Mapping 30 Years of Sustainability of Solar Energy Research in Developing Countries: Indonesia Case

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Abstract: Research into converting solar light energy into electricity using so-called photovoltaic (PV) technology or solar cells (SCs) was started a long time ago. However, most developing countries tend to lag behind. The present work delivers a bibliometric mapping analysis of 30 years of Indonesian solar energy research papers in the Scopus database. A multidisciplinary point of view is used to cover the findings comprehensively, highlighting the emerging gaps, orientation, and promising future research that will benefit many researchers, governments, and industry. Two essential keywords, “photovoltaic” and “solar cell”, were used to harvest the data. A total of 1886 documents were finally investigated. The VOSviewer was utilized as a proper complement for visualizing and analyzing the publication trends based on the keywords and authorships. Many aspects of solar research have been explored, including the basic science of semiconductors, simulation, lab-scale device fabrication, and the application of technologies and policies. The findings show that the two keywords determined the research characteristics. It also reveals that the geographical location had a remarkable impact on publication distribution. The most striking result is that a minimum of 1146 documents are centralized on Java Island. In addition, the policies related to renewable energy show a strong impact: two years after the policies were announced, the publications exhibited a two-fold increase. The results also suggest that future research should focus on the increasingly significant domestic component of silicon-based solar cells, the various multidisciplinary approaches for making PV utilization more affordable, and on shifting towards the use of perovskite solar cells. Solid national and international collaboration should be continued for the sustainability of Indonesian solar energy research.

Keywords: solar cells; photovoltaic; Indonesia; research; sustainability; renewable energy

1. Introduction

Indonesia became an oil-importing country in 2004, and its dependency on fossil fuel has been significantly increasing ever since. Currently, around 40% of Indonesia’s oil fuel is imported from abroad [1]. Moreover, in 2018, the importation of oil fuel was the primary cause of the trade balance deficit, which reached USD 8.5 billion. The energy supply of new and renewable energy (NRE) is expected to continue to significantly increase to meet the energy demand and balance the trade deficit while, simultaneously, reducing greenhouse gas (GHG) emissions. In fact, Indonesia’s government has made strategic attempts, starting with delivering energy law in 2007. Law No. 30 of 2007 aims to significantly reduce the
economy’s dependence on imported refined oil while boosting the use of other energy sources, including renewable energy resources [2]. In article 1, Section 6 of this law, it is stated that: renewable energy sources shall mean the energy sources produced from sustainable energy resources if well managed such as geothermal, wind, bioenergy, sunlight, water flow, and waterfall, and the movement and difference of sea layer temperature [2].

At present, the use of NRE in the power plant is still dominated by hydropower, followed by geothermal energy, biomass, biodiesel, and solar energy [3]. In the case of solar energy, Indonesia is known for its abundance of sunny days. The country receives 3.6–6 kWh/m²/day of solar irradiation intensity, equivalent to the annual power output of 1170–1530 kWh/kWp [4,5]. Therefore, photovoltaic (PV) technology or solar cells (SC) have excellent potential to be implemented as electricity generation devices.

With its National Energy Policy (Kebijakan Energi Nasional or KEN), Indonesia has set solar energy generation targets of 6.5 GW in 2025, and 45 GW in 2050 [6]. These targets are supported by the National Energy General Plan (Rencana Umum Energi Nasional or RUEN), which firmly imposes the mandatory use of rooftop PV technology for government and public buildings at a minimum of 30% of their roof space area [7]. However, the cost of installing rooftop solar PV technology is found at a range of IDR 13–18 million/kWp, resulting in a high initial capital investment [8]. Until late 2018, it was reported that the total installed capacity of solar power plants had only reached 95 MW [9]. With a planned total capacity of about 985.5 MW in 2028, Indonesian PV industries still have many challenges [10].

Unlike the PV industry, solar energy research in Indonesia has had a long journey and a unique timeline. Although the energy policy was announced in 2007, Indonesia’s solar energy research was already started a long time ago. Suppose the development of the PV industry can be observed by its installed capacity; in that case, a simple approach for measuring the output of solar energy research is investigating the publications [11]. The publications are a significant indicator of the performance of scholarly activities, the production of knowledge, and the achievement of recognition among communities [12]. For this reason, the bibliometric method is one of the most common and accepted techniques for analyzing the evolution, productivity, and quality of research publications [13]. The first step in performing the bibliometric analysis of a research field is to select the available databases (DBs), their suitability, and the consequences of using one over another [14]. They are vital parts of the investigation, as they enable the analysis of the scientific activity conducted by researchers, institutions, regions, and countries, and identify trends in the research. It is widely known that Web of Science (WoS) and Scopus are the two bibliographic DBs strongly considered the most comprehensive data sources [15,16]. For more than 40 years, WoS was the only source of bibliographic data, until 2004 when Elsevier launched Scopus [17]. Gradually, Scopus became recognized and used as the preferred regular database for conducting university scientometric studies and it is considered to be even superior to WoS in some particular respects [18,19].

On the basis of the Scopus data, Indonesia’s solar energy research was started by photovoltaic installation in a rural area of East Timor in 1989 [20]. After three decades of research, academics, industries, and societies argue that the solar energy research results are not yet visible. It is believed that there is no link between academic and research institutions that connects to industries. Hence, most of the research is arguably basic research. Therefore, a comprehensive investigation is urgently needed to map Indonesia’s solar energy research and establish what must been done, and where the pathway should go.

Many works that used bibliometrics have been reported. However, they mainly utilize a numbers approach, such as for publications and citations. This work presents new ideas: firstly, it is an investigation of the policies that affect those numbers. In addition, connections between the numbers and demographic aspects have been proposed. As a result, the publication itself could also reveal the actual condition of the country’s development. Here, we report a comprehensive bibliometric methodology that combines
performance analysis and a multidisciplinary perspective in mapping Indonesian solar energy research. It will benefit many parties: researchers, governments, and industry. For the researcher, this work presents a research record of the past three decades. It offers information on how far they have contributed to solar energy research. The results can be considered as a measurement of the research effectiveness. In some particular fields, it will also deliver the formed network to researchers so they can work and collaborate in order to have more impact on the research. For this purpose, VOSviewer is often utilized as a suitable tool to visualize and analyze publication maps \[21–24\]. It can measure how far the research product has entered into the industry. To a greater degree, the map could be used to observe the development of the country. Here, the government could utilize it as a guide for making policies for industry, research, and education.

2. Solar Cell Technologies and Research

The development of solar cells is classified into three categories: first-, second-, and third-generation solar cells.

2.1. First-Generation Solar Cells

First-generation solar cells consist of a single-layer, a p-n junction of large-area silicon wafers that delivers around 20–24% module performance \[25\]. This type is now the leading technology in the industrial development of solar cells, accounting for more than 94% of the market demand \[26\]. The main advantage of this solar cell technology is the stability of its efficiency. However, silicon wafer production is still a high-cost procedure, requiring high temperatures, high vacuum, and several lithographic techniques. Therefore, the research community focuses on the quest for new materials and devices to further reduce the cost of the PV electricity generated.

2.2. Second-Generation Solar Cells

Second-generation solar technologies are thin-film solar cells focused on inorganic semiconductor materials, such as cadmium telluride (CdTe), and chalcogenides, such as copper-indium-gallium-diselenide (CuInxGa1-xSe2, CIGS) \[27,28\]. The highest recorded module performance for both types is about 19% \[25\]. They can also be produced on various substrates, and even on flexible substrates \[29\]. Although these thin-film solar cells have a competitive edge over the first-generation solar cells, they have some drawbacks. Most of the materials of this generation of solar cells are based on either scarce elements, which are sometimes expensive (indium), or ones that are highly toxic (cadmium) \[30\]. Because of these drawbacks, another generation of solar cells emerged.

2.3. Third-Generation Solar Cells

The most popular developments for third-generation cells include: (i) dye-sensitized solar cells (DSSCs), which are electrochemical cells with an electrolyte \[31\]; (ii) organic solar cells (OSCs), which are based on the excitonic mechanisms from the composites of fullerenes and conjugated polymers \[32\]; (iii) hybrid solar cells (HSCs), where fullerenes are replaced by inorganic semiconductors with organic materials \[33\]; and, most recently, perovskite solar cells (PSCs) \[34\]. Although DSSC has already begun to be commercialized, most of these PV technologies are still in the R&D phase. It remains to be seen how successful they will be in taking the market share from first-generation technologies. The certified efficiencies of DSSC, OSC, and PSC modules at the moment are 8.7%, 8.8%, and 17.9%, respectively \[25\]. They have great potential for achieving low-cost solar cells by facilitating solution-based and low-temperature roll-to-roll manufacturing methods. They can be fabricated on flexible plastic substrates. Hence, they are able to be integrated into the surfaces of facades, walls, and windows. However, the stability of third-generation solar cells is still limited compared to first- and second-generation solar cells.
3. Materials and Methods

To achieve the purpose of this work, a comprehensive analysis of Indonesian solar energy research publications was performed. The investigation was begun by collecting high-quality scientific publications. In order to ensure the downloaded data was appropriate to the research objective, we used the inclusion/exclusion criteria shown in Table 1.

Table 1. Publication inclusion criteria.

| Publication type | Rationale | Included | Excluded |
|------------------|-----------|----------|----------|
| All publication types, such as research articles, conference papers, reviews, book chapters, and more |
| Quality of Publication | High-quality content ensures the validity and reliability of output research. Here, the publications were only taken from an indexed-reputable database |
| Scopus-indexed | Outside Scopus-indexed |
| Affiliation | The author(s) only select the publications that display Indonesian research institutions in the affiliation |
| Has at least one Indonesian institution in the affiliation | Publication does not display Indonesian institutions in the affiliation |
| Timeframe | The timeframe was not specified because the goal of this study is to build a comprehensive understanding of the topic rather than just the most recent. However, we restricted the timeframe to until 2020 |
| Before 2021 | From 2021 onward |
| Content | This study aims to investigate all publications affiliated with Indonesian institutions concerned with photovoltaic or solar cell technology |
| The title, abstract, and keywords include “photovoltaic” or “solar cell” |
| It does not have the words “photovoltaic” or “solar cell” in the title, abstract, or keywords. |

The aforementioned criteria in Table 1 can be directly applied in the Scopus filtering section. It was necessary to adopt strategies in the searching process in Scopus since the keywords have inherent properties and determine the research focus of the resulting documents. Hence, the preference for utilizing the keywords “solar cell” and photovoltaic” in Scopus was crucial. Generally, these two words are considered to have similar meanings; however, they might be used differently in research publications. Therefore, this work utilized these words to optimize the harvesting data from the database. We did not employ a year limitation when searching publications since we did not want to miss any
groundwork conducted decades ago. Hence, the data timeframe was only restricted until 2020. The data was downloaded on 6th September 2021. In this work, three main keywords, “photovoltaic”, “solar cells”, and “Indonesia” were adopted in order to harvest the data. The filter setting in Scopus was based on (TITLE-ABS-KEY (solar AND cells) OR TITLE-ABS-KEY (photovoltaic) AND AFFILCOUNTRY (Indonesia)). It extracted any documents from Indonesian affiliations that had “photovoltaic” and “solar cells” in their title, abstract, and keywords. It harvested 1907 publications. It is expected that some documents may not represent the objective data. Therefore, the data validation was performed by careful abstract checking based on the criteria, as illustrated in Figure 1.

**1907 documents**

- basic or fundamental knowledge of photovoltaic technology
- fabricate, assess specific functional parts of photovoltaic
- real application photovoltaic
- governments’ side, economic policies of photovoltaic

**1886 documents**

Figure 1. Schematic illustration of data validation.

The criteria for the validation were as follows: (1) publications concerning the basic or fundamental knowledge of photovoltaic or solar cell technology; (2) publications on how to create, fabricate, and assess the specific functional parts of photovoltaic or solar cell devices; (3) publications concerning the real/daily application of photovoltaic or solar cell device technology; and (4) publications concerning the government side of photovoltaic or solar cell technology. On the basis of these criteria, we excluded publications that did not focus on photovoltaic or solar cells. The remaining 1886 publications were comprised of 534 journal articles, 1323 conference papers, 15 reviews, 11 book chapters, 1 business article, 1 data paper, 1 erratum, and 1 short communication. We excluded 21 documents that were relatively close with solar thermal because we focused on research concerning “light to electricity” instead of “heat to electricity”. However, this indicates that the first filter used in Scopus is considerably effective.

After validation, an additional investigation was conducted with the help of the data mining software VOSviewer. VOSviewer was utilized as a proper complement to visualize and analyze the publication trends. The documents were characterized based on their bibliographic information, such as keywords, citations, and authorships. We also visualized the harvested data based on two separate categories, Solar cells and Photovoltaic, for further investigation. A detailed analysis of this part is provided in Sections 4.4 and 4.5.

4. Results and Discussion

This section deals with the evolution of research in terms of publication during three decades of Indonesia’s solar energy research. The analysis is structured into six parts:
research publications; the effect of policies on research publications; the geographical distribution of the solar energy research; the polarization of solar energy publications; the evolution of research clusters; and the distribution of publications based on keywords and co-authorships.

4.1. Research Publication

Figure 2 displays the distribution of publications related to solar energy research in Indonesia for the last three decades (1989–2020). It shows that the number of publications has increased dramatically in recent years. The first publication on solar energy research was recorded in 1989 by Moechtar et al. from the Agency for the Assessment and Application of Technology (Badan Pengkajian dan Penerapan Teknologi or BPPT) [2]. They reported a hybrid photovoltaic (PV)-diesel generator power system for a remote TV receive-only (TVRO) station power system installed in Maliana, East Timor, in November 1985. Since then, the projects have been solely focused on demonstrating PV system feasibility in rural areas. There was no consistency in the publications during 1989–1999. However, it is noteworthy that BPPT had successfully shared seven publications in the journals during that first decade.

On the basis of the results, two milestones can be observed. The first milestone was in 2000–2009, the interval during which researchers had been consistently publishing their work every year. Moreover, in 2009, 12 documents were published, which resulted in the highest productivity for this period. It can be concluded from the interval of 2000–2009 that the average publication rate was four documents per year. The second milestone was in 2010–2019, the third decade. At this time, the publication rate was increasing tremendously. This extraordinary pathway started in 2013, when 49 documents were published. Only six years after that, in 2019, an almost ten-fold publication rate was achieved with 454 documents. From 2010–2019, a total of 1420 documents were displayed in Scopus. That value was the highest recorded during three decades of solar energy research in Indonesia.

Here, we filtered the publications based on the affiliations. The affiliations that published a minimum of 30 documents during these three decades were selected. With this requirement, 14 universities and one research institute successfully emerged. The distribution of publications based on the affiliations is shown in Figure 3.
It can be observed that four universities successfully produced remarkable publication rates: the Bandung Institute of Technology (ITB); Universitas Indonesia (UI); Institute Teknologi Sepuluh November (ITS); and Universitas Sebelas Maret (UNS). ITB was the most productive university, with 234 documents, followed by UI, ITS, and UNS, with 181, 180, and 149 documents, respectively. The Indonesian Institute of Science (LIPI), now integrated into the National Research and Innovation Agency (Badan Riset dan Inovasi Nasional or BRIN), produced 84 documents. Universitas Gajah Mada (UGM) contributed 78 documents. Universitas Negeri Malang (UM) and Universitas Hasanuddin (UNHAS) delivered 59 and 51 documents, respectively. At the same time, Politeknik Elektronika Negeri Surabaya (PENS), Universitas Diponegoro (UNDIP), Universitas Brawijaya (UB), Universitas Sumatera Utara (USU), and Universitas Padjajaran (UNPAD) exhibited tight publication numbers with 48, 47, 45, 44, and 43 documents, respectively. Lastly, comparable publication numbers of 31 and 35 documents were shown by Universitas Riau (UNRI) and Universitas Andalas (UNAND), respectively. The combination of these 15 affiliations successfully contributed to 1336 documents and, hence, they share 71% of the total of three-decades of publication.

Figure 4 shows the distribution of documents based on the publication type, with a total publication from 1989–2010 (31 years) of 1886 documents, distributed into conference papers (1323), journal articles (534), reviews (15), book chapters (11), data papers (1), erratum (1), and short communication (1). On the basis of these numbers, the massive domination was exhibited by conference papers with a 70% share, followed by journal articles with 28%. A small portion of 2% was contributed by reviews, book chapters, and others. In order to further investigate, it would be interesting if those numbers were compared and displayed per year in order to present the detailed progress. Since the reviews, book chapters, and others are very few, the comparison is focused on the conference papers and journal articles and is shown in Figure 5.
In Figure 5, it can be observed that, since 2013, the productivity for both publication types has risen every year. The productivity of conference papers is much higher compared to that of the journal articles. This is natural because journal publishing is more challenging in the process. First, the research results displayed in the journals should be more comprehensive and, thus, more experiments are mandatory. Second, the peer-review stage after journal submission is more demanding. The feedback from reviewers and the arguments and responses of authors is time-consuming, and sometimes it demands some additional experiments. Moreover, after the manuscripts have been accepted, authors still have to wait for some time. On the contrary, the conference paper is a faster way of making publication. The peer-review process for the conference paper is not as rigorous as that of the journal article. As a result, the publications per year of journal articles is not as massive as conference papers. For instance, in 2018 and 2019, the productivity of the journal article was stagnant. Simultaneously, 254 conference papers were published in 2018, and this was raised to 358 documents in 2019, increasing by 40.3%. On the basis of the 2009–2020 interval, it can be concluded that the total publications per year of conference papers is double or triple that of journal articles.

In 2020, the total publication declined (see Figure 2) due to the global coronavirus pandemic. Many of the laboratories of the universities and research institutions were closed and experiments were shut down, resulting in lower scientific publication results.
Interestingly, the productivity for journal articles slightly increased, from 97 (in 2018) to 118 documents (in 2020). On the other hand, conference paper productivity decreased from 358 to 309 documents. As we know, most conference events were canceled or postponed because of the pandemic. In a normal situation, the researchers believe that the total productivity of 2020 would have been higher than that of 2019, and possibly a new record would have been set.

With that huge productivity number, it is important to investigate where the publications were distributed. Table 2 displays the top five most frequent publication venues. The list strongly confirms the results presented in Figure 3: conference papers dominate the publications. The Institute of Physics (IOP) Publishing, and the Institute of Electrical and Electronics Engineers (IEEE), were the favorites for the proceeding publishers during these timeframe studies. With 164 documents, the American Institute of Physics (AIP) was also shown as the best alternative publisher for conference proceedings. The *International Journal of Power Electronics and Drive Systems*, published by the Institute of Advanced Engineering and Science (IAES), was considered a suitable photovoltaic research journal. Articles published by Universitas Ahmad Dahlan, *Telkomnika* also dominated the PV research results. With its *International Journal of Technology*, Universitas Indonesia publishing recently revealed a progressive approach for solar cell publication. The two eminent journals related to photovoltaic or solar cells, *Renewable Energy* and *Solar Energy Materials and Solar Cells*, delivered 16 and 10 documents, respectively.

| Publication Venue | Conference Proceeding | Journal Publication | Documents | Rank |
|-------------------|-----------------------|---------------------|-----------|------|
| 1                 | Institute of Physics (IOP) Publishing | International Journal of Power Electronics and Drive Systems | 31 | 1   |
| 2                 | Institute of Electrical and Electronics Engineers (IEEE) | Telecommunication Computing Electronics and Control (Telkomnika) | 28 | 2   |
| 3                 | American Institute of Physics (AIP) | International Journal of Technology | 17 | 3   |
| 4                 | E3S Web of Conferences | Renewable Energy (Elsevier) | 16 | 4   |
| 5                 | Trans Tech Publications Ltd | Solar Energy Materials and Solar Cells | 10 | 5   |

4.2. Policies Effect on Research Publication

It is essential to analyze the factors that play important roles in increasing Indonesian solar energy research publication. Besides the increased research funding, facilities, quantity, and quality of researchers, another critical point is policy. The Indonesian government has produced several policies to support their renewable energy vision during the last three decades. In this work, we note several energy policies that have been created in Table 3.
Law No. 30 of 2007 on Energy was the first step for Indonesia in deciding its position in the global energy transition. The strategy was followed up by the National Energy Policy (KEN), which states in Presidential Regulation No. 79 of 2014 that Indonesia mandates the use of NRE, with a share of 23% in the primary energy mix by 2025, and increasing to 31% by 2050. Three years later, another policy was announced as the General Planning for National Energy (RUEN), as supported in Presidential Regulation No. 22 of 2017. The use of NRE, based on RUEN, is not restricted to the electricity generation sector but can also be used by the transportation, industry, household, commercial, and other sectors. This regulation mandates a reduction in energy intensity by 1% annually from 2015 to 2025. However, there are also numerous challenges to the adoption of this proposal. By 2018, NRE capacity had only reached a 14% share of the total primary energy mix [35].

A unique relationship has been found over the years that the policies and publications were produced, as shown in Figure 6. We conclude that these aforementioned policies significantly impacted the research community and, hence, the ecosystem of solar energy research. The issues related to energy, primarily renewable energy, encouraged the research community to participate in accelerating the realization of national goals. In a more practical view, these policies strengthened the research atmosphere, for instance, by increasing the research allocation in the state budget. The successful utilization of all potencies, such as knowledge, skill, networks, and technology facilities by researchers, universities, and many institutions is represented in the massive productivity of publications.

| Year | 2007 | 2009 | 2014 | 2016 | 2017 | 2019 |
|------|------|------|------|------|------|------|
| Policy | Law No. 30 of 2007 on Energy | Government Regulation No. 79 of 2014 on National Energy Policy | Presidential Regulation No. 22 of 2017 on General Planning for National Energy |
| Publication | 1 | 12 | 63 | 127 | 237 | 454 |

Figure 6. Relationship between the policies and solar energy research publications.

Further investigation on the instant effect of policies on research productivity can be observed by the publication numbers, especially during the two-year interval after policies were announced. For example, the number of publications recorded in 2007 is one document; in 2009 (two years after the announcement of Law No. 30 of 2007) this increased to 12 documents. Afterwards, the publication results dramatically rose every year. The second policy was announced in 2014 and a two-fold increase in publications was achieved two years later. A similar trend was also found for 2017 and 2019. From this trend, it can be assumed that the communities spent one year on research after the policy announcement and published the results in the following year. The numbers presented describe the importance of government policies on solar energy research.

4.3. Geographical Distribution of the Solar Energy Research Publications

If we look further at the 15 affiliations (see Figure 3), they can be classified based on their geographical locations. They are distributed among only three islands, as shown in
Figure 7. The three universities are on Sumatera Island, located in Medan, Padang, and Pekanbaru, respectively. There are ten universities on Java Island, distributed among Depok (1), Bandung (2), Semarang (1), Solo (1), Yogyakarta (1), Malang (2), and Surabaya (2). A research institute, LIPI, is also located in Java. There is one university located in Makassar, Sulawesi Island. The total publications of the affiliations can be clustered based on their respective islands. The combination of universities in Sumatera Island shared 139 documents, Java Island contributed 1146 documents, and Sulawesi produced 51 documents. In other words, the 11 affiliations on Java Island already contributed to 61% of the entire Indonesian publications on solar energy research. Thus, three Sumatera universities contributed 7%, and a university in Sulawesi contributed 4% of the publications. This finding represents the real condition of Indonesia. It confirms that development is focused on Java Island. As a result, many universities are located on this island and, hence, most research facilities, funding, and researchers are also concentrated here.

Figure 8 shows how the words “solar cells” and “photovoltaic” polarized the distribution of Indonesia’s solar energy publications. The term “photovoltaic” (PV) was already established in the industry. Therefore, the “photovoltaic” keyword is found for research publications mainly related to the practical or industrial issues regarding solar cells. Hence, the research topic of “photovoltaic” is dominated by the type of solar cells already mature in the market. This type is the so-called first-generation solar cells, which are based on silicon. The PV research is often focused on the installation procedures, optimization approaches, or on making PV more massive in the market. Therefore, “photovoltaic” is usually accompanied by other keywords, including: “maximum power point tracking”; “fuzzy logic”; “microcontroller”; “microgrid”; “converter”; “position”; “tilt”; “PV modules”; “DC motor”; “policy”; “investment”; “cost”; and many more. All publications that used these terms as keywords are addressed as “PV group” publications.

4.4. Polarization on Solar Energy Publication

This section is devoted to analyzing the distribution of publications from the scientific point of view. VOSviewer was utilized to characterize the data based on the keywords. It is widely known that the two terms “photovoltaic” and “solar Cells” (SC) are the main keywords of the publications. They have close scientific definitions; however, they are practically separated in some particular issues. Here, we present the facts and analysis of the solar energy research conducted in Indonesia during 1989–2020.

Figure 8 shows how the words “solar cells” and “photovoltaic” polarized the distribution of Indonesia’s solar energy publications. The term “photovoltaic” (PV) was already established in the industry. Therefore, the “photovoltaic” keyword is found for research publications mainly related to the practical or industrial issues regarding solar cells. Hence, the research topic of “photovoltaic” is dominated by the type of solar cells already mature in the market. This type is the so-called first-generation solar cells, which are based on silicon. The PV research is often focused on the installation procedures, optimization approaches, or on making PV more massive in the market. Therefore, “photovoltaic” is usually accompanied by other keywords, including: “maximum power point tracking”; “fuzzy logic”; “microcontroller”; “microgrid”; “converter”; “position”; “tilt”; “PV modules”; “DC motor”; “policy”; “investment”; “cost”; and many more. All publications that used these terms as keywords are addressed as “PV group” publications.
4.5. Evolution of Research Cluster

In order to further investigate the polarization of solar energy research in Indonesia, a mapping of the research cluster evolution was performed for 2009–2020. The starting point of 2009 was chosen since it is the year when publications started to evolve consistently. The research cluster evolution was divided into four intervals: (a) 2009–2011; (b) 2012–2014; (c) 2015–2017; and (d) 2018–2020.

4.5.1. 2009–2011

For this interval, a total publication of 49 documents is recorded. The research clusters are still few and dominated by SC topics. Here, researchers who published more than three documents are clustered and displayed in Figure 9a. The cluster from UI started their research on the photovoltaic activity of barium strontium titanate (BST), tetraether lipids, TiO$_2$, and CulnSe$_2$ [36–38]. The Bandung universities, represented by ITB and UNPAD, contributed to TiO$_2$ and ZnO for DSSC and poly(alkylthiophene)/ZnO for HSC, respectively [39–41]. Simultaneously, UGM publications also show a tendency to focus on OSC, represented by copper phthalocyanine (p-type), perylene (n-type), P3HT, and PCBM [42,43]. UK Petra represented the PV topics by exhibiting the documents focused on maximum power point tracking (MPPT) [44,45].
A total of 129 documents were published during this interval. Figure 9b shows that some new research clusters have emerged. UI continuously performed on DSSC application [46,47]. UNS is shown to have two DSSC clusters that work on TiO$_2$ preparation and transparent conductive oxide (TCO) fabrication [48,49]. ITB has three clusters devoted to SC research; one of them showed strong collaboration with UNPAD on hybrid solar cells [50–52]. PV research is also shown progressively by many emerging new clusters. ITS exhibited both publication topics on SC and PV, with research on the oxide semiconductor and MPPT [53,54]. In addition, UNUD, a university from Bali Island, had also evolved [55,56]. In this period, there was remarkable PV research from Sulawesi Island, represented by UNHAS, on MPPT and fuzzy logic [57,58]. UNHAS also collaborated with Politeknik Negeri Malang (Polinema). Universitas Tanjung Pura, UNTAN, the sole university from Kalimantan Island, also emerged and exhibited research on PV systems [59].

4.5.3. 2015–2017

A total of 447 documents were published during this interval. The cluster mapping is denser compared to that of the first two intervals. It can be seen in Figure 9c that the clusters of universities that focus on SC topics are more localized in the center. It can be observed that ITB, UNPAD, LIPI, and UNS are closely located on the map. It means that the researcher’s network within these universities has formed [60,61]; they have collaborated on the publications. A few clusters with the same research topic are still not connected, such as UI, UB, UNRI, and UNAIR. This strongly indicates that the distance between universities remains a challenge.

Interestingly, many new PV clusters that have appeared and shown significant productivity, such as UNAND, UI, LIPI, and UGM, are focusing on performance and cost analyses [62–65]. Institut Teknologi Medan (ITM) from Sumatera Island displayed outstanding performance on PV topic research with 11 documents [66,67]. ITS was considered the most productive university in PV research, with 39 documents recorded. PENS has emerged and is shown to have had a strong collaboration with ITS on the MPPT topic [68,69]. This collaboration strongly confirms why the ITS and PENS clusters are located closely on the map; they collaborated with ITS, Universitas Surabaya (UBAYA), and Universitas Bhayangkara.

Figure 9. Evolution of research cluster for intervals: (a) 2009–2011; (b) 2012–2014; (c) 2015–2017; and (d) 2018–2020.
Surabaya (UBHARA), who also worked on PV [70–73]. It can be concluded that the ITS is the center of PV research in East Java, forming a collaboration network with its neighbors.

4.5.4. 2018–2020

The mapping morphology of this interval is the densest compared to the others. A total of 1230 documents were published during this interval. From the map’s color density, it can be observed that UI, ITB, UNS, and ITS are still the most productive universities. In addition, UM displayed intense publication on many aspects of SC topics, such as DSSC, thin-film, and perovskite [74,75]. Moreover, the number of PV research clusters dramatically increased, and new PV clusters have emerged from Universitas Syiah Kuala (UNSYIAH), Politeknik Negeri Lhokseumawe (PNL) Politeknik Negeri Sriwijaya (POLSRI), Universitas Ahmad Dahlan (UAD) [76–79].

4.6. Polarization of Publication in the Affiliation

Figure 10 shows the polarization effect on distributing the total publications of 15 affiliations for three decades. A total of 1307 documents from these affiliations were investigated intensively to identify the characteristics of their publication topic, PV or SC.

![Figure 10. Distribution of publications based on the research topic category: PV (right) and SC (left).](image)

Generally, from the total of 15 affiliations, PV research publications shared 54% (704 documents), and SC contributed 46% (603 documents). However, if a detailed observation was to be conducted for each affiliation, it would show a different story. Each affiliation has its own research preferences, which can be seen in their respective publications. It can be seen that ITB, UNS, LIPI, UM, and UNPAD are intensely focused on SC research topics. PV research topics dominated ITS, UI, UGM, UNHAS, PENS, USU, and UNAND. UNDIP, UB, and UNRI are arguably balancing PV and SC in their research. PENS and UNPAD showed the most striking distribution: PENS devoted their research entirely to PV, while UNPAD did the opposite, choosing SC as the main research focus. ITB and UNS show remarkable SC productivity by their shared 135 and 123 documents, respectively; in other words, they produced 43% of the total SC group publications. ITS displayed a massive performance in PV research by delivering 20% of the entire PV group publications.

4.7. Collaboration

This section displays the co-authorship mapping from the downloaded data. From a total of 3842 authors, a selection was performed. Hence, for Figure 11, we extracted the authors with a minimum publication of ten documents, leading to 79 authors meeting the threshold.
Most affiliations outside Java tend to focus their research on PV. Interestingly, this also happens in east Java with ITS and PENS. The domination of SC research is clearly concentrated in west and central Java. Therefore, the number of publications on this topic is striking from ITB, UNPAD, and UNS (see Figure 9). The cluster mapping of Indonesian solar energy researchers is displayed in Figure 11. The universities have clusters or groups that specialize either in PV or SC. For example, UI, ITB, and ITS have groups that independently contribute to this research. The lines linking researchers mean that there have been collaborations between co-authors in the publications. The researchers who specialize in PV do not link directly to SC researchers and vice versa. They are only connected if there is a third person (researcher) who links them. This is expected since solar energy research provides many common topics for them. As we can see, all of the SC researchers on Java Island are connected to the network. Contrary to the expectation, the PV research network is only found in east Java, ITS, and PENS. These two institutions have a strong collaboration, resulting in a massive number of publications.

Figure 12 shows the mapping of co-authors from other countries. It displays the countries that have at least five shared publications with Indonesian affiliations. It can be seen that the thickness of the curve link represents the amount of shared publications. The thickest link is shown between Indonesia and Malaysia, which both contributed to 166 documents, followed by the links to Japan and Australia, both countries having delivered 94 and 42 documents, respectively. It also can be observed that, in 2018, Indonesia started to have shared publications with European countries, such as Germany, Switzerland, Sweden, and the United Kingdom. With 20 documents, Germany contributed the highest number of shared publications compared to other European countries.
Figure 12. Distribution of co-authors based on the countries.

4.8. Future Research

This work has identified that the PV research topics mainly focus on three parts of the PV system: the maximum power point tracking (MPPT), the inverter, and the converter. These parts are widely known as imports, already mature in the market. It is a big challenge to compete with these existing products. However, the research on innovation to strengthen the local industrial content (TKDN), thus reducing imports, is still open. Another aspect that is open for research is the demographic approach. Indonesia has a large area that has many various landscapes with rapid weather changes. Therefore, installation, optimization, and evaluation research regarding a specific case or place would be interesting. Research on policies, especially research dealing with the electricity tariff, would be of benefit. Tariff policies are far from encouraging PV as a more attractive option for customers [80]. For example, it would be attractive to receive credits equal to 100 percent of the applicable PLN customer tariff for every kWh of power exported to the PLN grid. According to the new regulations, any energy exported by the customer to the PLN grid will be discounted by approximately 35% [81]. Thus, multidisciplinary research on PV feasibility is expected to evolve.

In terms of SC research, the third generation of dye-sensitized solar cells (DSSC) involving semiconductor oxide of titanium dioxide (TiO\textsubscript{2}) and natural dye is an overused topic. Shifting to perovskite solar cells (PSCs) would be seen as significant progress. Displaying high efficiency and a low manufacturing cost, PSCs have emerged as the most promising SC technology and have attracted global attention [82]. Indonesian research institutions should revolutionize their facilities because PSC research typically involves more sophisticated characterization tools [83]. Characterizations on time-resolved photo-induced and photovoltage/photocurrent transient are two mandatory techniques in producing high-quality research [84,85]. Therefore, strategies, such as joint research and the sharing of facilities, domestic and international, would be an appropriate way to overcome the problem on this topic.

5. Conclusions

The total publication of 1886 documents obtained for three decades (1989–2020) has been mapped. The starting point of solar energy research happened in 2009, which was two years after the first policy, Law No. 30 of 2007 on Energy, was announced. Afterwards, a pattern of policy-publication relationships emerged. It has been found that, many times, two years after a policy is announced, the number of publications increases almost two-fold. This confirms that those policies had a significant impact on the ecosystem of solar energy research. On the basis of publication types, 70% of documents were shared by conference papers. This indicates that quality improvement in solar energy
research remains a challenge. In addition, the publications can be classified into two categories, representing their research characteristics. The typical research focused on mature solar cell technology (silicon-based) mainly used “photovoltaic” (PV) as the primary keyword. On the other hand, the publications of solar energy research that deals with fundamental aspects, new technology, and the lab-scale usually can be identified with the “solar cell” (SC) keyword. The percentage of publications for both categories is 54% for PV and 46% for SC. From a geographical perspective, research institutions located on Java Island played a significant role by contributing 61% (1146 documents) of Indonesia’s solar energy publications. Interestingly, most universities in Java are focused on SC research. Most universities outside Java tend to be independent in research and mainly prefer PV as the core of their research topics. Interestingly, east Java universities, located in the city of Surabaya, have been shown as leaders in PV publications. On the basis of co-author mapping, the SC researchers’ network is more prominent and well-connected compared to that of PV researchers. International collaboration was also formed, with Malaysia as the preferred counterpart, contributing to 166 co-authorships. The future agenda for PV research could focus on increasing the domestic component and proposing various multidisciplinary approaches to make PV utilization more feasible. Lastly, the shift towards eminent perovskite solar cells would be considered significant progress. The results of this work confirm that all of the aspects have a relationship with each other. Government policies, research characteristics, publication productivity, and even the COVID-19 pandemic, have influenced solar energy sustainability. In the global context, all developing countries can use the approach of this work as a benchmark or reference in assessing the sustainability of their research, especially in solar energy. Comprehensive research mapping can be used to evaluate the activity and effectiveness of the research, as well as the development of the countries. The cooperation of all parties, universities, research institutes, industries, and the government is inevitable and necessary for the sustainability of solar energy research.

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