies	5	110	1.56	1.29	111	0.65	3.54
United Kingdom	International journal of energy research	5	37	1.56	0.43	102	0.81	5.18
United Kingdom	Journal of cleaner production	5	196	1.56	2.29	232	1.92	10.95
Netherlands	Solar energy materials and solar cells	5	75	1.56	0.88	195	1.52	6.76
Switzerland	Applied sciences switzerland	4	7	1.25	0.08	75	0.51	3.14
United Kingdom	Energy	4	143	1.25	1.67	212	2.04	8.51
Switzerland	Sustainability switzerland	4	31	1.25	0.36	109	0.66	4.17
United Kingdom	[2]Nature nanotechnology	1	1000	0.31	11.70	368	11.7	22.75
United States	[2]Nano letters	1	751	0.31	8.79	511	3.76	11.37
United Kingdom	[2]Nature communications	1	549	0.31	6.42	410	4.85	15.40

[1]Citation by documents (2 years), [2]Journals with the highest number of citations by document. SJR: Scimago journal rank

Figure 5: Collaboration networks of the 26 countries in the field of emerging technologies in solar thermal energy and solar photovoltaic energy



countries. Table 5 shows the top 10 authors, where Eslamian, M from the M-SJTU Joint Institute and Mueller T from the Vienna Institute of Photonics, present an equal number of articles in the area, however, Mueller's citation rate is quite representative, with 24.3% of the total citations, and his article related to "Solar energy conversion and light emission in an atomic monolayer p-n diode" presents 1008 citations, that is 11.7% of the total citations in this study.

Figure 7 shows the relationship between the number of authors per publication and the number of citations per year. It was found that articles with two authors represent 21%, with three authors 18.8%, and with four authors 20.1%, i.e., with 2, 3, and 4 authors accounting for 60% of the total number of publications and publications, with only one author accounting for 9.6%. It is worth noting that 2014 was a year in which its articles received a high degree of citation with 39.6%, followed by 2018 with 14.5% and 2020 with 7.7% with respect to the total number of citations. Similarly, that year was characterized by publications with five authors.

Figure 6: Distribution of publications by research areas

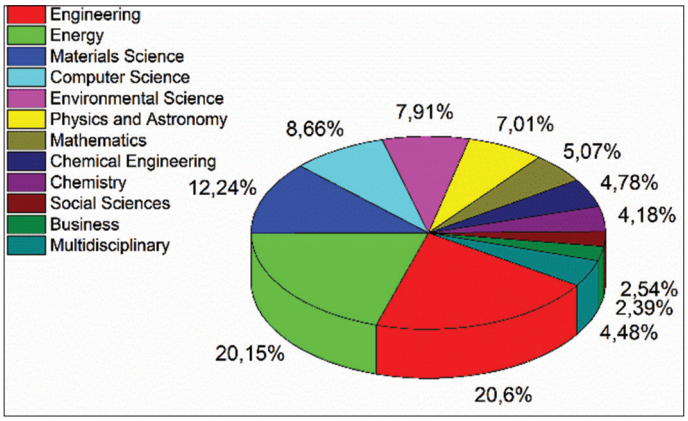
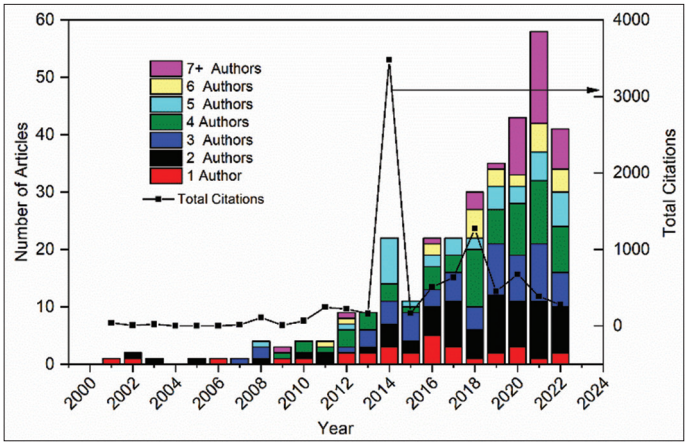


Figure 7: Ratio of the number of authors per article in the area of technology in TSE and PSE and the number of citations per year



3.1.7. Keyword occurrence

Figure 8 shows a correlation graph of keywords in solar thermal and photovoltaic system technologies. In the present study, 1714 keywords were found; using Vosviewer software, a co-occurrence analysis was performed with a minimum of five documents for the analysis of 134 correlations. The size of the spheres indicates the number of documents containing each word, and the colors indicate cluster formation. A cluster is a set of elements within the map, not overlapping, characteristic of a theme. In this case, six clusters were found. The first cluster describes energy-related areas related to its conversion, storage, efficiency, and utilization. A second cluster is related to estimation parameters, temperature effect, modules, and equipment. The third cluster refers to environmental impacts, life cycles, panels, carbon effect, and fossil fuels. A fourth cluster refers to electric and photovoltaic power systems, solar cells, and inverter systems. The fifth cluster is related to the use of nanostructures, materials such as perovskite, thin films, and components such as selenium, graphite, among others, areas analyzed by Moro et al., (Moro et al., 2020), where it was found that technologies using perovskite and thin films show a technological readiness level of 4-5 and 3-4 respectively, this to observe the importance of this area. Finally, cluster six relates renewable energy, solar radiation, collectors, thermal energy, and photovoltaics.

Keywords such as solar cells, solar power generation, photovoltaic cells, and photovoltaic solar energy are the most cited in the document, according to the current trends.

3.1.8. Most cited key articles

According to Table 6, which shows the analysis of the ten most cited articles, it was found that most of them, i.e., 60%, corresponding to the year 2014, with a high citation, which was previously expressed in the analysis of citation and authors.

The most frequently treated topics in the abstracts are based on: two-dimensional semiconductors used in electronic devices,

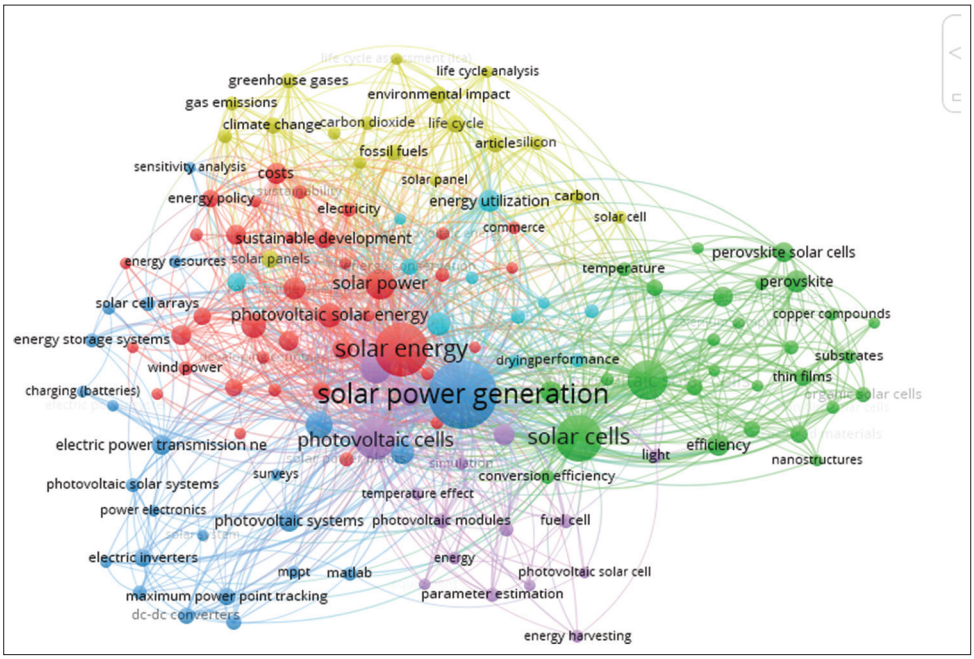
Table 5: Top 10 authors in the area of solar thermal and solar photovoltaic technology

Journals	Affiliation	TA	TC	AC	h-index topic	h-index author	IP
Eslamian	UM-SJTU joint institute	4	238	3	4	31	0.602
Mueller and Malic	Photonics institute, Vienna	4	2079	4	4	37	0.602
Chen	Key laboratory of intelligent image processing and analysis, Wenzhou	3	39	0	2	66	0.477
Furchi	Technische universität wien, Vienna	3	1804	3	3	14	0.477
Heidari	University of Tehran, Tehran	3	59	0	2	49	0.477
Paul	De Montfort University, Leicester	3	27	0	3	16	0.477
Rumbles	National renewable energy laboratory, Golden	3	2	0	1	61	0.477
Zakutayev	National renewable energy laboratory, Golden	3	106	1	3	43	0.477
Akinoglu	Middle east technical university (METU), Ankara	2	29	0	2	13	0.301
Almeida	Instituto superior técnico, Lisboa	2	7	0	1	38	0.301

Table 6: Analysis of the ten most cited key articles in the period 2000–2022

No	Year	Author	Title	Journal	Citations
1	2014	Pospischil et al.	Solar-energy conversion and light emission in an atomic monolayer p-n diode	Nature nanotechnology	1000
2	2014	Furchi et al., 2014	Photovoltaic effect in an electrically tunable Van der Waals heterojunction	Nano Letters	751
3	2014	Mwasilu et al., 2014	Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration	Renewable and sustainable energy reviews	587
4	2014	Buscema et al., 2014	Photovoltaic effect in few-layer black phosphorus PN junctions defined by local electrostatic gating	Nature communications	549
5	2017	Sampaio and González	Photovoltaic solar energy: Conceptual framework	Renewable and sustainable energy reviews	327
6	2018	Mueller and Malic, 2018	Exciton physics and device application of two-dimensional transition metal dichalcogenide semiconductors	NPJ 2D materials and applications	278
7	2018	Urieta-Mora et al.	Hole transporting materials for perovskite solar cells: a chemical approach	Chemical society reviews	248
8	2011	Amer and Daim	Selection of renewable energy technologies for a developing county: A case of Pakistan	Energy for sustainable development	238
9	2014	Shah et al.	Energy and exergy analysis of typical renewable energy systems	Renewable and sustainable energy reviews	169
10	2014	Motevali et al.	Comparison of energy parameters in various dryers	Energy conversion and management	150

Figure 8: Keywords in the area of solar thermal system and solar photovoltaic system technologies



systems with atomic crystals of graphene and transition metals (MoS2, WSe2), with a high potential and quality of the material for application in different solar (Pospischil et al. 2014; Furchi et al. 2014; Mueller and Malic, 2018). Applications in the automotive area related to the advances in the interaction of electric vehicles with a smart grid, analyzing their infrastructure, communication, and network control. This topic has generated wide expectations for developing more eco-environmental systems (Mwasilu et al., 2014). Another important topic lies in the use of perovskite. This element has come to the forefront of research compared with already established technologies such as CdTe and silicon, where structure-property relationships, stability, conductivity, and device performance are analyzed (Urieta-Mora et al., 2018).

3.2. Scientometric Analysis

The scientometric analysis was developed from databases using Espacenet software, using a list of keywords on solar thermal and solar photovoltaic technologies.

Patents are key indicators to measure the progress of technologies in countries, with a high impact on the development of these, as well as reflect the dynamism in the production of knowledge that impacts societies. Our case study is to evaluate, from scientometrics, the impact of TSE and PSE technologies at the international level and their impact on our society. From the Esp@cenet software, the following equation was used for patent analysis: (nftxt = "thermal solar" OR nftxt = "photovoltaic solar")

AND (nftxt = "emerging" AND nftxt = "technolog*') AND pd = "2000-2022"; 1000 documents were found there.

Figure 9 shows the timeline of patents in the study area in the period 2000-2022, obtained from the Esp@cenet software. An important aspect is the significant growth of patents between 2010 and 2014 due to the fact that the leading countries in this technology, such as China, Japan, USA, Germany, and the United Kingdom, represented 80% of photovoltaic installations in that period, guaranteed by financing, research, and development in this type of technology; in addition, solar thermal energy, in this period, was growing as an alternative that began to be implemented, avoiding the use of fossil fuels, and working hard to increase its performance and efficiency in storage processes (Gul et al., 2016; Saikia et al., 2020; Kant et al., 2016; Rashidi et al., 2018).

The growth of scientific publications in the study period has been ascending, as seen in Figure 1; however, making a comparison of articles with respect to patents, in the period 2010-2014, 48 scientific documents were found compared to 176 patents, this taking as a source the Scopus database, which indicates an advance in technological development in this area. For the scientometric study and taking the Esp@cenet software as a source, a total of 1000 documents were found under the same equation. For the greatest growth (2010-2014), 399 patents were found, corresponding to 39.9% of the total, which indicates that the growth of patents in this energy TSE and PSE area has been significant for the development of technologies in these countries.

3.2.1. Patents by country

Figure 10 shows the number of patents per country; in this case, the United States had the highest production with 41.6%, followed by China with 25.9%, then Australia and Canada, countries with a high degree of development in these technologies. In the case of Latin America and the Caribbean, there is a minimal contribution of patents in this area; only Brazil presents one patent for the study equation.

3.2.2. Applicant companies

Patent applicants are individual users, companies, organizations, or universities. From the analysis in Figure 11, it can be observed that the largest number of applicants corresponds to companies (57%), independent persons (22%), Universities (16%), and patents (5%) that do not present applicants yet. This indicates the commitment of the companies at the time of protecting an invention. The applicant companies with the highest number of patents in the area are shown in Table 7. Solutia INC. presents 14 patents. This company is a U.S. manufacturer of special chemical products applied to laminated glass, window films, protective barriers, and rubber processing; the applications are mainly in the process of painting, safety, and energy efficiency in the automotive and architectural accessories market.

On the other hand -3M innovative properties co-provide hardware and healthcare products. The Company offers products for aircraft, abrasives, animal, architectural, construction, and automotive. Szydlowski Allen and Szydlowski Ian work on developing patents

Figure 9: Timeline of patents found in the study area in the period 2000-2022

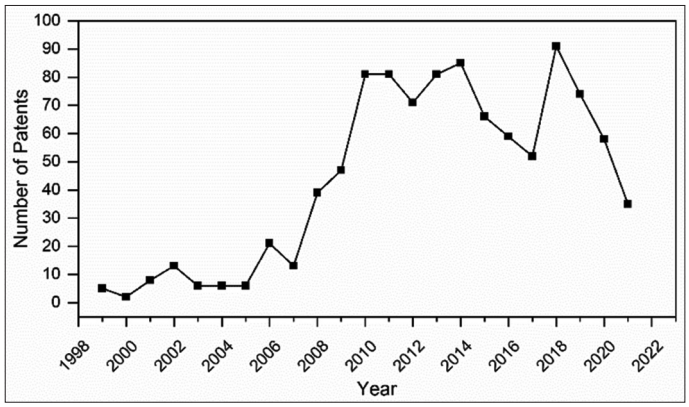


Figure 10: Number of patents by country

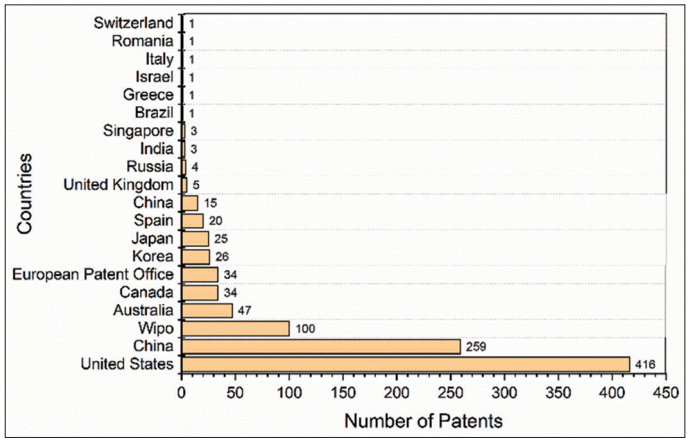
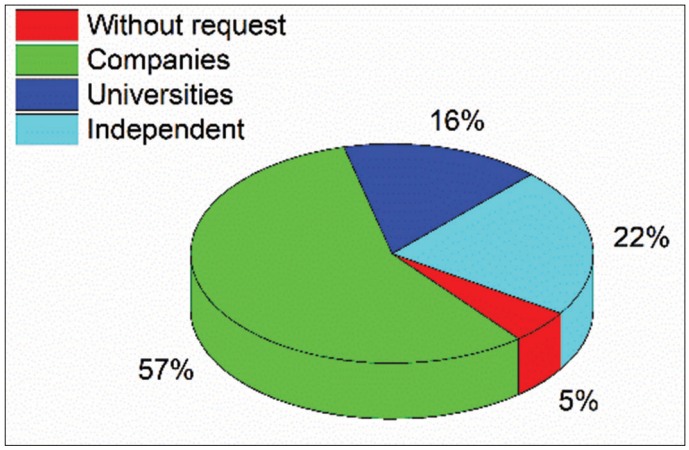


Figure 11: Number of patents by country



in different areas, especially for the liquid transport and chemical area, Table 8.

3.2.3. Inventors

Figure 12 shows the number of documents and the country of the inventor. It is worth noting that the United States has the most inventors (44%), followed by Canada (5%) and France (3%).

3.2.4. Patent groups

Figure 13 shows the percentage of documents according to the classification of patents. It is worth noting that the largest number

Figure 12: Number of patents by country

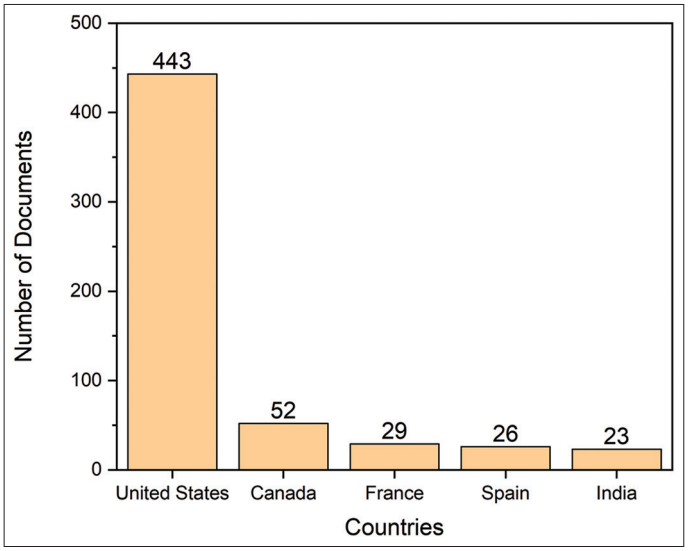
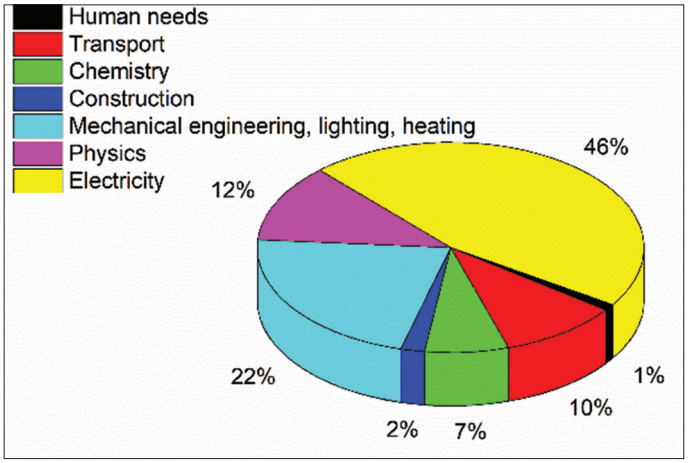


Figure 13: Percentage of documents according to patent classification



of patents is in the general area of electricity (46%), followed by mechanical engineering in the area of lighting and heating (22%) and the Physics section (12%), totaling 80% of the total number of documents.

In the ranking of patents, Table 9 shows the five areas with the most documents in the area of TSE and PSE with the International Patent Classification (IPC).

The production of technologies in the TSE and PSE area represented by patents shows several aspects:
From the point of view of patents in the area of solar photovoltaic energy, and according to statistics, the development generated in this area is growing. The United States is where most patents are produced, with the highest number of inventors and applicant companies, followed by Germany. In the case of solar thermal energy, patent production is similar between China and the United States. However, the same trend is seen, i.e., the inventors and applicant companies are the United States and Spain in this case. An important aspect in this area is based on the support that the country generates to science and technology processes in the continuous development of these types of processes, as is the case of China and the United States (Kant et al., 2016; Rashidi et al., 2018).

Another important element, especially from the point of view of environmental impact, lies in the development of alternatives for managing waste generated by TSE and PSE technologies. According to Nain and Kumar (Nain and Kumar, 2022), it is necessary the analysis of waste from the solar PV industry, which significantly impacts the generation of heavy metals, which can exceed the allowed limits and significantly alter the environment due to their release in different media, soils, and tributaries. Similarly, it is relevant to understand the benefits of photovoltaic energy and review the development of new sustainable and sustainable policies.

Table 7: Companies applying for patents in the area

Applicants	Number of patents
Solutia Inc	14
Harvard college	8
3m Innovative properties Co	7
Szydlowski allen	6
Szydlowski Ian	6
Commissariat Energie Atomique	5
Hunan red solar new energy science and technology co ltd	5
Bluescope steel Ltd	4
Cooperrider paul H	4
Eaton Intelligent power Ltd	4

Table 8: Top 10 most representative inventors

Inventors	Number of patents
Donelson michael eugene	12
Karagiannis aristotelis	12
Tran khanh Duc	12
Wade bruce Edward	12
Duan Xiangfeng	7
Lieber Charles M	7
Cui Yi	6
Huang Yu	6
Szydlowski Allen	6
Szydlowski Ian	6

Table 9: Main groups of patents

IPC main groups	Number of patents	Area
H01L31	132	Electricity; basic electrical elements, semiconductors
H02S40	49	Electricity; generation, electrical power conversion, photovoltaic energy
H02S20	45	Electricity; generation, electrical power conversion, photovoltaic energy
F24J2	29	Heating, ventilation; solar heating systems
H01L21	27	Electricity; basic electrical elements, semiconductors, solid-state devices
H01L31	132	Electricity; basic electrical elements, semiconductors
H02S40	49	Electricity; generation, electrical power conversion, photovoltaic energy
H02S20	45	Electricity; generation, electrical power conversion, photovoltaic energy
F24J2	29	Heating, ventilation; solar heating systems
H01L21	27	Electricity; basic electrical elements, semiconductors, solid-state devices

4. CONCLUSIONS

Regarding the most cited topics in scientific articles and papers, researchers focus on the development of semiconductors, more efficient systems with different types of materials and processes that guarantee viability and sustainability, without neglecting the importance of electrical systems applied to vehicles and their interaction with safer and more environmentally friendly smart grids.

The production of patents, from the point of view of the integration of solar photovoltaic and thermal energy areas, shows a high production in countries such as the United States and China, countries that contribute significantly to R&D&I systems.

The contribution of patents in TSE and PSE energy are mainly focused on electricity and the development of solar heating systems (Group of H0 and F0 patents).

5. ACKNOWLEDGMENTS

The author wishes to acknowledge the support of the UNIVERSIDAD DEL ATLÁNTICO in the development of this research.

REFERENCES

Amer, M., Daim, T.U. (2011), Selection of renewable energy technologies for a developing county: A case of Pakistan. Energy for Sustainable Development, 15(4), 420-435.

Atwater, H.A., Polman, A. (2010), Plasmonics for improved photovoltaic devices. Nature Materials, 9, 205-213.

Awasthi, A., Shukla, A.K., Manohar, M.S.R., Dondariyaa, C., Shukla, K.N., Porwalab, D., Richhariyac, G. (2020), Review on sun tracking technology in solar PV system. Energy Reports, 6, 392-405.

Bautista, M.M.C., Chamorro, M.V., Piñeres, J. (2020), Impacto de investigaciones sobre grafitización de antracitas durante Los Años 1960-2018/impact of research on anthracite graphitization during the years 1960-2018. Prospectiva, 18(1), 32-39.

Bortoluzzi, M., De Souza, C.C., Furlan, M. (2021), Bibliometric analysis of renewable energy types using key performance indicators and multicriteria decision models. Renewable and Sustainable Energy Reviews, 143, 110958.

Buscema, M., Groenendijk, D.J., Steele, G.A., Van Der Zant, H.S.J., Castellanos-Gomez, A. (2014), Photovoltaic effect in few-layer black phosphorus PN junctions defined by local electrostatic gating. Nature Communications, 5, 4651.

Chandrasekar, M., Senthilkumar, T. (2021), Five decades of evolution of solar photovoltaic thermal (PVT) technology-a critical insight on review articles. Journal of Cleaner Production, 322, 128997.

Chamorro, V., Cecilia, M. (2012), Estudio Del Mecanismo de Grafitización de Antracitas Sudafricanas. Spain: Universidad de Oviedo. Available from: https://www.digibuo.uniovi.es/dspace/handle/10651/13202

Furchi, M.M., Pospischil, A., Libisch, F., Burgdörfer, J., Mueller, T. (2014) Photovoltaic effect in an electrically tunable van der waals heterojunction. Nano Letters, 14(8), 4785-4791.

Gul, M., Kotak, Y., Muneer, T. (2016), Review on recent trend of solar photovoltaic technology. Energy Exploration and Exploitation, 34, 485-526.

Kant, K., Shukla, A., Sharma, A., Kumar, A., Jain, A. (2016), Thermal energy storage based solar drying systems: A review. Innovative Food Science and Emerging Technologies, 34, 86-99.

Kumar, R.K., Chaitanya, K., Kumar, S. (2021), Solar thermal energy technologies and its applications for process heating and power generation-a review. Journal of Cleaner Production, 282, 125296.

Kumar, S. (2016), Renewable and sustainable energy reviews solar photovoltaic energy progress in India : A review. Renewable and Sustainable Energy Reviews, 59, 927-939.

Lazzarin, R.M. (2014), Solar cooling: PV or thermal? A thermodynamic and economical analysis refroidissement solaire : Photovoltaque ou thermique ? Analyse thermodynamique et é conomique. International Journal of Refrigeration, 39, 38-47.

Lyu, W., Liu, J. (2021), Artificial intelligence and emerging digital technologies in the energy sector. Applied Energy, 303, 117615.

Moro, A., Joanny, G., Moretti, C. (2020), Emerging technologies in the renewable energy sector: A comparison of expert review with a text mining software. Futures, 117, 102511.

Motevali, A., Minaei, S., Banakar, A., Ghobadian, B., Khoshtaghaza, M.H. (2014), Comparison of energy parameters in various dryers. Energy Conversion and Management, 87, 711-725.

Mueller, T., Malic, E. (2018), Exciton physics and device application of two-dimensional transition metal dichalcogenide semiconductors. Npj 2D Materials and Applications, 2(1), 29.

Mwasilu, F., Justo, J.J., Kim, E.K., Do, T.D., Jung, J.W. (2014), Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. Renewable and Sustainable Energy Reviews, 34, 501-516.

Nain, P., Arun, K. (2022), A state-of-art review on end-of-life solar photovoltaics. Journal of Cleaner Production, 343. 130978.

Padmanathan, K., Govindarajan, U., Ramachandaramurthy, V.K., Rajagopalan, A., Pachaivannan, N., Sowmmiya, U., Padmanaban, S., Holm-Nielsen, J.B., Xavier, S., Periasamy, S.K. (2019), A sociocultural study on solar photovoltaic energy system in India: Stratification and policy implication. Journal of Cleaner Production, 216, 461-481.

Pospischil, A., Furchi, M.M., Mueller, T. (2014), Solar-energy conversion and light emission in an atomic monolayer p-n diode. Nature Nanotechnology, 9(4), 257-261.

Rajmati, M., Vrushabh, A., Shital N. (2021), A review on recent developments in solarphotovoltaic cell technology. International Journal of Engineering Applied Sciences and Technology, 5(11), 211-216.

Rashidi, S., Kashefi, M.H., Hormozi, F. (2018), Potential applications of inserts in solar thermal energy systems-a review to identify the gaps and frontier challenges. Solar Energy, 171, 929-952.

Saikia, K., Vallès, M., Fabregat, A., Saez, R., Boer, D. (2020), A bibliometric analysis of trends in solar cooling technology. Solar Energy, 199, 100-114.

Sajid, M. (2022), Nanomaterials: Types, properties, recent advances, and toxicity concerns. Current Opinion in Environmental Science and Health, 25, 100319.

Sampaio, P.G.V., González, M.O.A. (2017), Photovoltaic solar energy: Conceptual framework. Renewable and Sustainable Energy Reviews, 74, 590-601.

Shah, P., Agrawal, R., Kachhwaha, S.S. (2021), Energy and exergy analysis of a hybrid renewable energy source. Lecture Notes in Mechanical Engineering, 30, 519-529.

Strupeit, L., Palm, A. (2016), Overcoming barriers to renewable energy diffusion: Business models for customer-sited solar photovoltaics in Japan, Germany and the United States. Journal of Cleaner Production, 123, 124-136.

Urieta-Mora, J., García-Benito, I., Molina-Ontoria, A., Martín, N. (2018), Hole transporting materials for perovskite solar cells: A chemical approach. Chemical Society Reviews, 47(23), 8541-8571.