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Analysis of India's solar photovoltaics research output

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Knowledge of national research trends and thrust areas as well as R&D capability in solar photovoltaics has become all the more essential following the launching of the National Solar Mission in 2010. The present study analyzes the status of solar PV research in India encompassing aspects such as pattern of output, impact of research, thrust of research; identifies the leading agencies, institutes and authors including their research thrust. Finally, the paper looks into the pattern of collaboration in Indian solar PV research including academia-industry collaboration. The study concludes that a comprehensive mapping of solar PV R&D capability of India should be taken out on a priority basis in order to make effective R&D strategies to take advantage of supportive policy initiatives like the National Solar Mission.

Keywords: Silicon, non-Silicon, Dye-sensitized solar cells, R&D strategy, National Solar Mission

Introduction

In India, solar energy research has been carried out since independence, with initial emphasis on defence requirements. Plausibly solar energy research for public usage in India began with the setting up of the 'Solar Energy Programme' in 1975, more as a response to the sudden hike in crude oil prices in 1973. This effort got buttressed with the establishment of the Department of Non-Conventional Energy Sources in 1982, the first government agency in the world for renewable energy[1] and it's subsequent up gradation to a full-fledged ministry in 1992. Despite being a first mover, today, India lags far behind many nations in exploiting the potential of solar energy as well as in solar energy technological competency. For instance, as on 2009, India does not figure in the top 10 countries in solar PV installations, which is headed by Germany with 47% of global installations[2]. Further, there are only 20 odd solar PV cell manufacturers in India. Though India occupies 8th position in the world in solar hot water/heating capacity, it's share (1.2%) of the global capacity is nowhere comparable with China's share of 70.5% who is the global leader in this. Nevertheless, with the launch of the 'National Solar Mission' in early 2010, India has re-emphasized its commitment to exploit the solar energy which seems more of an awakening step due to the developments in the global arena.

So far, solar energy has been harnessed mainly through two technological routes - solar photovoltaics and solar thermal. Of the two routes, solar PV is more advanced and developed than solar thermal with the former contributing 0.25% to the world electricity generation while the contribution of the latter is 0.01%. As solar PV is the dominant route, the present study is centered on it.

The low level of solar energy utilization in India and for that matter the world as whole is because the unit cost of solar energy is relatively higher than other traditional fuel, even after incorporating positive externalities such as GHG emission reduction, energy security etc[3]. The high cost of solar energy, in turn, is mainly due to the low conversion efficiency which again depends on the type of materials used in solar cells and technology employed. Further, high cost of the solar cell materials also increases the overall cost of solar energy. Thus, it is apparent that there are two main approaches/strategies to reduce the unit cost and thereby increase the utilization of solar energy. These are i) technological improvement to enhance the conversion efficiency of presently used materials and/or ii) to search and develop potential low cost solar cell materials.

As far as India is concerned, the above-mentioned two strategies have been rightly identified in the 11th Five Year Plan. In addition, the National Solar Mission, to meet the ambitious target of 20,000 MW by 2022, has identified these two areas for huge R&D investment. The mission document also mentions setting up of a Solar Research Council to oversee research capabilities and resources of existing as well as to be created dedicated solar energy research institutes. To fulfill the mission objectives, India will need a large pool of highly skilled technical manpower, scientists/engineers and highly specialized and best performing institutes to carry out highly specific, time bound and result oriented research. In view of the solar mission, it has become all the more necessary to map the solar PV research in India including who is doing what, and potential global collaborators including industries and areas of collaboration.

Objectives of the study

- To analyze the Indian solar PV research output during 2000 to 2009,
- To identify leading Indian institutes and authors in solar PV research and impact of their output,
- To study the pattern of collaboration , and,
- To understand the involvement of industry in Indian solar PV research

Methodology

In the present study, the Scopus database was used. The occurrence of the keywords "solar power*", "solar generation", "solar energy*", "solar cell*", "solar photovolt*","solar PV", "solar cell material*", and "photovolt*" in the title, abstract and keywords was searched for the period 2000-2009. The query returned 1874 records. However, only 1808 records were considered for the analysis as 6 of the documents were published as letters, editorials, erratum, notes and did not contain sufficient information such as authors and their affiliation. For the analysis, the first author approach, where only the first author of a paper is taken into account (straight counts), was applied. However, if the first author is non-Indian, then Indian author and corresponding institution in the subsequent position was also taken into consideration.

To compare the scientific impact of the institutes and authors, two relative impact indicators were used, namely citation per paper (CPP) and relative citation index (RCI). CPP is the most common and frequently used indicator in publication-related performance evaluation studies. RCI on the other hand is relatively a new indicator developed by Thomson Reuters to calculate Science and Engineering indicators. This indicator has been used by Kumari[4] to examine the impact of different countries in the field of synthetic organic research. Subsequently, Joshi *et al.*[5] extended the use of RCI for evaluating the performance of institutes also. In this study, we extended it further to the next level, i.e. performance of authors.

Relative Citation Impact (RCI) = A (institute/author)'s share of total national citations/ A (institute/author)'s share of total national publications

RCI = 1 indicates that the author's/institute's citation rate is equal to national citation rate; RCI>1 indicates that the author's/institute's citation rate is higher than the national citation rate and RCI<1 indicates that the author's/institute's citation rate is less than national citation rate.

RCI is more robust than other indicators in the sense that it measures both the influence as well as visibility of research activity, irrespective of the level of evaluation, either country or institute or author.

The Activity Index (AI) suggested by Frame[6] and elaborated subsequently by Schubert and Braun[7] has been used to analyze the agency-wise activities in solar PV research. It is also used to understand whether an institute is more into domestic collaboration or international collaboration. AI is a relative indicator and takes into consideration the effect of the size of the organization/institute as well as the size of the sub-domain. The change in thrust of research in different solar PV materials has been studied using a modified form of AI, termed Transformative Activity Index (TAI) which was first suggested by Guan and Ma.[8] TAI has been used earlier by Garg *et al.*[9] and Joshi *et al.*[5] in their studies on global malaria vaccine research and global forest fungal research respectively which also reflects the applicability of the index in studying change in research thrust in any discipline.

The nature of collaboration between different institutes with regard to domestic and international collaborative publication was analyzed using the domestic collaborative index (DCI) and international collaborative index (ICI) suggested by Garg and Padhi[10]. DCI was calculated as

$DCI = [(D_i/D_{io})/D_o/D_{oo})]*100$, where

D_i = number of domestically co-authored papers in a particular block of year,

D_{io} = total output in that particular block,

D_o = total number of domestically co-authored papers,

D_{oo} = total Indian output

And ICI was calculated as

$ICI = [(I_i/I_{io})/I_o/I_{oo})]*100$, where

I_i = number of internationally co-authored papers in a particular block of year,

I_{io} = total output in that particular block,

I_o = total number of internationally co-authored papers,

I_{oo} = total Indian output

DCI/ICI=100 indicates that the collaborative effort corresponds to Indian average, DCI/ICI>100 reflects higher collaborative effort than Indian average and DCI/ICI<100 indicates less collaborative effort than the national average.

Analysis

Pattern of output

During the period 2000-2009, India has published 1814 papers in the area of solar photovoltaics (PV). This accounted for ~ 3.7 % of the global publication during the same period which stands at 48926 documents. Indian solar PV output comprises of 1375 journal papers, 381 conference papers, 52 reviews and 6 other types of documents which includes letters, editorials, erratum and notes. In the study period, solar PV publications from India have increased almost steadily at the rate of ~ 16 % per year (global AAGR ~19%), with a slight dip in 2001 and a somewhat larger decline in 2005. Banerjee[11] also noticed a similar trend of solar PV publication from India though the absolute number of yearly publications was higher than the presently reported one. This is because he used a more generalized and broader string of keywords in the search. Nevertheless, the rate of growth during the last 5 years of the decade was relatively higher than the first five years (Fig. 1). Overall, during 2000-09, India published ~181 papers per year in the area of solar PV. The correlation between the yearly number of publications and the years was found to be weak (R^2=0.8).

Channels of communication

During the study period, Indian solar PV researchers published their findings in 481 journals (including conference proceedings) originating from

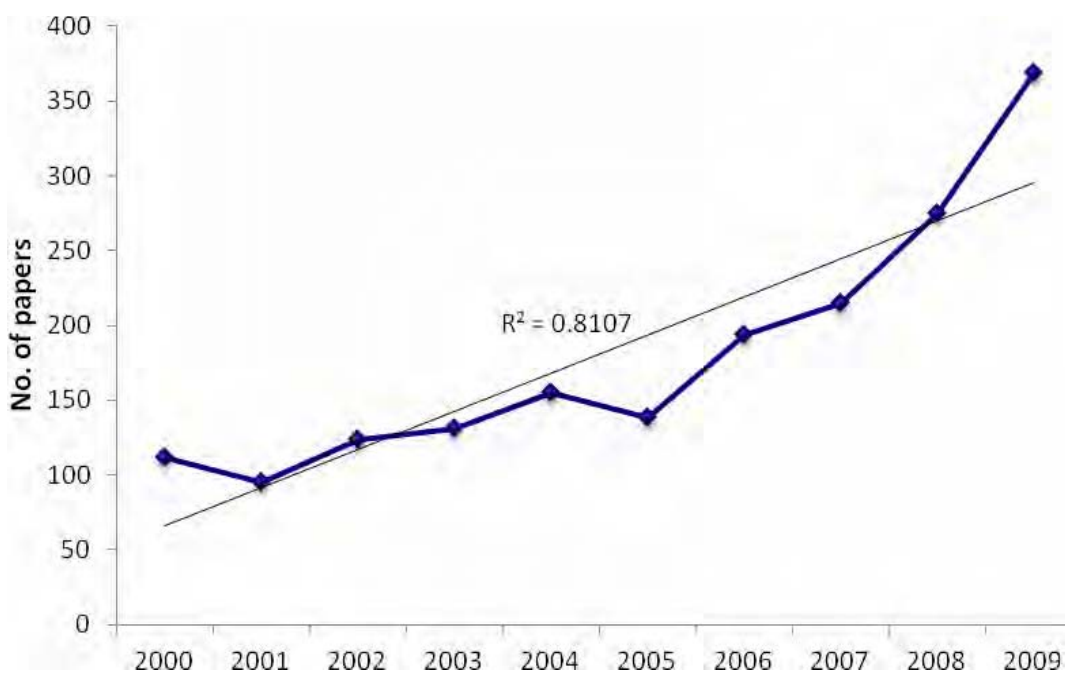

Fig. 1—Pattern of solar PV publication in India during 2000-2009

33 countries. Only 185 papers (~10%) were published in Indian journals and the rest 90% papers were published in journals originating from foreign countries. Indian solar PV researchers have published highest number of papers in journals originating from USA (512), followed by those in from England (423) and The Netherlands (392). Thus, about two thirds of the total Indian output appeared in journals published from these 3 countries alone. Though, solar PV research findings were communicated through 481 different journals, the top 15 journals (having > 1% of total output) together attracted 591 papers accounting for about 33% of the total publications (Table 1). The journal, *Solar Energy Materials and Solar Cells*, The Netherlands attracted the highest number of papers (165, ~9%). Publication of highest number of papers in this journal indicates that it is the most relevant and most preferred journal for solar PV material research publications.

In addition, analysis of impact factor (IF) of journals used for publication provides insights into the communication behaviour in any discipline. Usually, IF is normalized before analyzing. This is done mainly to eliminate the biasness associated with IF across space and time, i.e. to neutralize the variation of IF across sub-disciplines and types of journal and also the variation of IF of a particular journal over the years. However, as the present study deals with a highly specific sub-domain of solar energy and the keywords were chosen accordingly, it is assumed that there will not be that much of variation of sub-disciplines. Further, irrespective of the year of publication of a paper, all the journals were assigned the IF of 2009. It is understood that by doing this one will be biased, but this biasness will be applicable to all the journals, thus, there will not be much difference in the end result. Though this will not provide an exact nature (impact) of Indian solar PV publication but an overall picture can be anticipated.

Based on 2009 IF of the journals in which Indian solar PV papers appeared it was found that Indian solar PV papers were published in journals with an average impact factor (AIF) of 1.8. Of the total 1808 documents, 378 (~21%) were published in non-SCI (no IF) journals (accounted mostly by conference proceedings) and the rest were published in SCI journals. It is apparent that more than one third of the papers have appeared in journals having above average IF and this share is much higher than the share of papers that appeared in low and around average IF journals (Table 2). This certainly indicates the above average standard of Indian solar PV research though not world class. However, the positive aspect of Indian solar PV research is that some papers have appeared in exceptionally high IF journals. Thus, it is desirable that India should increase the share of papers in high and exceptionally high IF journals in the near future.

Table 1—Top 15 most-preferred journals of publishing Indian solar PV research

Journals	TP	% share	Pap/yr	IF_2009
Solar Energy Materials and Solar Cells, Netherlands	165	9.1	16.5	3.853
Solar Energy, England	58	3.2	5.8	2.011
Renewable Energy, England	56	3.1	5.6	2.226
Proceedings of SPIE the International Society for Optical Engineering, USA	51	2.8	5.1	0.553
Energy Conversion and Management, England	33	1.8	3.3	1.994
Thin Solid Films, Switzerland	31	1.7	3.1	1.727
Journal of Applied Physics, USA	24	1.3	2.4	2.072
Materials Chemistry and Physics, Switzerland	24	1.3	2.4	2.015
Journal of Materials Science Materials in Electronics, Netherlands	22	1.2	2.2	1.020
Journal of Non Crystalline Solids, Netherlands	22	1.2	2.2	1.252
Applied Physics Letters, USA	22	1.2	2.2	3.554
Journal of Physics D Applied Physics, England	21	1.2	2.1	2.083
Desalination, Netherlands	21	1.2	2.1	2.034
Journal of Crystal Growth, Netherlands	21	1.2	2.1	1.534
International Journal of Energy Research, England	20	1.1	2	1.928
Total	591			
Average		2.2	4	1.990

Citedness/impact of Indian solar PV research

The output of 1808 papers have received a total of 8379 citations during the period 2000-2009 with an average of about 5 citations per paper (CPP). Of the 1808 documents, 775 (~43%) papers did not receive a single citation and the remaining 57% papers received one or more citations (Table 3). Of the 775 non-cited papers, 297 were published in 2009 and the rest 478 papers were published during 2000-2008. Of the 1033 cited papers, ~62% (639) papers received citation in the range of 1-5, and the remaining 38% papers received more than 5 citations each. The numbers of papers which have received more than the average citation are 394. Only 5 papers received 100 or more citations.

Table 2—Distribution of Indian solar PV output according to 2009 impact factor

IF range	TP (% share)
Nil (0)	378 (20.9)
Low (<1.6)	541 (29.9)
Around average (1.6-2)	208 (11.5)
Above average (>2 and <5)	648 (35.8)
High (5-10)	23 (1.3)
Very high (>10 and <20)	2 (0.1)
Outstanding (≥ 20)	8 (0.4)

Table 3—Analysis of citations of Indian solar PV output

Times cited	No. of papers (%)	Total citations
	775 (42.9)	0
1	202 (11.2)	202
2	144 (8)	288
3-5	293 (16.2)	1135
5-10	189 (10.5)	1436
10-20	139 (7.7)	2006
21-50	47 (2.6)	1398
51-100	14 (0.8)	1047
101-200	3 (0.2)	416
>201	2 (0.1)	451
Total	1808	8379

The papers which attracted 100 or more citations are considered here as highly cited papers. There are 5 such papers. Of the 5 highly cited papers, 2 are articles, 2 are reviews and 1 conference paper. Four out of the 5 highly cited papers were written in joint collaboration with foreign institutes except the one from Shivaji University which can be said a true Indian solar PV publication (Table 4). NIIST (CSIR), Shivaji University, Mysore University, IISc, TIFR and BARC have their presence in the top cited papers. The absence of centres of excellence such as IITs, NITs, and nationally reputed universities in the list of top-cited papers is not a good sign for Indian solar PV research and needs immediate attention of the respective competent authorities.

Thrust areas in solar PV research

Research is precursor to development of new promising technologies. In this context, it is important to capture the direction of solar PV research especially with regard to materials used in the solar PV cells, because solar energy conversion efficiency depends to a great extent on these cells. It has been shown that statistical analysis of author keywords and title-words gives valuable clue to the direction of research[12]. Further, 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[13].

Table 4—Top 5 highly cited papers in solar PV research in India

Bibliography	**TC**	**Institute(s)**
Thomas KG & Kamat PV. Chromophore-Functionalized Gold Nanoparticles. *Acc. Chem. Res*., **2003**, 4746: 105-107	239	CSIR- National Institute for Interdisciplinary Science and Technology; Notre Dame Radiation Lab
Mane RS & Lokhande CD. Chemical deposition method for metal chalcogenide thin films. *Mat. Chem. Phy*., **2000**, 141: 581-590	212	Shivaji University
El-Khouly ME *et al*. Intermolecular and supramolecular photoinduced electron transfer processes of fullerene-porphyrin/phthalocyanine systems. *J Photochem. Photobio. C:*, **2004**, 583: 134-148	192	Tohoku Univ.; Wichita State Univ.; Tanta Univ.; Chiba Univ.; Mysore Univ.; IISc; Univ. of Houston; Univ. de Bourgogne
Basu S & Antia HM. Seismic determination of solar heavy element abundances. *ESA Spl. Publ*., **2006**, 46 : 373-376	115	Yale Univ.; Tata Institute of Fundamental Research
Deb SK *et al*. Pressure-induced amorphization and an amorphous - Amorphous transition in densified porous silicon. *Nature*. **2001**, 5: 79-104	109	Bhabha Atomic Research Centre; Univ. of California at Davis; Argonne National Laboratories; Univ. College London; Royal Institution of Great Britain

Of the total 1808 solar PV publications, only 1202 (65%) papers had author keywords. Analysis of the author keywords of the 1202 documents revealed that there were altogether 5444 keywords; thus, each paper used ~ 5 keywords. The keywords were standardized by expanding the abbreviations and chemical formulas to their corresponding words and grouping up very closely related keywords. For instance, protocrystalline, nanocrystalline and microcrystalline Si were included in the category of amorphous Silicon (a-Si) as all these were used in the manufacture of Si thin film cell, thus a-Si basically meant Si thin film cells. Similarly, crystalline Silicon (c-Si) included mono crystalline, multicrystalline, polycrystalline and ribbon silicon. And Dye-sensitized solar cells (DSSC) also included Tin Oxide thin film cells as Tin Oxide is the most commonly used material in DSSCs. Standardization of the keywords, thus, resulted in 1998 unique keywords. Of the 1998 keywords, 1488 (75%) appeared once and 232 (12%) appeared twice. Large number of once-only author keywords indicates lack of continuity in research and wide disparity in research focuses[14, 15]. Thus, solar PV research in India appears to be still exploratory in nature and well corroborates with the fact that the search for a just suitable solar PV cell material is continuing not only in India but also across the world.

The thrust in solar PV research was studied with regard to the different materials used in solar PV cells. During the study period, India worked on 20 different types of solar PV materials. It is apparent that efforts are being made to study the feasibility of a whole lot of non-silicon materials. This appears to be in the right direction of the prediction made after the development of first solar PV cell (Si-based) that Si will soon be replaced by another material more suitable for solar cells because Si not an ideal material for photovoltaic (PV) conversion[16]. Of the 20 different materials, the major ones were selected to analysis the shift in solar PV research thrust.

Observation of the TAI values revealed that research in Si materials has decreased while there was a relative increase in non-Si material research. Though activities in both c-Si and a-Si have decreased, the intensity of decrease in a-Si was comparatively higher than those in c-Si (Fig.2). In other words, within silicon, more research was being carried out on the crystalline form. Relatively higher publication activity in c-Si is an indication of enhanced research thrust and correlates well with the anticipated dominance of solar PV by c-Si during the next few years, as other thin-film technologies such as a-Si or CIGS still awaits significant technological breakthroughs[17].

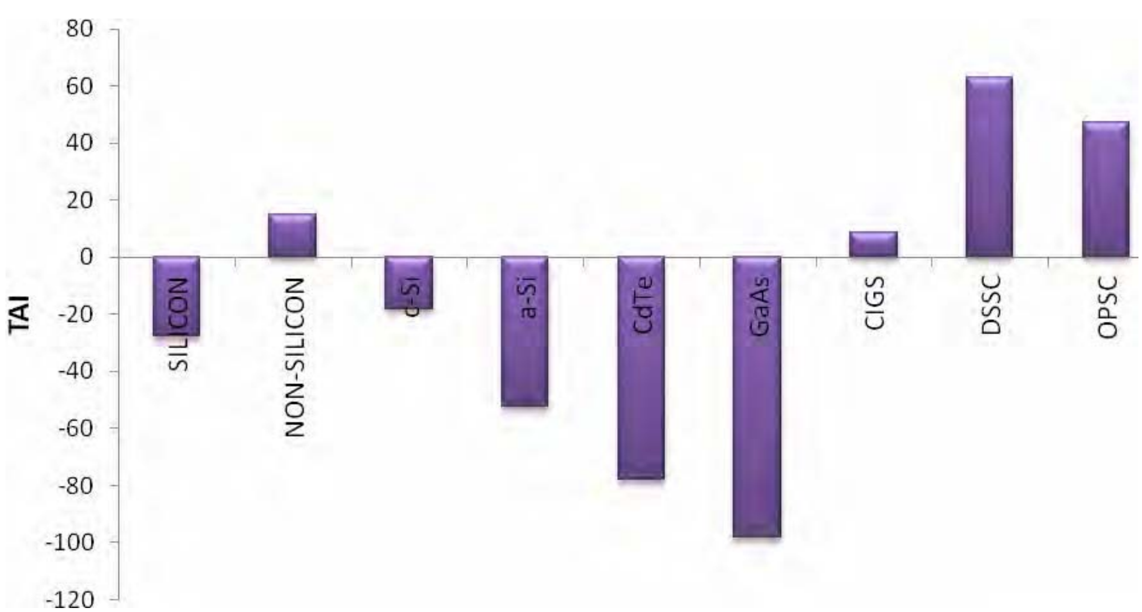

Fig. 2—Changes in TAI of different solar PV materials

Among the non-Si materials, the growth of research activity in DSSCs and OPSCs was outstanding. For instance, TAI of DSSCs have increased from 0.5 during 2000-04 to 1.2 during 2005-09. Similar trends of higher publication activity in DSSCs at the global level especially after 2000 have been observed[18]. Likewise, the TAI of OPSCs have increased by 0.5 points (Table 5). It seems likely that silicon will lose its unquestionable leadership in the next decade or so, as there are indications of impressive growth of new emerging solar cell technologies across the world[18]. At the global level also, a similar trend of shift in solar PV research have been noticed[19].

Though analysis of the author keywords provided some trends/thrusts of solar PV materials research in India, the findings should be taken with a little caution. Because the observations are based on author keywords of only 1202 (67%) documents, not the total output of 1808 papers. Hence, the observations may not be the true reflections of the exact state of affairs rather just an approximate reflection of the scientific attention.

Agency-wise distribution of output

It is useful to study the agency-wise distribution of research output in any discipline. Because bulk of the R&D funding comes from the central government and is routed through these agencies such as Council of Scientific & Industrial Research (CSIR), Department of Science & Technology (DST), Department of Atomic Energy (DAE), Department of Space (DoSp), Defense Research & Development Organization (DRDO) and Indian Council of Agricultural Research (ICAR) etc. Understanding of the trend of research output and thrust of research at the agency level has important policy implications. For instance, it will be easier and more effective to define future R&D strategies at the agency level instead of defining them at the level of each daughter institutes separately.

As observed in the case of Indian science as a whole by Garg *et al.*[20], academic institutes (universities and colleges) were the major contributors (~39%) to the total Indian solar PV output. The next highest contribution (31%) was made by the engineering universities (including IITs and engineering colleges). This was followed by DST (7%) and CSIR (6%). DAE and DoSp contributed 3% each while DRDO, industry and agricultural universities contributed 2% each to the total output (Table 6). Though all the agencies have increased absolute number of publication during 2005-09 over those of 2000-04, but their relative publication activities provide a grim picture. The AI of all the agencies have decreased in the latter half of the study period except those of engineering universities, industries and agricultural universities (Fig. 3). This is a matter of serious concern and the policy planners should take serious note of this development.

Analysis of the agency-wise thrust of research in solar PV materials indicate that engineering universities, DST, DoSp and industry are giving more emphasis on Si materials while academic institutes, DAE and DRDO are carrying out more research on non-Si materials (Table 7). CSIR is maintaining a balance between Si and non-Si solar cell materials research which is evident from exactly equal TAI in both the forms of materials. A more detailed analysis of the research thrust of different agencies reveal that only academic institutes,

Table 5—Transformative Activity Index (TAI) of different solar PV materials

Solar PV material	2000-04		2005-09		Total
	TP	TAI	TP	TAI	
A: Broad categories					
SILICON PV materials	35	1.2	73	0.9	108
NON-SILICON PV materials	48	0.9	152	1.0	200
Total	83		225		308
B: Sub categories					
Crystalline silicon (c-Si)	7	1.1	17	1.0	24
Amorphous Silicon (a-Si)	20	1.4	36	0.9	56
Cadmium telluride Solar cells (CdTe)	15	1.6	22	0.8	37
Gallium Arsenide solar cells (GaAs)	8	1.7	10	0.7	18
Copper indium gallium selenium solar cell (CIGS)	6	0.9	19	1.0	25
Dye-sensitized solar cells (DSSC)	12	0.5	76	1.2	88
Organic and polymer solar cells (OPSC)	8	0.6	40	1.1	48
Total	76		220		296

Table 6—Activity Index (AI) of different agencies in solar PV research

Agency	Total	2000-04		2005-09	
		TP	AI	TP	AI
AI	705 (39)	257	1.1	448	1.0
ENGU ↑	564 (31)	127	0.7	437	1.2
DST	122 (7)	59	1.4	63	0.8
CSIR	112 (6)	42	1.1	70	0.9
DAE	55 (3)	34	1.8	21	0.6
DoSp	53 (3)	25	1.4	28	0.8
DRDO	40 (2)	20	1.5	20	0.8
Industry ↑	38 (2)	8	0.6	30	1.2
AGRU ↑	30 (2)	6	0.6	24	1.2
ICAR	20 (1)	11	1.6	9	0.7
Others	69 (4)	28		41	
Total	1808	617		1191	

AI: Universities/deemed universities & college, ENGU: Engineering universities/colleges including IITs, DST: Department of Science & Technology, CSIR; Council of Scientific & Industrial Research, DAE: Department of Atomic Energy, DoSp: Department of Space, DRDO: Defense Research & Development Organization, AGRU: Agricultural Universities, ICAR: Indian Council of Agricultural Research

Figures in parenthesis is % share of India's total publication

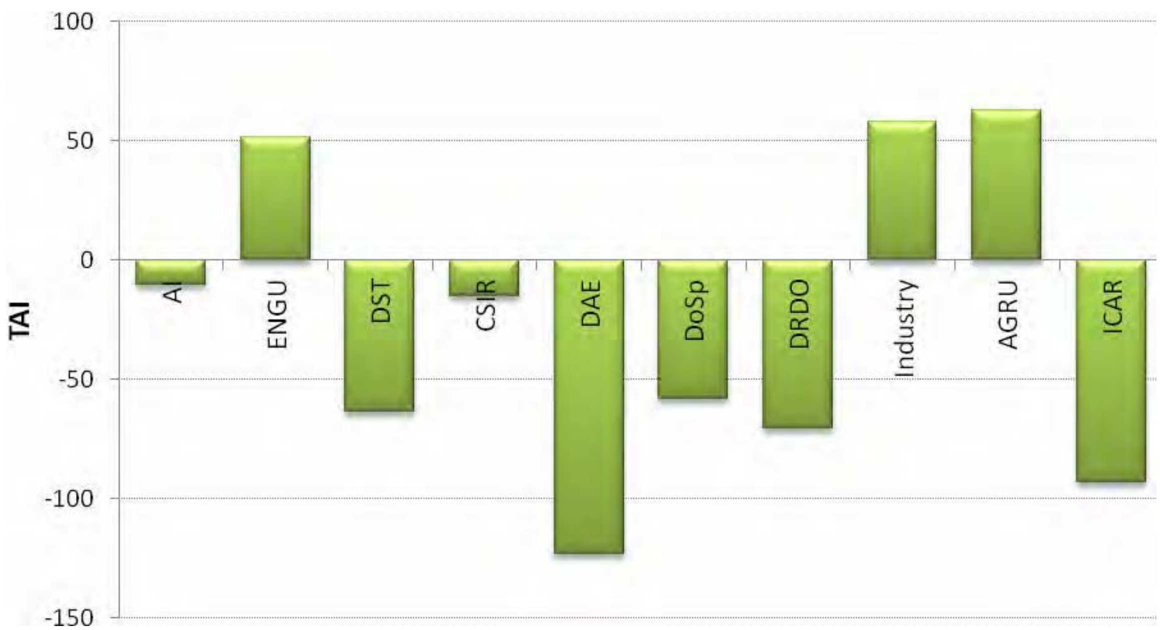

Fig. 3—Agency-wise changes in solar PV AI during 2000-2009

engineering universities, DST and CSIR are carrying out research in all the different types of solar cell materials considered in the present study. The major thrust of academic institutes and CSIR is on DSSC while that of engineering universities and DST is on a-Si (Fig. 4).

Institutions and their performance

Indian solar PV output of 1808 documents during 2000-2009 came from 934 institutes including those from other countries. However, on the basis of first author and corresponding affiliation, altogether 388 institutes contributed to the total output, with an average of 5 papers per institute. Of the 388 institutes, only 100 (26%) have CPP either equal to or higher than the national CPP while CPP of the remaining 288 (74%) institutes was lower than the national CPP. In terms of RCI values also, a similar picture was observed. 95 (25%) institutes have RCI>1, 288 (74%) institutes have RCI<1 and the remaining 5 institutes

Table 7—Agency-wise thrust (TAI-based) in solar PV materials research

Agency	Si		non-Si		Total
	TP	TAI	TP	TAI	
AI	36	0.6	124	1.2	160
ENGU	24	1.3	30	0.9	54
DST	29	2.3	7	0.3	36
CSIR	12	1.0	24	1.0	36
DAE	1	0.7	3	1.1	4
DoSp	3	1.7	2	0.6	5
DRDO	1	0.3	9	1.4	10
Industry	1	1.4	1	0.8	2
Others	0		1		1
Total	107		201		308

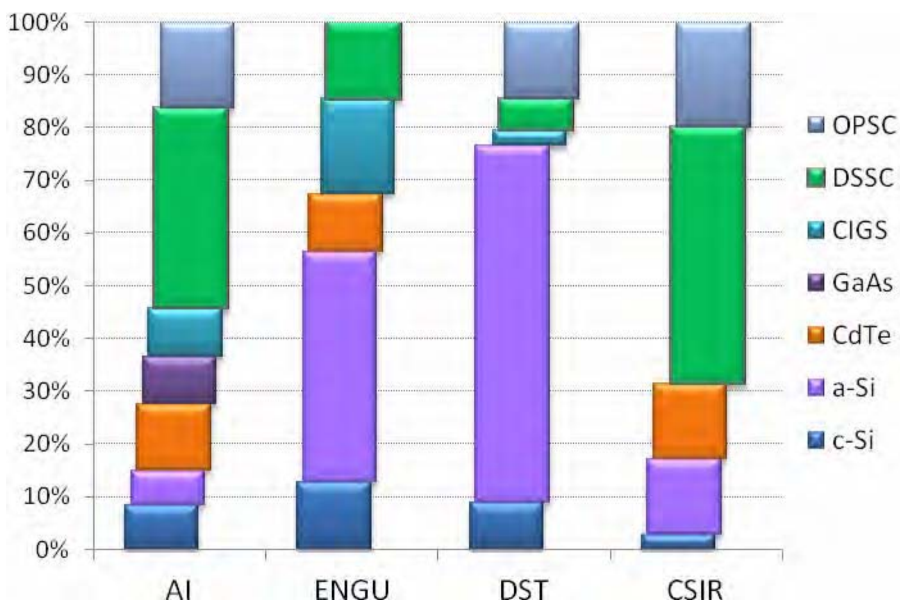

Fig. 4—Thrust of solar cell material research of select agencies

have RCI = 1. Thus, it is apparent from the pattern of distribution of both CPP and RCI that the impact of the research done by most of the Indian institutes is below the national average. Some of the institutes having outstanding and very high RCI values in decreasing order are National Institute for Interdisciplinary Science and Technology-CSIR, Trivandrum (17.3), Raman Research Institute, Bangalore, (11.4) and Saha Institute of Nuclear Physics, Kolkata (10.9).

Highly productive institutes

Taking 1% share of the total national output as cut-off criteria for a prolific institute, the most productive institutes are listed in Table 8 along with their total publication (TP), total citations (TC), CPP and RCI values. These 20 institutes together contributed 890 papers or almost half of the national output and the citations received by these 20 institutes also accounted for about half of the total national citations. With a total of 160 papers, accounting for 8.8% of the national output, Indian Institute of Technology, Delhi (IIT-D) heads the most prolific institutes and is simply unmatched by any other institute. CPP of half of the 20 most prolific institutes was higher than the national average while the remaining half exhibited below national CPP. Further, the performance of the institutes judged from their RCI values revealed that 10 institutes had RCI >= 1 and the remaining 10

Table 8—Top 20 publishing institutes and relative impact of their research output

Institute	TP	India's share (%)	TC	India's share (%)	CPP	RCI
Indian Institute of Technology-New Delhi	160	8.8	791	9.4	4.9	1.1
Indian Association for the Cultivation of Science-Kolkata	89	4.9	500	6.0	5.6	1.2
Jai Narain Vyas University-Jodhpur	63	3.5	167	2.0	2.7	0.6
CSIR-National Physical Laboratory-New Delhi	48	2.7	110	1.3	2.3	0.5
Jadavpur University-Kolkata	48	2.7	117	1.4	2.4	0.5
Shivaji University-Kolhapur	47	2.6	404	4.8	8.6	1.9
Indian Institute of Technology-Bombay	43	2.4	163	1.9	3.8	0.8
Banaras Hindu University-Varanasi	42	2.3	139	1.7	3.3	0.7
Anna University-Chennai	39	2.2	221	2.6	5.7	1.2
Indian Institute of Science-Bangalore	36	2.0	192	2.3	5.3	1.2
University of Delhi-New Delhi	33	1.8	133	1.6	4.0	0.9
Alagappa University-Karaikudi	33	1.8	297	3.5	9.0	1.9
ISRO Satellite Centre-Bangalore	32	1.8	65	0.8	2.0	0.4
Indian Institute of Technology-Kanpur	32	1.8	61	0.7	1.9	0.4
Sri Venkateswara University-Tirupati	30	1.7	110	1.3	3.7	0.8
CSIR-Central Electrochemical Research Institute-Karaikudi	29	1.6	135	1.6	4.7	1.0
Cochin University of Science and Technology-Cochin	27	1.5	174	2.1	6.4	1.4
Indian Institute of Technology-Madras	21	1.2	104	1.2	5.0	1.1
Indian Institute of Technology-Roorkee	20	1.1	49	0.6	2.5	0.5
Tata Institute of Fundamental Research-Mumbai	18	1.0	104	1.2	5.8	1.2
Total	890	49	4036	48		
Average					4	1

institutes had RCI<1. These indicate that though some institutes are publishing more papers, impact of their research (those with below national CPP and RCI<1) is not equivalent to the overall national impact. Thus, all highly productive institutes do not attract more citations. A generalized observation, however, is that institutes with higher CPP also have higher RCI.

Authors and their performance

Irrespective of their affiliation and position of authorship in the paper, a total of 3406 authors contributed to the 1808 documents published during the study period. Based on first author, however, 1147 contributed to this total output. Of the 1147 participating authors, 248 (22%) had CPP higher than the national average, and the CPP of 864 (75%) authors was below the national average. Based on RCI values, it is evident that impact of the research done by 284 (25%) authors was higher than the national level, those of 862 (75%) authors was below the national level.

Highly productive authors

Table 9 lists the 10 most prolific authors, selected by setting the cut-off at 0.05% share of the national output; along with their corresponding indicators of impact such as CPP and RCI. Together, these 10 authors contributed 111 papers or 6% of the national output, and received 465 citations which again accounted for ~ 6% of the national citations. However, analysis of the citations of these 10 authors indicates that only 3 authors had higher than the national CPP and are K. Ramamoorthy of Alagappa University (10.8), M. Veerachary (8.3) and GN Tiwari (6), both from IIT, New Delhi. Further, only these 3 authors had RCI>1 indicating that the citation rate of these authors was higher than the national citation rate. Thus, authors with high CPP also have higher RCI values. But what is important to note here is that all prolific authors are not always highly cited. This is apparent from the low CPP and RCI values of 7 out of the top 10 most prolific authors.

Table 9—Most prolific authors and impact of their research output

Author	TP	India's share (%)	TC	India's share (%)	CPP	RCI
Sharma GD, JNVUniv.-Jodhpur	25	1.4	93	1.1	3.7	0.8
Vinod PN, NPOL-Cochin	11	0.6	17	0.2	1.5	0.3
Ramamoorthy K, Alagappa Univ.-Karaikudi	10	0.6	108	1.3	10.8	2.3
Veerachary M, IIT-New Delhi	10	0.6	83	1.0	8.3	1.8
Tiwari GN, IIT-New Delhi	10	0.6	60	0.7	6.0	1.3
Sethi VP, PAU-Ludhiana	9	0.5	34	0.4	3.8	0.8
Sharma TK, RRCAT-Indore	9	0.5	28	0.3	3.1	0.7
Roy MS, Defence Lab.-Jodhpur	9	0.5	25	0.3	2.8	0.6
Genwa KR, JNVUniv.-Jodhpur	9	0.5	15	0.2	1.7	0.4
Murali KR, CSIR-CECRI-Karaikudi	9	0.5	2	0.0	0.2	0.1
Total	111	6.3	465	5.5		
Average					4.2	0.9

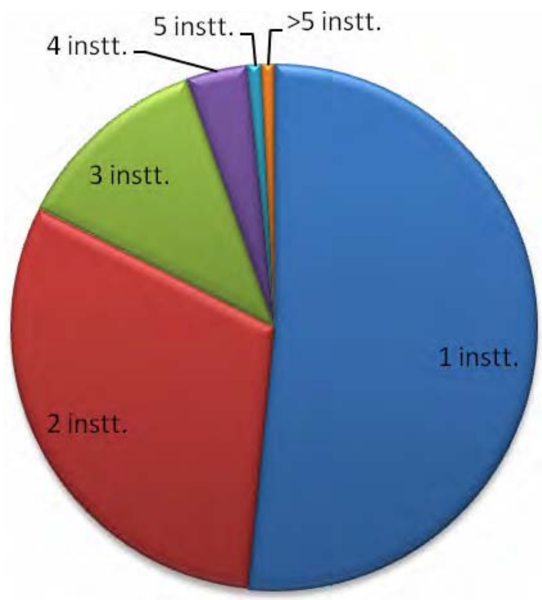

Fig. 5—Distribution of solar PV output according to number of collaborating institutes

Collaboration pattern in Indian solar PV research

The pattern of collaboration in Indian solar PV research was studied at the institute level. In the present study, a paper written by multiple authors but belonging to the same institute is considered as a non-collaborative paper for the sake of simplicity and all such papers are termed as domestic single-institute publications. Thus, this paper focused on two major modes of collaboration, i.e., domestic and international. Analysis of the data indicates that out of 1808 papers published during 2000-09, 933 (52%) were domestic single-institute publications and the remaining 875 (48%) were written in domestic and international collaboration. The maximum collaboration in a single paper was between 54 institutes. It is to be mentioned here that most of the collaborative papers have been produced through bilateral collaboration (Fig. 5).

It is very interesting to note here that there seems to be a balance between domestic and international collaboration in solar PV research in India. Because out of the 875 collaborative papers, 440 were written in domestic collaboration and almost equal number of papers (435) were written in international collaboration. However, if the component of domestic collaboration associated with the so called international collaborative papers is added, then the share of domestically collaborative papers will be definitely higher. For instance, if a paper was written by more than one Indian institute and either

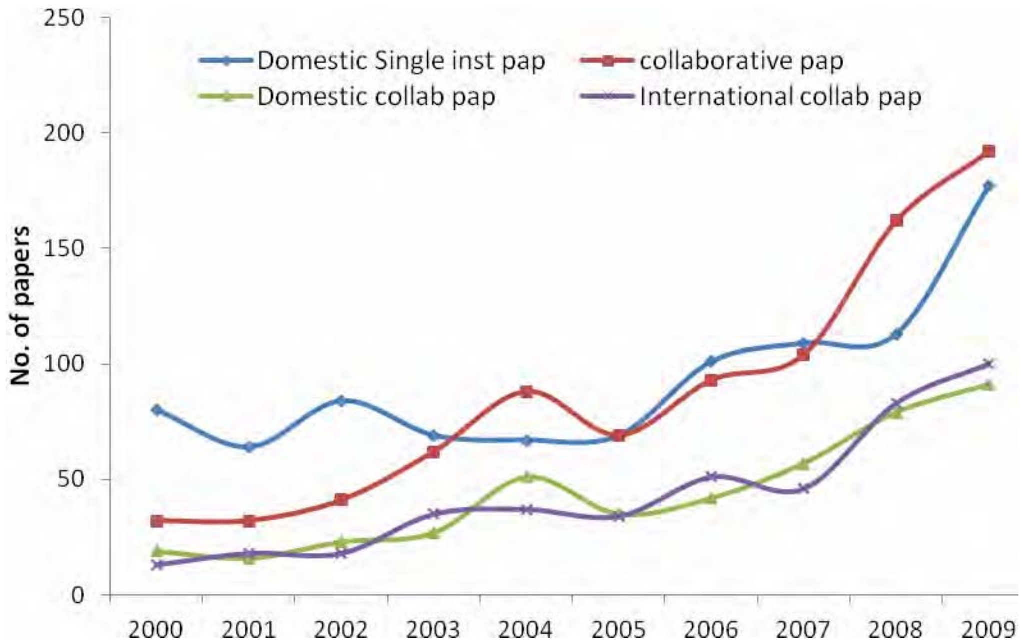

Fig. 6—Trend of collaboration in solar PV research in India

Table 10—Domestic and international collaboration in Indian solar PV research during 2000-04 and 2005-09

Years	Domestic	International	Total Indian output	DCI	ICI
2000-2004	134	121	617	89	82
2005-2009	306	314	1191	106	110
Total	440	435	1808		

one or more foreign institute, then the usual practice followed so far is to classify them as internationally collaborative papers. While such papers are no doubt internationally collaborative papers, but the component of domestic collaboration in these papers is not accounted for. Nevertheless, till 2003, publications by domestic single institute was higher than collaborative papers, afterwards both increased simultaneously but there was a rapid increase in the number of collaborative papers since 2008 (Fig. 6). Within the collaborative papers, both domestic as well as international collaboration have increased almost in parallel.

Domestic and international collaborative profile

The number of papers written in domestic and international collaboration and the corresponding DCI and ICI values in two blocks of years, i.e., 2000-04 and 2005-09 is given in Table 10. It is apparent that during the first half of the decade both domestic as well as international collaborative publication was less than the national effort but domestic collaborative effort was relatively higher than the international collaborative effort. During 2005-09, both domestic as well as international collaborative publication effort was higher than the national effort but international collaborative effort was relatively higher than domestic collaborative effort. This indicates that in solar PV research, more papers are being written in international collaboration or in other words can we say globalization of Indian solar PV research is happening slowly.

Highly collaborative institutes

To find out the most collaborative institutes, normal counting has been used, i.e., if a paper has been written by 2 or more institutes, all the participating institutes were credited with 1 paper each. By doing so, the number of collaborative papers have inflated from 875 to 1536. But the analysis has been done with this inflated number for a comprehensive picture of the nature of collaboration. Taking 2% share of the total collaborative papers as cut-off, the top collaborating Indian institutes were selected. The top 10 collaborating Indian institutes together contributed 414 (27%) of the total

Table 11—Collaboration nature of highly collaborative institutes

Institute	Domestic collaboration		International collaboration		TCP
	TP	AI	TP	AI	
Indian Institute of Technology-New Delhi	57	1.1	26	0.9	83
Jai Narain Vyas University-Jodhpur	38	1.3	7	0.4	45
Alagappa University-Karaikudi	23	0.9	18	1.3	41
CSIR-Central Electrochemical Research Institute-Karaikudi	28	1.1	13	0.9	41
Indian Institute of Science-Bangalore	26	1.0	13	1.0	39
Defence Laboratory-Jodhpur	33	1.4	3	0.2	36
Jadavpur University-Kolkata	19	0.8	16	1.3	35
Anna University-Chennai	14	0.7	18	1.6	32
Indian Association for the Cultivation of Science-Kolkata	7	0.3	25	2.2	32
CSIR-National Physical Laboratory-New Delhi,	16	0.8	14	1.3	30
Others	738 (364 inst.)		384 (167 inst.)		1122 (445 inst.)
Total	999		537		1536

TCP: total collaborative papers

Fig. 7—India's leading collaborative countries in solar PV research

collaborative papers. The Activity Index (AI) of the top 10 collaborating Indian institutes indicates that half of them are producing more international collaborative papers and the other half publishing more papers in collaboration with domestic institutes (Table 11). A general statement may be made here that highly collaborative institutes were more into domestic collaboration and less collaborative institutes were inclined more towards international collaboration. For instance, IIT, Delhi tops the list of highly collaborative institutes with 83 papers and its AI of domestic collaboration is higher than the AI of international collaboration. On the other hand, IACS, Kolkata is one of the lower collaborative institutes but the AI of its international collaboration is much higher than the AI of domestic collaboration.

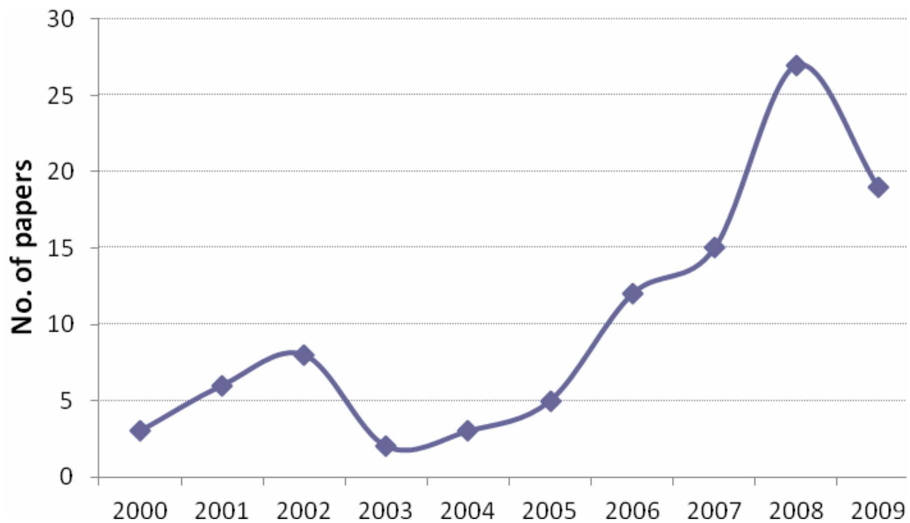

Fig. 8—Industry involvement in Indian solar PV research

Collaboration with foreign institutes

In solar PV research, India collaborated with 391 foreign institutes belonging to 54 countries. Some of the most preferred foreign institutes in descending order of number of collaborative publication are Hanyang University, South Korea (18), Sungkyunkwan University, South Korea (18), Ecole Polytechnique, France (17), Institute of Electrical and Electronics Engineers, United States (15), National Autonomous University of Mexico (UNAM), Mexico (14), Nagoya Institute of Technology, Japan (12) and Chubu University, Japan (11). At the country level, India published highest collaborative papers with United States (104) as in other branches of science, followed by South Korea (78), Japan (47), Germany (46), United Kingdom (44) and others (Fig. 7). Higher number of collaborative papers with some countries may be an outcome of the increased bilateral/multilateral cooperation for taking up joint R&D programmes in the broader area of solar energy systems/devices and thereby establishing institutional linkages between institutions of India and other countries (www.mnre.gov.in; www.stic-dst.org).

Academia-Industry collaboration in solar PV research

Research collaboration between academia and industry is important for technology creation and knowledge transfer. It is even more important for emerging highly technical domain of knowledge such as solar PV technology, which builds on interdisciplinary expertise[13]. With an effective collaboration, both the institutional sectors can understand the requirement of each other and carry out focused, time-bound and result-oriented research. The participation of industry in solar PV research in India have increased steadily especially since 2004 reaching a maximum of 27 papers in 2008 after which it started declining again (Fig. 8). However, collaborative scientific publication between academia and industry still seems prelusive. Out of the total solar PV output of 1808 papers, industry collaborated in only 112 papers. In these 112 academia-industry joint papers, as many as 88 industries belonging to 15 countries (including India) were involved. This indicates very low level of industry participation in solar PV research, only 1.3 papers per industry. Low level of industry participation may provide an explanation of the less developed solar PV sector in India.

Nevertheless, of the 88 industries that collaborated with the academia in scientific publications, 59 are Indian industries and 29 are foreign industries. The 59 Indian industries together participated in the writing of 76 papers and the remaining 36 papers were written in collaboration with 29 foreign industries. The number of papers written in collaboration with American industries (13) was the highest among joint papers with industries belonging to any foreign country. Among all the industries, Tata Consultancy Services Ltd, India, participated in maximum number of papers (13). It is surprising to note the virtual absence of leading Indian solar PV cells and/or modules manufactures such as IndoSolar Ltd, Tata BP Solar India Ltd, Solar Semiconductor Pvt Ltd, Moser Baer Photovoltaic Ltd, Websol Energy Systems Ltd.

and Titan Energy Systems and similar others, in the publication arena. This further strengthens the observation about low level of industry participation in solar PV basic research or in other words most of the industries are directed towards manufacture and production of PV cells and modules based on existing and/or imported technologies.

Conclusion

In spite of being the first country in the world to have a dedicated agency/department/ministry for renewable energy, today, India lags far behind many nations in solar energy technology competence, generation and utilization. However, with the formal launching of the National Solar Mission in 2010 India conveys the message to the rest of the world about its intention to exploit the ultimate sources of energy in a massive way. To achieve the mission objectives, it will be necessary to carry out a lot of R&D activities in solar energy related areas. This, in turn demands knowledge of the present status of research in the country as well as the research thrusts. The present study is perhaps the first attempt that analyzes the status of solar PV research in India.

It has been observed that the AAGR of Indian solar PV output is less that the global rate and it needs to be accelerated to be at least at par with the world average. There is also a need to improve the standard of solar PV research output particularly publication in high IF journals so as to have greater impact in the form of citations.

In terms of research thrust, Indian solar PV research still seems to be of exploratory nature as it tries out the suitability of more than 20 odd PV materials. But the good point is that research in the promising non-Si materials such as DSSCs and OPSCs have increased manifold in comparison to research in the traditional Si materials.

Besides, the present study has identified the major agencies and their research thrust, institutes including most productive institutes, authors and most productive authors. The study also highlighted the pattern of collaboration in Indian solar PV research and identified the highly collaborative national institutes, highly collaborating foreign countries as well as institutes and finally the nature of academia-industry collaboration.

Though the study has provided some valuable insights on the status and trend of solar PV research in India, there is a necessity to prepare a comprehensive profile of solar PV R&D capacity and capability in India. This will be useful in making wise decisions about future solar PV R&D strategies in the country, more so in view of large-scale ambitious project like the *National Solar Energy Mission*.

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References

1 Parthsarathi A, A champion of new technologies, *Nature*, 422 (2003) 17-18.

2 REN21, Renewables 2010 Global Status Report (Paris: REN21 Secretariat) (2010) 80.

3 Borenstein S, The Market Value and Cost of Solar Photovoltaic Electricity Production. CSEM WP 176, University of California Energy Institute, (2008) 38.

4 Kumari G L, Synthetic organic chemistry research: Analysis by scientometric indicators, *Scientometrics*, 80 (3) (2009) 559-570.

5 Joshi K, Kshitij A and Garg K C, Scientometric profile of global forest fungal research, *Annals of Library and Information Studies*, 57 (2) (2010) 130-139.

6 Frame J D, Mainstream research in Latin America and Caribbean, *Interciencia*, 2 (1977) 143-148.

7 Schubert A and Braun T, Relative indicators and relational charts for comparative assessment of publication output and citation impact, *Scientometrics*, 9 (5-6) (1986) 281-291.

8 Guan J and Ma Nan, A comparative study of research performance in computer science, *Scientometrics,* 61(3) (2004) 339-359.

9 Garg K C, Kumar S, Madhavi Y and Bahl M, Bibliometrics of global malaria vaccine research, *Health Information and Libraries Journal*, 26 (1) (2009) 22-31.

10 Garg K C and Padhi P, A study of collaboration in laser science and technology, *Scientometrics*, 51 (2) (2001) 415-427.

11 Banerjee R, Solar photovoltaics in India. Presentation at DST-EPSRC workshop on 23rd April 2009 at IIT Delhi. 2009.

12 Garfield E, KeyWords Plus, ISI's breakthrough retrieval method. Part 1. Expanding your searching power on current contents on diskette, *Current Contents*, 32 (1990) 5–9.

13 Vidican G, Woon W L and Madnik S, Measuring Innovation Using bibliometric Techniques: The case of solar photovoltaic industry, 2009, http://web.mit.edu/smadnick/www/wp/2009-05.pdf

14 Chunag K Y, Huang Y L and Ho Y S, A bibliometric and citation analysis of stroke-related research in Taiwan, *Scientometrics*, 72 (2) (2007) 201-212.

15 Xie S, Zhang J and Ho Y S, Assessment of world aerosol research trends by bibliometric analysis, *Scientometrics*, 77 (1) (2008) 113-130.
16 Goetzberger A, Luther J and Willeke G, Solar cells: past, present, future, *Solar Energy Materials and Solar Cells*, 74 (1-4) (2002) 1-11.
17 Singh D and Jennings P, The outlook for crystalline silicon technology over the next decade. In *Renewable Energy for Sustainable Development* (ed. Jennings, et al.), American Institute of Physics, 2007, p. 98-110.
18 Goncalves L M, Bermudez V Z, Ribeiro H A and Mendes A M, Dye-sensitized solar cells: A safe bet for the future, *Energy and Environmental Science*, 1 (2008) 655-667.
19 Sinha B, Trends in global solar photovoltaic research: Silicon vs non-silicon materials, *Current Science*. 100 (5) (2011) 654-660.
20 Garg K C, Dutt B and Kumar S, Scientometric profile of Indian science as seen through the Science Citation Index, *Annals of Library and Information Studies*, 53 (3) (2006) 114-125.