Trends in global solar photovoltaic research: silicon versus non-silicon materials

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This article reports a comparative analysis of the thrust in solar photovoltaic (PV) research during 1981–1988 and 2001–2008. Global solar PV literature in the latter period recorded a 4.5-fold increase over those in 1981–1988. The USA leads all the countries in terms of absolute number of publications as is the case in other areas of basic sciences. But its relative activity in solar PV research in terms of transformative activity index (TAI) values has decreased from 1.8 in 1981–1988 to 0.9 in 2001–2008. The performance of National Renewable Energy Laboratory of USA, the top institute is similar to its national trend, i.e. increase in absolute number and decrease in TAI. Presence of 3 German institutes in the top 10 institutes is an indication of Germany's emphasis as well as the leadership in global solar PV research. The share of silicon-based papers as percentage of total solar PV publication has decreased from around 36% in 1981–1988 to 34% in 2001–2008. The share of non-silicon-based publication has increased from 9% in 1981–1988 to 17% in 2001–2008. Within silicon, the emphasis is still on crystalline silicon while among non-silicon materials, the growth of dye-sensitized solar cells output is outstanding. The developments especially in the areas of non-silicon solar PV cells, thus, raise hopes of the possibility of developing cost-effective and more efficient solar cells.

Keywords: Amorphous silicon, cadmium telluride, crystalline silicon, dye-sensitized solar cells, gallium arsenide.

ENERGY is what keeps the world going. Global primary energy consumption has increased by an overwhelming 155% in the last 40 years, up from 4.4 Gtoe in 1968 to 11.3 Gtoe in 2008 (ref. 1). The projected increase in global energy consumption by 44% from 2006 to 2030 (ref. 2) too reflects the importance of energy in the global economy. However, the finite reserves of fossil fuels and the emission of greenhouse gases are hurdles in the realization of societal or national aspirations of economic development. Because of the exhaustible source of carbonized energy, an incremental transition to renewable energy is critical.

Renewables contributed about 13% of total primary energy supply in 2004; the share of solar photovoltaic (PV) was only 0.04% (ref. 3) and is expected to reach a maximum of 1% by 2030 (ref. 4). As per the International Energy Outlook 2009, the share of renewable energy in world electricity generation will grow by an average of 2.9% in the next 25 years. A major portion of this share will come from hydropower and wind power. This is despite the proven potential of the Sun in providing enough energy in one hour to meet the annual global consumption of energy[5]. Some optimistic scenario prediction indicates that solar power (PV and thermal) would contribute around half of the global primary energy supply by 2100 (ref. 6). However, owing to the recent economic slowdown and its associated developments, one might doubt the predicted magnitude of contribution of solar power in the global primary energy use in the long run. Achieving such ambitious targets demands reduction in the cost of solar energy per kWh than those of other renewables and definitely than those of conventional fuel.

The low share of solar energy in the global energy mix is primarily due to the relatively higher per unit price of solar energy. The present retail price of solar energy is 20–65 USD cents per kWh. Those of other renewables like small hydro, biomass, geothermal and wind is less than 20 USD cents[3]. Reduction in the retail cost of solar energy is achievable by enhancing the conversion efficiency from solar to electrical energy and by reducing the energy pay-back period. The conversion efficiency depends on the technology and the material used in solar cells.

The first PV solar cell was developed using silicon (Si) at Bell Laboratories in 1954 (ref. 7). It was then predicted that Si would soon be replaced by another material more suitable for solar cells because Si is not an ideal material for PV conversion[8]. For instance, 100 μm of crystalline Si is required for 90% light absorption in comparison to only 1 μm of other materials like gallium arsenide (GaAs). However, despite this, Si, particularly crystalline silicon (c-Si) dominated the solar PV market until recently[9]. The main reason for the dominance of the PV market by Si is the availability of a mature Si processing technology that existed even before the advent of PV and the availability of rejected Si from the high-tech semiconductor industry.

An ideal solar cell material needs to fulfil some basic qualities like band gap, band structure, etc[8]. The industry has began to explore other promising new classes of materials like cadmium telluride (CdTe), GaAs, copper

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indium gallium selenide (CIGS), dye-sensitized solar cells (DSSC) and organic solar cells (OSC) with proven potentialities[10,11] to substitute silicon. With so many options, realization of low-cost, high-efficiency solar cells seems achievable. It seems likely that silicon will lose its unquestionable leadership in the next 25 years[12], as there are indications of impressive growth of new emerging solar cell technologies. It is reported that the estimated average annual growth rate of non-Si cells will jump by an impressive 43% in the next decade or so[13].

Several authors have studied academic publications to assess the progress of research and technological development and to predict future trends[14–19]. Some aspects of solar cell material research were studied using bibliometrics; measurement of innovation in the photovoltaic industry in USA[20], knowledge network hubs in the area of nanostructured solar cells[21], global research activities in nanotechnology enhanced thin film solar cells[22]. There is, however, no bibliometric study on the growth of global solar PV research *per se* and no information on the changes in research thrust over time. This paper tries to analyse the trend as well as the thrust of solar photovoltaic research across the world at country and institutional level.

Methodology

This paper examines the trend in solar PV research and the shift in thrust from silicon to non-silicon materials using papers indexed by Scopus database for two different periods, i.e. 1981–1988 and 2001–2008. These two blocks were chosen because the energy sector has undergone substantial changes during these periods and there has also been global emphasis on renewable energy in general, and solar energy in particular. The following query was run to download the records from the Scopus database (www.Scopus.com). The Scopus database was used instead of the commonly used Web of Science (WoS) of Thomson Reuters, because running the query in the latter returned relatively fewer records that were essentially included in the output from the Scopus database. ('solar power' or 'solar energy' or 'solar cell' or 'solar photovolt' or 'solar PV' or 'solar cell material'.)

The occurrence of any of the selected keywords was matched across title, abstract and keyword section of the papers in the database. From the downloaded records, only journal papers, conference papers and reviews were selected for detailed analysis. This data was used to present the overall picture of solar PV output during the two study periods. However, all the subsequent analysis is based only on those documents having author affiliation, as the study was intended to see the involvement of countries and institutions in solar PV research and their shift in thrust, if any. In each period, an overall picture of publications in solar PV such as total output, countries and institutes involved was constructed. Based on the keywords (both author and index) of each paper, the publication data was classified into two categories, i.e. publications having the various forms of the word silicon (including its chemical formula) and publications having the various forms of the wordings of the different types of non-silicon materials (including their chemical formulae) being considered in this study.

Publications having the keyword 'silicon' were again broadly divided into two groups: crystalline and amorphous silicon. The choice was based on the two main forms of silicon used in solar cells. The data were filtered using the keywords 'amorphous silicon' or 'a-Si' and 'crystalline silicon' or 'c-Si' for the two forms of silicon. Non-silicon-based publications were categorized under the sub-headings of CdTe, GaAs, CIGS, DSSC and OSC (using both the abbreviations and the expanded words), the promising new classes of solar cell materials. The purpose of using a query instead of extracting the publication records directly from the database using the desired keyword was to ensure accuracy as well as filtering only those publications related to solar PV cell. Efforts were made to capture the change in research thrust from silicon to non-silicon-based solar PV cells. The top 10 countries and institutes were selected on the cumulative publication of both the periods.

The change in output between the two periods under consideration, both for country, institution and for different types of solar PV materials, was analysed using the transformative activity index (TAI) suggested by Guan and Ma[23]; as the absolute output of publications is confounded by the size of the country as well as the size of the specialty. TAI is a relative indicator and takes into consideration the effect of the size of the country as well as the size of the sub-domain. This has been used earlier by Garg *et al.*[24] and Joshi *et al.*[25] in their studies on global malaria vaccine research and global forest fungal research respectively. TAI is similar to activity index, first suggested by Frame[26] and elaborated by Schubert and Braun[27].

Mathematically, $\text{TAI} = [(C_i/C_o)/(W_i/W_o)] \times 100$.

where C_i is the number of publications of the unit (particular country or institution or type of PV material) in the ith block, C_o is the total number of publications of the unit during the period of study, W_i is the number of publications of all units in the ith block and W_o is the number of publications of all the units during the period of the study.

Results and discussion

Type of documents published

A total of 1932 documents were published during 1981–1988, while 7574 documents were published during 2001–2008. The distribution of output in different type of

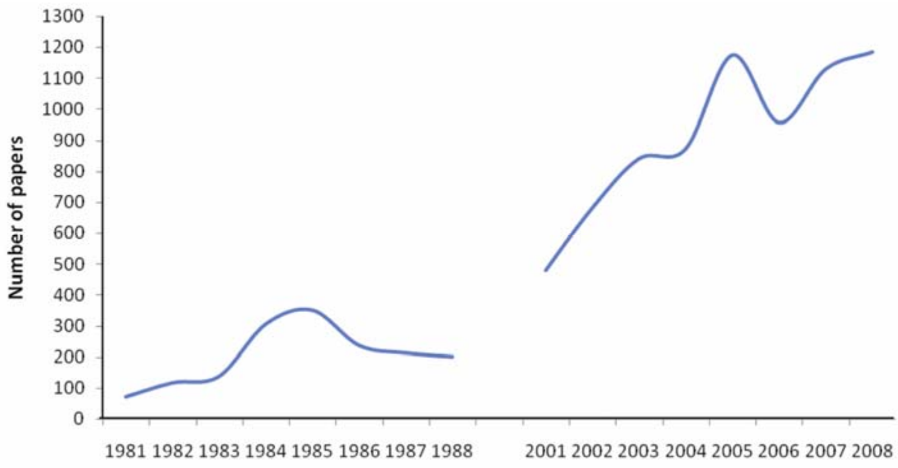

Figure 1. Trends of global solar photovoltaic (PV) publication during 1980–1988 and 2000–2008.

Table 1. Types of documents in solar PV research communications

Document type	1981–1988 (% share)	2001–2008 (% share)
Journal paper	833 (43.1)	3809 (50.3)
Conference paper	786 (40.7)	3259 (43.0)
Review	8 (0.4)	254 (3.4)
Conference review	57 (3.0)	90 (1.2)
Book	30 (1.6)	0
Report	8 (0.4)	0
Note	0	83 (1.1)
Short survey	0	30 (0.4)
Others	210 (10.9)	49 (0.6)
Total	1932	7574

documents is given in Table 1. The others category includes documents such as editorials, erratum, letters, business articles, abstract reports and unidentified documents. Data presented in Table 1 indicates a significant increase in the number of journal papers. For other forms of literature output, the increase is marginal.

Pattern of output

Of the 1932 documents published in 1981–1988, only 1477 documents had affiliation information while 7137 out of 7574 documents published during 2001–2008 had information on authors. The intensity of publication such as the number of papers published per year and the annual growth of publication was comparatively higher in the latter period (Figure 1). During the eighties, the number of papers published shows a steady increase beginning 1981 onwards reaching a peak in 1985 after which it started declining. In contrast, during the later period, the trend of publication shows a sharp increase from 2001 onwards which attained maximum output in 2005. In 2006, there was a sharp decline in the number of papers published but afterwards it started increasing again. While studying the solar PV output in USA, Vidican *et al.*[20] have also observed similar trend of decreased output in 2006. Thus, it is clear that by 1988, we see a declining trend of solar PV publication while at the end of 2008, we observe an increasing trend.

During 1981–1988, on an average 203 papers were published whereas the average annual publication during 2001–2008 was 914 papers. It is important to note here that the numbers of papers published during 2001–2008 were 4.5 times more than those published during the eighties. Within a span of two decades, there has been a massive increase in the solar PV research output, which indicates the global thrust on solar PV research. The concerns about climate change and energy security across nations and government support in commercializing renewable energy technologies might have increased the interest in solar energy technologies among the institutes and countries leading to enhanced publication in solar PV after 2000. Increased solar PV publication is also due to the undertaking of extensive research projects by researchers concerned with harnessing renewable energy including solar energy, which in turn has been fuelled by the encouraging market developments[28,29].

Performance of different countries and institutes: A total of 1477 documents published during 1981–1988 came from 527 institutes/research organizations belonging to 57 countries, whereas 2205 institutes/research organization from 95 countries contributed to the 7137 number of documents published during 2001–2008. In assessing the contribution of countries and institutes, the method of normal counting is used, i.e. in case of joint papers; all the contributing countries or institutes were given equal weights. The top performers (countries/institutes) were selected on the total publication of both the periods. It is apparent from Table 2 that all the top 10 countries have increased their publication during the latter period indicating more emphasis on solar PV research. Seven out of

Table 2. Top 10 countries in solar PV publication and their TAI

Country	1981–1988	TAI_1981–1988	2001–2008	TAI_2001–2008	Total
United States	664	1.8	1838	0.9	2502
Germany	108	0.6	1160	1.1	1268
Japan	127	0.8	1006	1.0	1133
China	19	0.2	557	1.1	576
France	100	1.6	332	0.9	432
United Kingdom	34	0.6	351	1.1	385
India	104	2.0	250	0.8	354
The Netherlands	12	0.2	342	1.1	354
South Korea	5	0.1	277	1.2	282
Spain	23	0.6	239	1.0	262
Others	318 (47 countries)		2450 (85 countries)		2768
Total	1514		8802		10,316

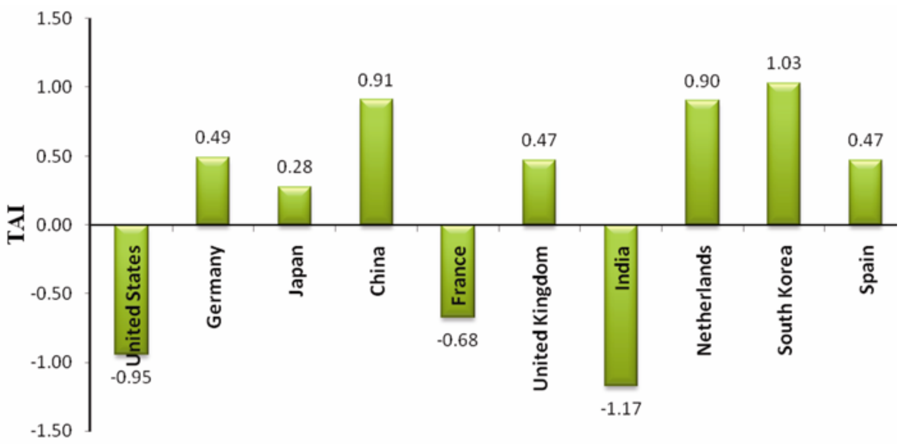

Figure 2. Differences in transformative activity index (TAI) between 1980–1988 and 2000–2008 among the top 10 countries in global solar PV publication.

the top 10 countries recorded a much higher TAI during 2001–2008 than those in 1981–1988, except USA, France and India (Figure 2). Of all the countries, the progress of South Korea in solar PV research is commendable from the fact that it has recorded the maximum increase in TAI by 1.03 points.

The top 10 institutes/organizations in solar PV publication during 1981–1988 and 2001–2008 are given in Table 3. Among the institutes, the changes in TAI are more prominent than those observed at the country level. Increase in the absolute number of publication by all the top 10 institutes during 2001–2008 indicate more emphasis on solar PV research. Despite this, some institutes like National Renewable Energy Laboratory (NREL), USA, National Center for Scientific Research (CNRS), France and Osaka University, Japan exhibits reduced TAI (Figure 3) indicating relatively lower intensity of increase by these institutes. In other words, relatively higher contribution by other institutes like Forschungszentrum Julich (fz-J), Germany; Chinese Academy of Sciences (CAS), China; and Fraunhofer-Gesellschaft (FhG), Germany. An indication of Germany's emphasis as well as the leadership on solar PV research is apparent from the fact that three out of the top 10 institutes in global solar PV research are from Germany.

Shift in thrust of solar PV material research

From the preceding paragraphs, it is apparent that global solar PV publications have increased by many folds in the first few years of the new century as compared to those made during the eighties of the last century. In view of the necessity to develop more cost-effective solar PV cells, it is important here to capture the direction of change (increase). Therefore, it is of special interest to see which are the dominant emerging solar PV materials. It has been demonstrated that analysis of trends in publication of text documents, rather the contents of the documents, help in identifying early technology focus in different areas within solar PV technologies[20]. The degree of occurrence of the terminologies of different solar cell materials in the keywords (author and index) and their percentage change in the recent period over the earlier

Table 3. Top 10 institutes in solar PV publication and their TAI

Affiliations	1981–1988	TAI_1981–1988	2001–2008	TAI_2001–2008	Total
National Renewable Energy Laboratory, United States	90	2.0	292	0.9	382
Hahn-Meitner-Institute Berlin GmbH, Germany	15	0.6	188	1.1	203
Fraunhofer-Gesellschaft, Germany	8	0.4	166	1.1	174
National Center for Scientific Research, France	47	2.3	127	0.8	174
National Institute of Advanced Industrial Science and Technology, Japan	9	0.5	160	1.1	169
Chinese Academy of Sciences, China	3	0.2	147	1.1	150
University of California, United States	9	0.5	141	1.1	150
University of New South Wales, Australia	13	0.8	119	1.0	132
Forschungszentrum Julich, Germany	2	0.1	125	1.1	127
Osaka University, Japan	29	2.0	93	0.9	122
Others	1394 (517 institutes)		10,521 (1195 institutes)		11,915
Total	1619		12,079		13,698

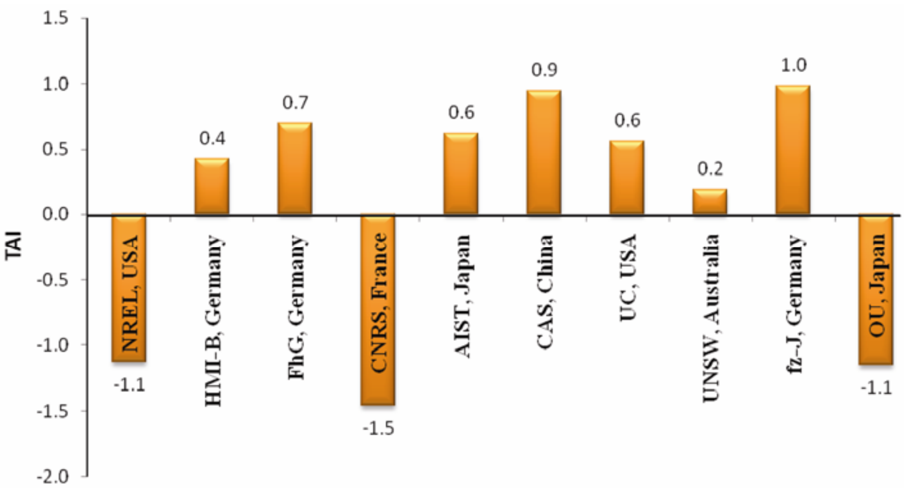

Figure 3. Differences in TAI between 1980–1988 and 2000–2008 among the top 10 institutes in global solar PV publication.

period, relative change in the share of total global solar PV publication and TAI are considered as indications of thrust in a specific area of solar PV materials.

Silicon versus non-silicon: During 1981–1988, there were 533 silicon-based papers. This has increased to 2441 publications in 2001–2008. In contrast, there were only 136 non-silicon based papers during 1981–1988 and during 2001–2008, the number of non-silicon papers increased to 1206 papers. Although, there is an increase in the number of publications in both the forms of materials, the intensity of increase appears to be more in non-silicon materials. That more research is being undertaken around non-silicon solar PV materials is apparent from the changes in the TAI of both Si and non-Si materials. Silicon materials had a TAI of 1.16 during 1981–1988 which has decreased to 0.97, a net decrease by 0.19 points. On the other hand, non-silicon materials have recorded a massive gain of 0.41 points by increasing the TAI from 0.65 in 1981–1988 to 1.06 in 2001–2008 (Table 4), and this could be made out very easily from Figure 4 also. The concerns about reducing the unit cost of solar energy and subsequent undertaking of projects across countries might have contributed to increased research in non-silicon solar PV materials and hence increased publication, especially in the beginning of the new century.

Silicon: crystalline or amorphous

Although there was an increase in the absolute number of both c-Si- and a-Si-based publications, the rate of increase of c-Si is much higher than those in a-Si. With only 68 papers, c-Si accounted for about 4.6% of the total solar PV output during 1981–1988. However, in 2001–2008, the percentage share has increased to 12.65%. On the other hand, the share of a-Si publication has decreased from 8.73% in 1981–1988 to 7.2% in 2001–2008 (Table 5).

Table 4. TAI of silicon and non-silicon solar PV materials research during 1981–1988 and 2001–2008

PV material	1981–1988	TAI_1981–1988	2001–2008	TAI_2001–2008	Total
Silicon	533	1.2	2441	1.0	2974
Non-silicon	136	0.7	1206	1.1	1342
Total	669		3647		4316

Table 5. TAI of different types of solar PV materials research during 1981–1988 and 2001–2008

PV material	1981–1988	TAI_1981–1988	2001–2008	TAI_2001–2008	Total
c-Si	68	0.6	903	1.1	971
a-Si	129	1.8	514	0.9	643
CdTe	39	1.5	198	0.9	237
GaAs	89	3.6	134	0.7	223
CIGS	5	0.2	196	1.1	201
DSSC	1	0.02	474	1.1	475
OSC	1	0.04	232	1.1	233
Total	332		2651		2983

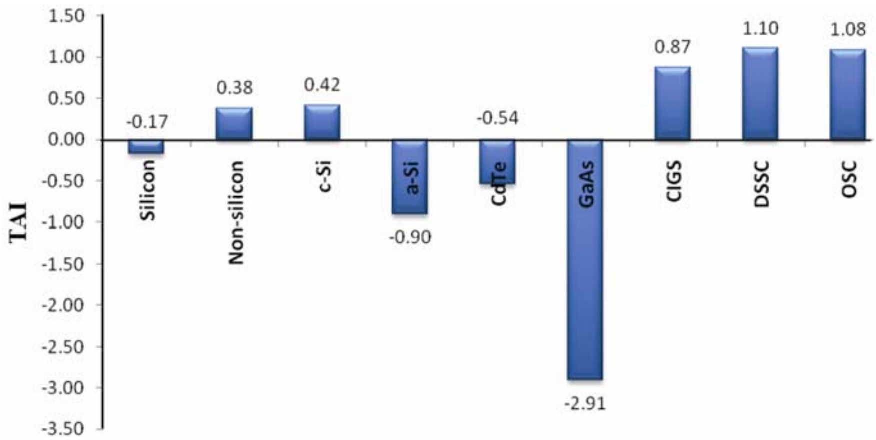

Figure 4. Differences in TAI of different solar PV materials between 1980–1988 and 2000.

This is clearly reflected in TAI the TAI of c-Si has almost doubled in 2001–2008 while that of a-Si has reduced to half (Figure 4). The relative dominance of c-Si research over a-Si research is also reflected in the performances of the top 10 countries as well as the top 10 institutes. The comparatively higher publication output in c-Si as an indication of enhanced research thrust and correlates well with the anticipated dominance of solar PV by c-Si during the next decade or so, as other thin-film technologies such as a-Si or CIGS still await significant technological breakthroughs[30].

Non-silicon solar PV materials

As in the case of total solar PV output as well as total Si-based and non-Si based publications, the absolute number of publication of all the different types non-silicon materials have increased considerably. However, the increase in the output of three materials, viz. DSSC, OSC and CIGS is highly significant. Both DSSC and OSC had just a single paper in 1981–1988 which has increased to 474 and 232 papers, respectively during 2001–2008 while the increase in case of CIGS is from 5 papers to 196 papers (Table 5). The individual percentage share of all these materials to the total solar PV output has also improved considerably. This is also reflected in the significant increase in TAI of all these three materials during 2001–2008 (Figure 4). Despite an increase in the absolute number of publications, both CdTe and GaAs have recorded a significantly lower TAI and the intensity of decrease is very acute in the case of GaAs. Its TAI has decreased from 3.59 in 1981–1988 to a mere 0.68 during 2001–2008. The decrease in overall percentage share of CdTe and GaAs is perhaps because of the increased thrust on other non-silicon materials and non-suitability of these two materials for developing cost-effective solar PV cells. Of all the non-silicon materials, the progress in the areas of DSSC research is outstanding. A direct function of the increased research and subsequent publication in DSSC, especially during the later part of 2001–2008 could be seen in the establishment of advantageous features like low-cost potential, simple processing, wide range of applicability and good performance[12].

Conclusion

In contrast to all other forms of renewables, based on all future projections of human energy consumption, both the technological and the sustainable potential of solar energy is practically unlimited. It is apparent from the present study that solar PV output in the first decade of the new century has increased by many folds as compared to those in the eighties. Within silicon, the emphasis is still on crystalline silicon research although amorphous silicon-based output has also increased substantially. Although silicon-based solar PV research has also increased, the growth is more in the area of non-silicon-based research. Among the non-silicon materials, DSSC-based solar PV research is growing at a much faster rate than any other. However, a detailed analysis of the patenting activity in solar PV would buttress the understanding of this change, as patents are considered to be the actual precursor of technological change. Another indicator would have been the amount of money invested in either form of solar PV research. Nevertheless, in the absence of information on pattern of research funding, trend of patent filling and holding; at least the trend of publication output does indicate that more thrust is being laid on non-silicon-based solar PV research. The developments especially in the areas of non-silicon solar PV cells, thus, raise hopes of the possibility of the development of cost-effective, more efficient solar cells. This would help in addressing the twin issues of energy security and climate change.

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