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Methodical review of the literature referred to the dye-sensitized solar cells: Bibliometrics analysis and road mapping

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This study presents a systematic review of the literature pertaining to dye-sensitized solar cells (DSSCs), in order to anticipate the direction and speed of change in technology trend. To study the general progression in DSSC research, we have assessed the evolution in annual DSSCs publications and their citations. Further, in order to identify the intellectual bases, we have also classified the journals, authors, institutes, and countries according to their scientific productivity in the field of DSSCs research during the period of 2007–2017.

Keywords: bibliometric analysis, dye-sensitized solar cells, scientific productivity, international cooperation network

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1. Introduction

In the past few decades, extensive R&D efforts have been directed in the field of eco-benign renewable energy research.[1–4] This immense research progress is stimulated by the growing global concerns regarding irreversible climate change, increased energy demand, and depletion of conventional fossil fuels.[5–7] By far, the photovoltaic technology has the highest potential among all the renewable energies.[8–12] For the promotion of social transformation and economic development, a strong and consolidated photovoltaic technology base is definitely vital.[13] The phenomenal research and innovation realized in solar cell devices have provided several environmentally friendly, technically and economically credible alternative concepts to the classical inorganic solid-state devices.[14–18] Among these, the dye-sensitized solar cells (DSSCs) are envisaged to be prominent third generation solar cells which exhibit superior photovoltaic performance both regarding conversion efficiency and long-term stability.[19–21] Also, DSSCs offer the prospect of the low budget, eco-benign, and simple fabrication process that has facilitated its commercialization remarkably.[21,22]

The intense global competition in innovation activities about DSSC research field has resulted in the rapid and vast amount of publications. It is therefore crucially important for researchers, policymakers, and industrial communities to analyze these scientific breakthroughs and catch up in global innovation race by (i) identifying the core research themes on DSSC technology and (ii) developing the framework for future macro-level trends in the policy, market, and semiconductor industry. Bibliometrics, which takes advantages of the modern technologies in computer engineering, database management, and statistics, is a powerful and flexible tool to analyze such vast volume of academic outputs in a way that individuals cannot handle. Bibliometric information, i.e., scientific publications, patents, and citations, constitutes an adequate information source for mapping the scientific and technological fields.[23] Also, bibliometrics benefits researchers enormously by providing them a structured approach to (i) recognize future academic collaborators, (ii) identify the appropriate institutes to pursue their academic degrees, and (iii) detect emerging research domains, thereby supporting the development of scientific and technological innovation.[24–27] Further, bibliometrics allows policymakers and industrial communities to explore, organize, and analyze massive amounts of experimental data, thereby facilitating the decision-making process and forecasting emerging technologies.

In the past, a number of academic studies have been conducted to assess and evaluate the progression of research and technological development in the field of solar energy in gen-

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eral. Garg and Sharma performed an analysis of the output of global literature (scanned in Engineering Index) during 1970–1984 on solar power research.[28] The authors observed an impressive growth in the volume of scientific publications after the energy crisis in 1973 till 1982. Du *et al.* also used bibliometric methods to examine the characteristics of the solar energy literature (based on SCI and SSCI databases) from 1992 to 2011.[29] They highlighted that the pace of publishing in this field increased exponentially over these two decades, with the US accounting for the highest number of publications (1273), followed by China and India. Similarly, Dong *et al.* (2012) assessed the situation and tendencies of solar energy research (based on SCI database) between 1991 and 2010.[27] Their study revealed that dye-sensitized solar cells and organic solar cells had extremely high increasing rates, which indicated that more attention was paid to kinds of eco-benign organic solar cells.

It is, however, pertinent to mention that these aforementioned bibliometric studies used "solar cells", "photovoltaic systems", "solar energy", and "solar power plants" as keywords. Therefore, these studies encompass an only limited number of publications that exist in the subfield DSSC research field. In literature, there have been quite limited strives with specific emphasis on DSSC technology to evaluate their growing body of knowledge in recent years.[30] This has resulted in a lack of full capture on recent research achievements in the field of DSSC technology. This study aims to implement bibliometric analytical techniques to assemble and analyze the academic landscape of DSSC research on a global scale. Herein, we intend to analyze the status and global trends of research activities within the DSSC research by reviewing the scientific papers published in the period from 2007 to November 2017. The temporal development of scholarly outputs, publication statistics, and geographical distribution of authors, institutions, and organizations with significant contribution in the field of DSSC research are specifically investigated in the present study.

2. Methodology

The methodology used in the present study is based on the online database of the Science Citation Index Expanded (SCI-EXPANDED) compiled by the Institute for Scientific Information (ISI). It has been retrieved from the Thomson Reuters Web of Science (accessed on 30th November, 2017 from the University of Malaya, Kuala Lumpur, Malaysia). The SCI-EXPANDED from Web of Science databases has been selected because it is one of the best sources for citation data and frequently used course database choice for an analysis of scientific publications.[31,32] Further, it allows the facile refinement of results regarding countries, organizations, authors, and journals (source titles).

In the present study, we have used the following queries, "dye* sensitized* solar* cell* or DSSC* (where * means wildcard), to search the titles within the top fifteen categories of Web of Science (during the time frame of 2007 to November 2017). This above set of keywords has been determined specifically by the authors to include a maximum coverage of research papers about dye-sensitized solar cells. However, it is also pertinent to mention that we have also incorporated few restrictions in queries, viz., "Distributed switch and stay combining (DSSC*)", "DSSC* detector", "DSSC* 1Megapixel detector", "DSSC* X-ray imager", "the DSSC* Chip", "XFEL-DSSC* Project", and "DSSC* Pixel Readout ASIC" to avoid noise (non-relevant papers).

3. Results and discussion

3.1. Publications and citations analysis

Windows of opportunity for technology development appear and change as novel and revolutionary technologies are introduced, hence early detection of these changes in technological surroundings is a critical factor in technology forecasting.[33] The strategic analysis of global technology foresight is in fact an integrated and comprehensive tool to be used by academic researchers and policy makers in decision making processes. It is envisaged to be a crucial approach in identifying strategic national demands and grasping the global trend of innovative technology.[34] It enables organizations, ranging from the multinational level (e.g., the European Union) to the individual level (e.g., a research center), to build roadmaps depicting their strategies to discover rational ways to develop technology and innovation policies when facing social and economic development uncertainties.[35,36] It further allows for the anticipation of technological ruptures, discontinuities, new perspectives, and opportunities in a given time horizon.

Daim *et al.* have however previously claimed that forecasting an emerging technology is daunting task as there is no historical data available, however in such cases the use of bibliometrics may provide useful data.[37] Hence accordingly, in the present study the international trends in DSSC technology have been analyzed using bibliometric approach. In total, there were 10484 research items pertaining to DSSC research field in the ISI web database between 2007 and November 2017, with eleven document types. Specifically, there were 9489 research articles comprising 90.51% of the total production, followed by proceedings papers (379, 3.61%), meeting abstracts (298, 2.84%), and reviews (215, 2.05%). The other research items with less significant percentage were cor-

rections (70), editorial materials (11), letters (7), news items (7), book chapters (5), retracted publications (2), and retraction (1). Since, the original research articles and reviews were frequently used document types and were also peer-reviewed. Therefore, both of them (9704 total publications with h-index = 187) were used for further analysis in the present bibliometric study.

The publications and citations trends related to DSSC research field within 2007 to November 2017 timeframe are depicted in Figs. 1(a) and 1(b), respectively. From Fig. 1(a), it may be observed that the annual global publications have increased significantly from 2007 to 2014. Specifically, the number of articles increased more than six times, i.e., 228 in 2007 to 1459 in 2014. The highest number of articles published in 2014 accounted for 15.03% of the total number of articles (9704) in the above time span. The general progression in DSSC research publications pertains to the growing importance of solar energy research under the pressures of reducing carbon emissions, meeting increasing electricity demand, and sustaining economic growth. Further from Fig. 1(b), it is observed that the annual citations of 9704 DSSC research documents also increased generally along the study period. Specifically, there were 272202 citations with an average of 28.05 citations per published article. The cumulative cited reference count increased nearly 190 times, from 205 to 38966, during these nearly eleven years of time span.

Interestingly, while characterizing the basic performance of scholarly outputs during the study period, it has been observed that the number of DSSC publications has decreased during 2014 to November 2017, as depicted in Fig. 1(a). The relative decrease in DSSC publications from 2014 to November 2017 may be an indication of the recent shift in global research interest towards developing a novel breed of highly efficient and stable hybrid organic–inorganic perovskite solar cells.[38–40] The emerging perovskite solar cells technology exhibits promising characteristics such as superior light absorptivity, higher charge-carrier mobility, tunable bandgap, longer exciton diffusion length, and low exciton binding energy.[33] By virtue of these enticing properties, the perovskite solar cells have undergone unprecedented development, resulting in a dramatic increase in their power conversion efficiency (PCE) exceeding 23% within past couple of years.[41]

Based on these aforementioned results, a review of technology foresight activities in organic–inorganic hybrid perovskites solar cells may be the future research agenda. It is particularly attractive in terms of governmental practices and policy applications, which may provide some potential implications for technology foresight practices and in identifying directions for future research initiatives related to organic–inorganic hybrid perovskites solar cells.

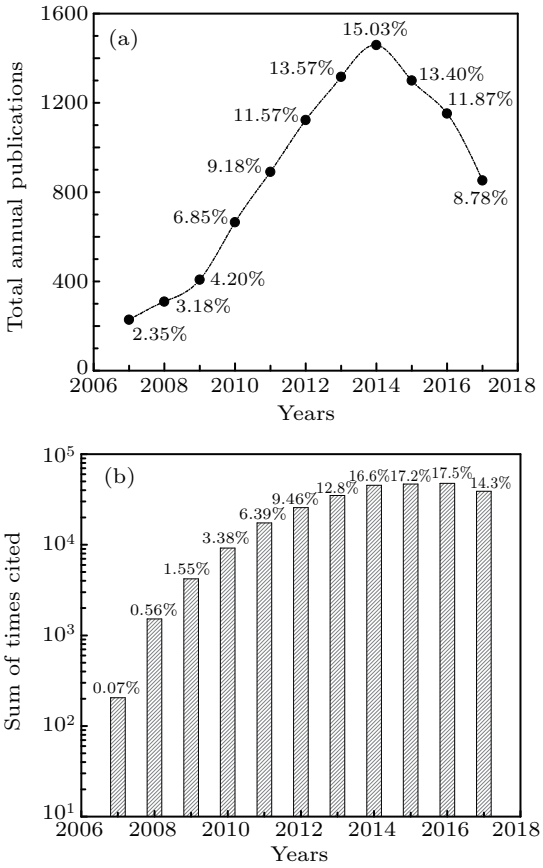


Fig. 1. The progression in annual (a) global research publications and (b) cumulative citations of DSSC publications along the study period (2007 to November 2017).

3.2. Overview of fifteen most cited DSSC publications

Table 1 shows the top fifteen publications pertaining to DSSC research, listed in the order of times cited. Admittedly, the cumulative citation is not a direct measure of the impact or importance of a particular scholarly work, it does, however, provide a marker of its recognition within the scientific community.[42] Also, the top-cited articles can also provide insights into how research fields have evolved.[43] From Table 1, it can be clearly observed that in DSSC research field, the most cited paper in the past 11 years is the review article "*Dye-sensitized solar cells*" by A. Hagfeldt *et al.* Within the review article, the authors have overviewed DSSC research in a broad sense, i.e., operational principles of DSSC (energetics and kinetics), development of material components along with the specific experimental techniques to characterize DSSC. Further intrigued by the fact that the manufacturing, reliability, performance, and stability of a DSSC module are complicated, the authors have also reviewed DSSC modules design and their performance with specific focus on manufacturing processes and accelerated stability testing of modules.

Table 1. Fifteen most frequently cited articles in the field of DSSC research along the study period.

No.	Title	Authors	Journal	Year	Times cited
1	Dye-sensitized solar cells	Hagfeldt *et al.*	Chemical Reviews	Nov, 2010	4745
2	Transparent, conductive graphene electrodes for dye-sensitized solar cells	Wang *et al.*	Nano Letters	Jan, 2008	2652
3	Dye-sensitized solar cells with 13% efficiency achieved through the molecular engineering of porphyrin sensitizers	Mathew *et al.*	Nature Chemistry	Mar, 2014	1824
4	Metal-free organic dyes for dye-sensitized solar cells: From structure: Property relationships to design rules	Mishra *et al.*	Angewandte Chemie International edition	2009	1611
5	Enhanced charge-collection efficiencies and light scattering in dye-sensitized solar cells using oriented TiO_2 nanotubes arrays	Zhu *et al.*	Nano Letters	Jan, 2007	1608
6	Growth of oriented single-crystalline rutile TiO_2 nanorods on transparent conducting substrates for dye-sensitized solar cells	Liu *et al.*	Journal of the American Chemical Society	Mar, 2009	1408
7	Fabrication of thin film dye-sensitized solar cells with solar to electric power conversion efficiency over 10%	Ito *et al.*	Thin Solid Films	May, 2008	1271
8	ZnO nanostructures for dye-sensitized solar cells	Zhang *et al.*	Advanced Materials	Nov, 2009	1056
9	Enhance the optical absorptivity of nanocrystalline TiO_2 film with high molar extinction coefficient ruthenium sensitizers for high performance dye-sensitized solar cells	Gao *et al.*	Journal of the American Chemical Society	Aug, 2008	1031
10	Highly efficient light-harvesting ruthenium sensitizer for thin-film dye-sensitized solar cells	Chen *et al.*	ACS Nano	Oct, 2009	836
11	The renaissance of dye-sensitized solar cells	Hardin *et al.*	Nature Photonics	Mar, 2012	729
12	Characteristics of the iodide/triiodide redox mediator in dye-sensitized solar cells	Boschloo *et al.*	Accounts of Chemical Research	Nov, 2009	705
13	Efficient dye-sensitized solar cells with an organic photosensitizer featuring orderly conjugated ethylenedioxythiophene and dithienosilole blocks	Zeng *et al.*	Chemistry of Materials	Mar, 2010	694
14	Mesoporous anatase TiO_2 beads with high surface areas and controllable pore sizes: a superior candidate for high-performance dye-sensitized solar cells	Chen *et al.*	Advanced Materials	Jun, 2009	684
15	Large π-aromatic molecules as potential sensitizers for highly efficient dye-sensitized solar cells	Imahori *et al.*	Accounts of Chemical Research	Nov 2009	653

3.3. Overview of top 15 journals

From the data analysis, it has been found that 4397 articles were published by top 15 journals which account for about 45.3% of the total publications. Table 2 arranges the top 15 journals in order of decreasing DSSC articles published along the study period. These fifteen journals may be regarded as the important set of journals in the DSSC research field. *Electrochimica Acta* (England) has been identified as a core journal with 595 articles, which is about 6.13% of the total publications, followed by *Journal of Physical Chemistry C* (United States), which published 519 articles ($\sim$ 5.35%) as shown in Table 2. It is also pertinent to mention that a total of 9582 publications ($\sim$ 98.75%) were in the English language, whereas 92 ($\sim$ 0.95%), 24 ($\sim$ 0.24%), and 3 ($\sim$ 0.031%) were in Chinese, Korean, and Japanese languages, respectively.

Table 2. Top fifteen productive journals in the field of DSSC research along the study period.

No.	Source titles	Impact factor (2017)	Country	Publications	% of total publications
1	Electrochimica Acta	4.798	England	595	6.131
2	The Journal of Physical Chemistry C	4.536	United States	519	5.348
3	RSC Advances	3.108	England	465	4.792
4	Journal of Power Sources	6.395	Netherlands	423	4.359
5	Journal of Materials Chemistry A	8.867	England	348	3.586
6	ACS Applied Materials & Interfaces	7.504	United States	301	3.102
7	Physical Chemistry Chemical Physics	4.123	England	244	2.514
8	Journal of Nanoscience and Nanotechnology	1.483	United States	220	2.267
9	Dyes and Pigments	3.473	England	215	2.216
10	Journal of Materials Chemistry A	8.867	England	211	2.174
11	Chemical Communications	6.319	England	201	2.071
12	Journal of Photochemistry and Photobiology A	2.625	Switzerland	180	1.855
13	Solar Energy	4.018	United States	167	1.721
14	Solar Energy Materials and Solar Cells	4.784	Netherlands	161	1.659
15	Energy & Environmental Science	29.518	United Kingdom	147	1.515

3.4. Publication performances — authors and countries

The top 15 authors acknowledged for making their potential contributions to the DSSC research field are listed in Table 3, along with their respective publication numbers, h-indices, total citations, and average citation per article. It may be observed that the top 15 authors tabulated below account for 20.5% of the analyzed publications (9704) and 47.9% of the total number of citations (272202) during the time span of 2007 to November 2017. Grätzel M is the most productive author with 262 publications, followed by Kim J H and Ho K C (each with 178 and 169 publications). It is well-understood that the academic productivity of the author is measured by the number of publications. However, the influence of research publication is evaluated by the number of citations.[44] Presently, the majority of citation databases are using h-index as a bibliometric indicator to assess significance and broad impact of a scientist's cumulative research contributions.[45] The h-index indicates the number of articles with citations that are greater than or equal to this number "h". Interestingly, during the past eleven years, Grätzel M has been found to be the most influential researcher as well from h-index perspective. Grätzel M ranks first in the influential global DSSC researchers list with the highest h-index and cumulative citations of 89 and 27921, respectively.

Table 3. Top fifteen most productive authors in the field of DSSC research along the study period.

No	Author	Total publications	h-index	Sum of times cited	Average citation per article
1	Grätzel M	262	89	27920	106.56
2	Kim JH	178	29	3020	16.97
3	Ho K C	169	40	5277	31.22
4	Hagfeldt A	161	58	16419	101.98
5	Wu J H	135	39	4792	35.5
6	Nazeeruddin M K	134	55	13204	98.54
7	Zakeeruddin S M	125	57	14001	112.01
8	Zhang J	124	33	5144	41.48
9	Dai S Y	120	27	2122	17.6
10	Sun L C	102	40	10653	104.44
11	Wang P	102	42	8895	87.21
12	Boschloo G	101	38	10619	105.14
13	Wang H	100	30	3155	31.55
14	Han L Y	92	29	2944	32
15	Tang Q W	90	26	2278	25.31

Among the top most productive institutes in DSSC, eight institutes are from China, four from South Korea, and one institute each from Switzerland, Sweden, and Singapore. The Chinese Academy of Sciences (China, Asia) has the maximum contribution with 591 articles (h-index = 70) in the total volume of publications, followed by the Ecole Polytechnique Federale De Lausanne (EPFL) in Switzerland (318 articles, 119 h-index). The higher output of DSSC research in Chinese Academy of Science is not surprising since in the past China's total expenditure on research and development (R&D) has been increasing by about 20% per year.[46] However, it is also pertinent to mention here that the Chinese Academy of Sciences is an integrated research center consisting of many relatively independent institutes distributed across China, thus their publication productivity is particularly notable. Interestingly, National University of Singapore (NUS) is the most productive university in the South-East Asian region. NUS ranked 14th in the global most productive institute's list with 115 DSSC related publications and 41 h-index. This performance of NUS should be seen in the light of the substantial scientific R&D funding in the Singapore federal budget.

3.5. Country/region wise distribution of research output

Table 4 shows the top 14 countries, ranked according to the total number of DSSC related publications along the study period (also shown in Fig. 2). The list of most productive countries includes six Asian countries, six European countries, America, and Australia. The People's Republic of China is the most productive country with $\sim$ 34.97% of the total output, followed by South Korea whose share is $\sim$ 15.04% of the total output. Five of the seven advanced economies of the world (G7), the USA, Japan, Italy, Germany, UK, and France, were in the top 14 productive countries list, while France and Canada took the 18th and 23rd place, respectively. The domination of the Asian countries in general in DSSC research publications reflects the high scientific investment and academic level of these countries. Moreover, since the Asian countries in general are in the process of industrialization and electricity is indispensable for their rapid industrial growth.[47,48] Therefore, the developments of eco-benign electric power industry, photovoltaic, energy saving, and greenhouse gases emission reduction are themes of paramount importance in the Asian countries.

Table 4. Top fourteen productive countries in the field of DSSC research along the study period.

No.	Country	Region	Publications	% of total publications
1	China	East Asia	4328	34.975
2	South Korea	East Asia	1460	15.045
3	USA	North America	840	8.656
4	Japan	East Asia	799	8.234
5	India	South and South East Asia	794	8.182
6	Switzerland	Europe	375	3.864
7	Sweden	Europe	305	3.143
8	Italy	Europe	300	3.092
9	Iran	Central Asia	267	2.751
10	Australia	Australia	260	2.679
11	Germany	Europe	242	2.494
12	England	Europe	228	2.35
13	Singapore	South and Southeast Asia	228	2.35
14	Spain	Europe	196	2.02

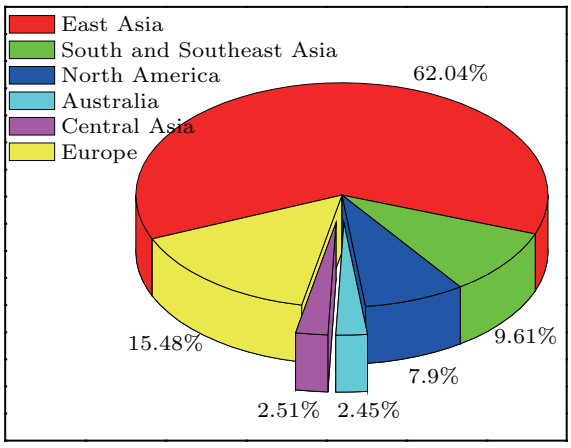


Fig. 2. Regional contribution (of top 14 productive countries) in the field of DSSC research along the study period.

From the perspective of socio-economic development, it is well known that science and technology policies have integrated with policies in other fields by means of their relation to economy and to the transformation of societies. Pelaiz A L has previously claimed that the technology plays an indispensable role in the evolution of society and of current economies, to the point that it has now become a central element of economic evolution.[49] For global development and prosperity, international academic cooperation is of prime importance since the developing countries with backward technologies can learn advanced experiences from the developed countries. Consequently, through synergistic collaborative efforts, the researchers may enhance their understandings, share ideas, and seek innovative solutions to research problems. Based on the statistics for various countries, the People's Republic of China has played a pivotal role in the collaboration network of the top 14 productive countries. It had research collaborations with nine top productive countries. Among them, the research cooperation between China and US is particularly notable, rising to the first place in intensity. Spain's relatively limited amount of DSSC related research publications accounts for its peripheral location in this network diagram, and the thin lines connecting it to other countries.

4. Conclusion

The speed and scope of development in dye-sensitized solar cell research make it critical for researchers and policymakers to overview the global DSSC research and predict the dynamics of the investigation. In the past, there have been quite limited strives to study the recent progression in DSSC research. Under such a circumstance, this bibliometric study fills the research gap by reviewing the status of DSSC research published globally across various research domains and different institutions from 2007 to 2017. It has been observed that the annual global publications have increased significantly from 2007 to 2014 and then interestingly slight decrease in the number of publications has been observed during 2014 to November 2017. Specifically, the highest number of DSSC research articles published in 2014 accounted for 15.03% of the total number of articles during 2007–2017 timespan. The language analysis reveals that English has been the dominant language of DSSC publications accounting for 9582 records ($\sim$ 98.75%). The present study has further identified the most frequently cited DSSC publication, core journals, prominent researchers, and key worldwide institutes contributing towards DSSC research. International cooperation network analysis has also been conducted wherein, the collaborative relationship between China and US has been found to be particularly notable. We believe that this study will benefit early stage researchers by helping them firstly, understand the panorama of recent global DSSC research and secondly, identify the potential researchers/institutes to capitalize on the mutual synergistic collaborations. Also, since the industry is also highly dependent upon recent research endeavors, therefore, this study should interest the policymakers in industries to predict future DSSC industrial growth. This study also concludes by highlighting directions for future research activities towards emerging organic-inorganic hybrid perovskite solar cells technology. Specifically, based on the recently reported high power conversion efficiency of the perovskite solar cells, the authors opine that the aforementioned emerging technology may be a potential theme that calls out for further analysis in future.

References

[1] Mao G, Liu X, Du H and Wang L 2015 *Renewable and Sustainable Energy Reviews* **48** 276
[2] Wang L, Wei Y M and Brown M A 2017 *Appl. Energy* **205** 57
[3] Yu H, Wei Y M, Tang B J, Mi Z and Pan S Y 2016 *Appl. Energy* **184** 960
[4] Gao C, Sun M, Geng Y, Wu R and Chen W 2016 *Appl. Energy* **182** 602
[5] Söderholm P and Sundqvist T 2007 *Renewable Energy* **32** 2559

[6] Resch G, Held A, Faber T, Panzer C, Toro F and Haas R 2008 *Energy Policy* **36** 4048
[7] Hu Y, Huang W, Wang J, Chen S and Zhang J 2016 *Renewable Sustainable Energy Rev.* **57** 1373
[8] Lee T D and Ebong A U 2017 *Renewable Sustainable Energy Rev.* **70** 1286
[9] Wazed S M, Hughes B R, O'Connor D and Calautit J K 2018 *Renewable Sustainable Energy Rev.* **81** 1206
[10] Branker K, Pathak M and Pearce J M 2011 *Renewable Sustainable Energy Rev.* **15** 4470
[11] Hoffmann W 2006 *Sol. Energy Materials Solar Cells* **90** 3285
[12] Jäger-Waldau A 2008 *Research, Solar Cell Production and Market Implementation of Photovoltaics, Renewable Energy Unit, 2008*
[13] de Miranda Santo M, Coelho G M, D M dos Santos and Fellows Filho L 2006 *Technol. Forecasting Soc. Change* **73** 1013
[14] Płaczek-Popko E 2016 *Opto-Electron. Rev.*
[15] Chopra K, Paulson P and Dutta V 2004 *Prog. Photovoltaics: Res. Appl.* **12** 69
[16] Pagliaro M, Ciriminna R and Palmisano G 2008 *ChemSusChem* **1** 880
[17] Lungenschmied C, Dennler G, Neugebauer H, Sariciftci S N, Glatthaar M, Meyer T and Meyer A 2007 *Sol. Energy Mater. Sol. Cells* **91** 379
[18] Brabec C J and Durrant J R 2008 *Mrs Bull.* **33** 670
[19] Richhariya G, Kumar A and Tekasakul P 2017 *Renewable Sustainable Energy Rev.* **69** 705
[20] Kumara N, Lim A, Lim C M, Petra M I and Ekanayake P 2017 *Renewable Sustainable Energy Rev.* **78** 301
[21] Gong J, Sumathy K, Qiao Q and Zhou Z 2017 *Renewable Sustainable Energy Rev.* **68** 234
[22] Sugathan V, John E and Sudhakar K 2015 *Renewable Sustainable Energy Rev.* **52** 54
[23] Kajikawa Y and Takeda Y 2009 *Technol. Forecasting Soc. Change* **76** 1115
[24] Kumar S and Jan J M 2014 *Scientometrics* **98** 387
[25] Kajikawa Y, Yoshikawa J, Takeda Y and Matsushima K 2008 *Technol. Forecasting Soc. Change* **75** 771
[26] Vidican G, Woon W L and Madnick S 2009 *Measuring innovation using bibliometric techniques: The case of solar photovoltaic industry*
[27] Dong B, Xu G, Luo X and Gao W 2012 *Scientometrics* **93** 1101
[28] Garg K and Sharma P 1991 *Scientometrics* **21** 147
[29] Du H, Li N, Brown M A, Peng Y and Shuai Y 2014 *Renewable Energy* **66** 696
[30] Li X, Zhou Y, Xue L and Huang L 2015 *Technological Forecasting and Social Change* **97** 205
[31] Braun T, Schubert A P and Kostoff R N 2000 *Chem. Reviews* **100** 23
[32] Shibata N, Kajikawa Y and Sakata I 2010 *Technol. Forecasting Soc. Change* **77** 1147
[33] Yoon B and Park Y 2005 *Technol. Forecasting Soc. Change* **72** 145
[34] Li N, Chen K and Kou M 2017 *Technol. Forecasting Soc. Change* **119** 246
[35] Daim T U, Yoon B S, Lindenberg J, Grizzi R and Estep J T 2018 *Technol. Forecasting Soc. Change* **131** 49
[36] T. F. A. M. W. Group 2004 *Technol. Forecasting Soc. Change* **71** 287
[37] Daim T U, Rueda G, Martin H and Gerdsri P 2006 *Technological Forecasting and Social Change* **73** 981
[38] Nie W, Tsai H, Asadpour R, Blancon J C, Neukirch A J, Gupta G, Crochet J J, Chhowalla M, Tretiak S and Alam M A 2015 *Science* **347** 522
[39] Ahn N, Son D Y, Jang I H, Kang S M, Choi M and Park N G 2015 *Journal of the American Chemical Society* **137** 8696
[40] Chen W, Wu Y, Yue Y, Liu J, Zhang W, Yang X, Chen H, Bi E, Ashraful I and Grätzel M 2015 *Science* **350** 944
[41] Zhao D, Wang C, Song Z, Yu Y, Chen C, Zhao X, Zhu K and Yan Y 2018 *ACS Energy Letters* **3** 305
[42] Shadgan B, Roig M, HajGhanbari B and Reid W D 2010 *Archives of Physical Medicine and Rehabilitation* **91** 806
[43] Ho Y S 2012 *Chinese Journal of Chemical Engineering* **20** 478
[44] Pedrycz W, Weber R and de la Sotta C 2018 *Information Sciences* **432** 245
[45] Hirsch J E 2005 *Proc. Natl. Acad. Sci. USA* **102** 16569
[46] Qiu J 2014 *National Science Review* **1** 161
[47] Palit D 2013 *Energy for Sustainable Development* **17** 270
[48] Masood M T and Shah F 2012 *Journal of Business and Management* **7** 231
[49] Peláez A L 2010 *Social and Econoomic Development* **3** 81