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Solar cell research in India: A scientometric profile

Bharvi Dutt[a] and Khaiser Nikam[b]

[a]Head, Knowledge Resource Centre, CSIR-National Institute of Science, Technology and Development Studies
Dr.K.S.Krishnan Marg, Pusa, New Delhi-110012 Email:bh_arvi@yahoo.com

[b]Professor and Chairperson, Department of Library and Information Science,
University of Mysore, Manasgangotri, Mysore - 570 006 Email: khaiser.nikam6@gmail.com

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The study examines solar cell research in India as revealed by the publications indexed in Web of Science (WoS) for a period of 20 years from 1991 to 2010. It was seen that academic institutions contributed about half of the total output. Indian Association for the Cultivation of Science outperformed all other institutes in the country. Solar cell research by Indian scientists is well connected to international research trends in the field. The recent trends suggest more domestic and international collaborative research involving larger team sizes. More emphasis is being given to research on solar cells based on materials other than silicon.

Keywords: Solar cell, Photovoltaics, Solar energy, Scientometrics, India

Introduction

Today, about four fifth of India's need for electricity are met by fossil fuels which may best supply our needs of electricity for another 100-150 years[1]. In India, the solar energy potential alone is many thousand times more than the total energy needs of the country[2]. With over 300 sunny days in a year, India's geo-position allows her to receive over 5000 trillion kWh of pure solar energy each year, with the potential to generate huge quantity of electricity through a high energy security and zero-carbon process[3]. Solar cell is a promising technology for addressing energy needs of India.

Solar cell is a key topic of energy technology research. Solar cells or photovoltaics directly convert sunlight into direct current (DC) electricity without going through any intermediate stage. They are normally rugged, simple in design and need little maintenance[4]. This technology can be used to electrify our villages in remote areas as standalone distributive systems. It can complement and supplement various energy needs in urban areas as well.

Presently, renewable (other than hydropower) resources contribute 7.7 per cent of India's energy mix. Out of this, the share of electricity generated through the solar cell is a very small fraction. However, in future, solar cell based systems may become one of the important sources of power for providing electrical energy for localized use in thousands of remote locations all over India[5]. Sukhatme[5] has estimated that if renewable sources are to meet the whole demand in future, solar power would provide ~ 47.4 per cent energy needs of the country. Ministry of New and Renewable Energy Government of India has launched Jawaharlal Nehru National Solar Mission (JNNSM) in 2010 with an ambitious target of 20,000 MW of electricity by 2022 and with the objective to establish India as a global leader in solar energy[6]**.**

The present state of science and technology development in the area of tapping solar energy through solar cells is far from realizable and cost effective. There are basically two Research and Development (R&D) challenges before the scientific community, (i) to improve the efficiency from the current 7-14 percent to higher levels and (ii) to identify or develop a low cost environmentally friendly solar cell material. Both these scientific and technological bottlenecks can be overcome by extensive and intensive R&D before this form of energy can be practically put to use in a cost effective, efficient and environmentally friendly manner to meet the requirements of India and other countries with similar solar radiant energy pattern over them.

Literature review

A few studies are reported in literature which have dealt with solar energy and allied areas. For instance, Garg and Sharma[7] have undertaken a scientometric study of world solar power literature from 1970-1984 using Engineering Index as the database. Dong et al[8] have undertaken a bibliometric study of solar power research for 20 years from 1991-2010 using WoS as the data source. Both these studies did not specifically pertain to solar cell research. Another study by Huang[9] et al studied the regional differences in collaboration in the field of solar cells during 1980-2009. This study relates to research papers in Science Citation Index (SCI) and patents in USPTO. Larsen[10] investigated knowledge network hubs, research impact, science structure and publication output in nano-structured solar cells indexed in SCI. Sinha[11] investigated trends in global solar photovoltaic research for two different periods 1981-1988 and 2001-2008 and solar photovoltaic research[12] in India during 2000-2009 using SCOPUS database. These studies have used keywords which were general in nature, like “solar power”, “solar generation”, “solar cell”, “solar photovoltaic”, “solar cell material” etc. Therefore, the data retrieved through these keywords may not be all encompassing.

The present study fills that void and examines solar cell research in India using a search strategy comprising of specific keywords denoting different types of solar cells and covers a period of twenty years from 1991-2010 to retrieve the data from Web of Science (WoS).

Methodology

The study is based on first author affiliation. However, in case the first author was from outside India, the next position of Indian author was considered.

Data downloading

Data was downloaded on 28th November 2011 for a period of 20 years (1991 to 2010) from the WoS of the Thomson Reuters, Philadelphia, USA using the search strategies 1 and 2 given in Appendix I. WoS has wide acceptance and is frequently used standard database of choice for undertaking scientometric studies[13-14]. It was necessary to form two search strategies because of the inherent limitations of the number of keywords which can be accommodated in a single strategy in WoS. These two strategies in all yielded 2101 records. The downloaded data comprised 2023 journal articles, 210 proceeding papers, 46 reviews, 18 notes, 9 letters, 2 corrections, 2 editorial meetings and 1 meeting abstract. These do not add up to 2101 as proceedings papers (210) are, in fact, published as journal articles and included in 2023 records. This paper examined only the journal articles and reviews which added up to 2069.

Data standardization

To ensure correctness of data, we went through each record and it was found that some papers in other disciplines were also part of the search results owing to the presence of the keywords “Photovoltaics”, “Solar cell”, “OSC”, “DSSC”, etc, but were not relevant to solar cell research, the topic of the present study. Hence, these irrelevant papers published in these journals were excluded which resulted in 2024 records.

Thomson Reuters[15] and Moed[16] suggest that the names of authors and their affiliations have to be standardized due to artifacts of variation. In view of this, each record was scrutinized and standardized to make the database authentic and amenable to meaningful and reliable analysis. Also, in a few records where the information about affiliation of authors was not available, this gap was filled from the affiliation information provided by reprint author.

Data enrichment

After cleaning and standardization, the data was enriched with various parameters, like, number of authors, number of institutions, nature of collaboration, research performing sectors, and impact factor of the journals, etc. After all the above was completed the citations were updated to allow for maximum possible citation window. This was done in September 2012.

Objectives of the study

- To examine the pattern of growth of the research output in solar cell research in India during the period 1991-2010;
- To identify different performing sectors and the change in activity during 1991-2000 and 2001-2010 using Transformative Activity Index (TAI);
- To identify most prolific institutions, their publication output and impact using different indicators;
- To examine the direction of research over a period of time;
- To examine the citation impact of the research output;
- To examine the pattern of co-authorship and collaboration, and shift in the pattern of co-authorship and collaboration; and
- To identify the prolific authors, highly cited papers and the most common journals used for publishing research results.

Indicators used

Following indicators have been used in the analysis of data.

Number of publications (P); number of citations (C); Citation per paper (CPP); publication per cent not cited (PNC); impact factor of the journal (IF); Relative Citation Index (RCI); Co-authorship Index (CAI); Transformative Activity Index (TAI); Domestic Collaboration Index (DCI) and International Collaboration Index (ICI).

The data was divided into two blocks of ten years 1991-2000 and 2001-2010 to study change, if any, from the first block to the other in parameters like publication output, co-authorship, and nature of collaboration, etc.

The publication numbers (P) and the number of citations (C) were obtained from the data downloaded. Citations per Paper (CPP) has been extensively used in scientometric assessment to normalize the inconsistencies in volumes of literature published by different institutions / sectors / countries, etc**.** The impact factor values for different journals which published the research papers were obtained from the Journal Citation Reports (JCR) 2010. RCI, an indicator of influence and visibility of research in global perspective, is defined as the proportion of an entity's share of world citations to that entity's share of world publications i.e. C % / P %. An entity's citation rate is equal to the world's citation rate if RCI=1; RCI>1 indicates that an entity's citation rate is higher than the world's citation rate and RCI<1 indicates that that entity's citation rate is less than the world's citation rate[17].

The change in the research productivity from the first to the second block has been examined by employing Transformative Activity Index (TAI) as used by Guan and Ma[18] which is similar to Activity Index suggested by Schubert and Braun[19]. It signifies the change in the research effort during different periods.

$TAI=\{(N_{ij} / N_{io}) / (N_{oj} / N_{oo})\} X 100$

N_{ij}: number of papers of entity i in block j;

N_{io}: number of papers of entity i for all blocks;

N_{oj}: number papers of all entities for block j;

N_{oo}: number papers for all entities and all blocks

The value TAI=100 indicates that research effort in a particular block corresponds to the Indian average, TAI>100 suggests higher than average and TAI<100 indicates lower than average effort in that entity.

To study the shift in the pattern of co-authorship during 1991-2010, CAI suggested by Garg and Padhi[20] was used. CAI is computed as follows.

$CAI = \{(N_{ij} / N_{io}) / (N_{oj} / N_{oo})\} X 100$ where

N_{ij} : numbers of papers having j authors in Block i;

N_{io} : total output of block i;

N_{oj} : number of papers having j authors for all blocks;

N_{oo} : total number of papers for all authors and all blocks.

J = 1, 2, (3 or 4), >= 5.

To examine the shift in pattern of collaboration DCI and ICI suggested by Garg and Padhi[20] and used by Dutt, Garg and Bali[21] were used.

$DCI = \{(D_i / D_{io}) (D_o / D_{oo})\} X 100$ where

D_i = number of domestically co-authored papers for block i;

D_{io} = total output of block i

D_o = total number of domestically co-authored papers

Doo = total output

Likewise

$ICI = \{(I_i / I_o) (I_o /I_{oo})\} X 100$ where

I_i = number of internationally co-authored papers for block i

I_{io} = total output of block i

I_o = number of internationally co-authored papers for all the blocks

I_{oo} = total output

The value of DCI or ICI = 100 suggests that a country's collaborative effort corresponds to world average. DCI or ICI > 100 indicates collaboration higher than the world average and DCI or ICI < 100 reflects less than average collaboration.

Results

Pattern of growth of output

During the 20 years period from 1991 to 2010 a total of 2024 papers were published in journals indexed in WoS on solar cell research by Indian researchers working in a broad spectrum of institutions and agencies spread all over the country. During the first decade the output has been almost steady with slight haphazard crests and troughs here and there and the number of publications varied from 55 to 326. The publication activity tends to rise from the year 2002 with a remarkable upward tendency from the year 2005 onwards (Fig. 1). The output gradually increased manifold successively each year after 2005 and reached the peak in the year 2010. The overall output had increased almost three times from the first block to the later block.

Performing sectors - output and Transformative Activity Index

Science and Technology (S&T) infrastructure has been growing in India since independence as the Government of India considered it as an instrument to bring about the much needed socio-economic transformation in the country. A wide range of scientific organizations dealing with various disciplines, comprising more than 400 laboratories have been established. In addition, more than 350 academic institutions (universities, deemed universities and colleges) as well as 1300 in-house industrial R&D units, a large number of government departments, private institutions and foundations too have the mandate to undertake scientific research[22]. Table 1 depicts how the entire output in solar cell research has been distributed among various performing sectors into two blocks of 10 years from 1991-2000 and 2001-2010.

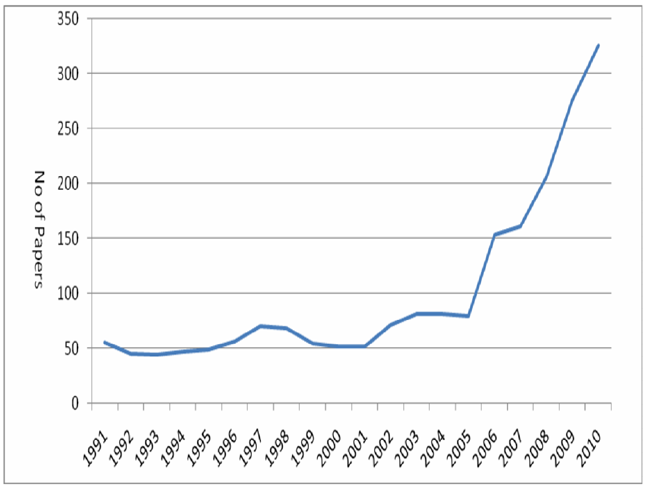

Fig. 1—Year-wise research output of solar cell research in India

The research output was concentrated in the top four performing sectors, Academic Institutions (AI), Indian Institutes of Technology (IITs), Council of Scientific and Industrial Research (CSIR) and Department of Science and Technology (DST) which accounted for more than 85 per cent of the total contribution. The top performing sector in the solar cell research was academic institutions which had published more than half of the publications and accounted for almost half of the citations, however, about 11 per cent of its papers remained uncited which was almost equal to the average uncited papers. The growth of AI in the country might be one of the probable reasons behind their outperformance in terms of quantum of publications. The academic sector was followed by IITs and CSIR whose output was more than 10 percent. Except for Public Sector Undertakings (PSUs) there was a rise in publication output from the first to the later block in respect of all the sectors, though a remarkable increase was witnessed in case of Engineering Colleges (EC) whose publications had tremendously increased in the later block. The values of TAI computed are shown in parentheses which provide an insight into the change in output of different sectors in relative terms from the first block to the later one. Fig. 2 depicts that the

Table 1—Distribution of output according to performing sector

Performing sector	1991-2000 (TAI)	2001-2010 (TAI)	Total papers (%)
Academic Institutions	294 (103)	778 (99)	1072 (53.0)
Indian Institutes of Technology	79 (109)	193(97)	272 (13.4)
Council of Scientific and Industrial Research	44 (78)	168 (108)	212 (10.4)
Department of Science and Technology	57 (110)	137(96)	194 (9.5)
Engineering Colleges	6 (20)	104(128)	110 (5.4)
Defence Research & Development Organization	25 (148)	38(227)	63 (3.1)
Department of Atomic Energy	9 (94)	27(102)	36 (1.8)
Department of Scientific & Industrial Research and other Ministries	11 (172)	13 (74)	24 (1.2)
Private Organizations	3 (53)	18(117)	21 (1.0)
Others*	11 (206)	9 (61)	20 (0.9)
Total	539	1485	2024

*Others: ISRO-Indian Space Research Organization (15), PSUs-Public Sector Undertakings (5) research output of AI, IITs, DST and DSIR&M had declined from the first to the later decade while the increase in output was evident in respect of CSIR, EC, DRDO and Private Organization (PVT). The increase was maximum in case of EC followed by DRDO, PVT and CSIR while the decline was minimal in respect of AI.

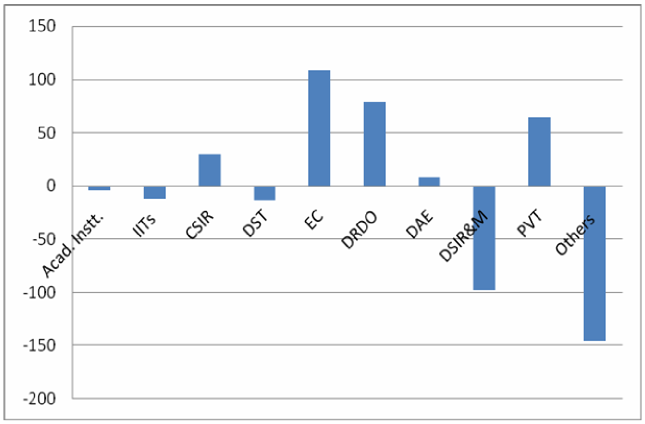

Fig 2—Change in Transformative Activity Index (TAI) from 1991-2000 to 2001-2010

Prolific institutions – output and impact

The publications emerged from 335 institutions located in different parts of India. Institutions that have contributed one per cent or more of the total output have been termed as prolific institutions. Table 2 lists 22 prolific institutions along with their number of publications (P), citations received (C), PNC, CPP and RCI.

Indian Association for the Cultivation of Science (IACS) outperformed all other institutions by producing 141 papers which was about 7 per cent of the total output. This was followed by Indian Institute of Technology, Delhi (IITD), CSIR-National Physical Laboratory (CSIR-NPL), and Shivaji University (SU). These four institutions contributed one-fifth of the total publication output in solar cell research.

The reason for IACS being top institutional performer was manifested in their research activities which included among others energy transfer in quantum dots at Department of Materials Science, development of materials and fabrication technology for thin film silicon solar cell at Energy Research Unit

Table 2—Prolific institutions involved in solar cell research in India

SI. No.	Institution*	No. of papers (%)	Citations (%)	PNC (%)	RCI	CPP
1	IACS	141 (7.0)	1239 (5.6)	16 (11.4)	0.8	8.8
2	IITD	102 (5.0)	1393 (6.3)	5 (4.9)	1.3	13.7
3	CSIR-NPL	90 (4.4)	731(3.3)	15 (16.6)	0.8	8.1
4	SU	84 (4.1)	1541 (6.9)	5 (5.9)	1.7	18.4
5	SVU	74 (3.6)	763 (3.4)	5 (6.7)	0.9	10.3
6	IISc	57 (2.8)	1202 (5.4)	5 (8.7)	1.9	21.1
7	JNVU	56 (2.8)	556 (2.5)	4 (7.1)	0.9	10.0
8	JU	50 (2.4)	270 (1.2)	8 (16.0)	0.5	5.4
9	IITB	45 (2.2)	427 (1.9)	2 (4.4)	0.9	9.5
10	BHU	44 (2.2)	406 (1.8)	4 (9.0)	0.8	9.2
11	DU	41 (2.0)	361 (1.6)	8 (19.5)	0.8	8.8
12	AU	39 (1.9)	593 (2.6)	1 (2.5)	1.4	15.2
13	CUST	36 (1.7)	389 (1.7)	5 (13.8)	0.7	10.8
14	IITM	35 (1.7)	263 (1.1)	1 (2.8)	0.7	7.5
15	CSIR-CECRI	34 (1.6)	168 (0.7)	11 (32.3)	0.4	4.9
16	CSIR-IICT	26 (1.3)	648 (2.9)	0 (0)	2.2	24.9
17	DRDO- SSPL	25 (1.2)	145 (0.6)	5 (20)	0.5	5.8
18	IITK	24 (1.1)	188 (0.8)	5 (20.8)	0.7	8.2
19	KASC	23 (1.1)	189 (0.8)	5 (21.7)	0.7	8.2
20	IITKH	22 (1.1)	199 (0.9)	1 (4.5)	0.8	9.0
21	DRDO-DL	20 (1.0)	175 (0.7)	2 (10.0)	0.6	8.8
22	BU	20 (1.0)	220 (1.0)	2 (10.0)	1.0	11.0
	Sub-total	1088 (53.2)	11878 (53.7)	106 (9.7)	1.0	11.0
	Others (313 institutions)	936	10208 (46.3)	129 (13.8)		
	Total	2024	22086	11.6		

*Full names of institutions are listed in Appendix II and research on materials with interesting properties at Centre for Advanced Materials – A Partner Institution of International Centre for Materials Research of University of California, Santa Barbara. The research activity in Centre of Materials at CSIR-NPL, among others includes silicon solar cells, amorphous and microcrystalline silicon solar cell, organic and hybrid solar cells. The Centre for Energy Studies at IITD has a Solar Energy Group which comprises a group on solar photovoltaics. Shivaji University has signed MoU with Bhabha Atomic Research Centre, Mumbai for research in Material Science. These research entities dedicated to solar cell, material science and energy research might have acted as a catalyst in relative outperformance of these institutions.

A raw analysis of data indicates that institutions like CSIR-Indian Institute of Chemical Technology (CSIR-IICT), Kongunadu Arts and Science College (KASC), Bharathidasan University (BU), CSIR-Central Electro-chemical Research Institute (CSIR-CECRI), Cochin University of Science and Technology (CUST), and Indian Institute of Technology, Kanpur (IITK) started solar cell research after the year 2001. Interestingly, seven state universities and one college namely, KASC affiliated to Bharathiar University figured among the top 22 institutions.

The highest proportion of papers not cited (PNC) was witnessed in respect of CSIR-CECRI followed by KASC, IITK, DRDO-SSPL, DU, Jadavpur University (JU), CSIR-NPL and IACS. AU, IITM, IITB and IITKH had the minimum proportion of papers not cited. CSIR-IICT was the only institution with all its papers receiving citations. The values of RCI were highest in case of CSIR-IICT, IISC, SU, and IITD implying the higher citation rate. The lowest citation rate was observed in case of CSIR-CECRI, and DRDO-SSPL. The values of CPP were highest and almost twice the average values of CPP in respect of CSIR-IICT and IISc. The institutions which had more than average value of CPP, included SU, AU and IITD. The value of CPP was lowest for CSIR-CECRI followed by JU. Though IACS outperformed all other institutions in terms of research output, however, its CPP was quite below the average.

Direction of research trends

A keywords analysis was undertaken to gain an insight into direction of research trends and frontier areas as to in which type of solar cell the Indian scientists were putting their efforts. The keywords reflect the focus of individual articles**.** The keywords (analysis) search was made in the WoS separately with all the keywords used in the search strategy in an interval of five years and for the year 2011 to obtain the latest developments. The most commonly occurring keywords that appeared in the research articles are presented in Table 3 which depicts only those keywords which yielded five or more than five total publications. Also for ease of presentation, the abbreviated (chemical names comprising symbols like CdTe solar cell etc.) keywords used in the search strategy have been merged with their expanded forms.

Two different scenarios emerged from this analysis. One indicated almost continuous research activity, though a little bit less initially since 1991 and the other suggested that the activity picked up in the recent past. The type of solar cell that attracted the continued attention of the scientists but resulting in relatively lower number of papers included cadmium telluride solar cell, microcrystalline silicon solar cell, gallium arsenide solar cell, polycrystalline silicon solar cell. This is so because R&D dynamics in solar cells entails exploration of and experimentation on newer and newer materials and technology to address the key issue of high energy conversion efficiency and lower cost[23]. Thus, the advent of newer materials may impede the research progress on earlier materials. In certain other types of solar cells the research activity picked up from the year 2005 which comprised of bulk heterojunction solar cell, conjugated polymer solar cell, dye-sensitized solar cell, organic solar cell, nano solar cell and polymer photovoltaic cell. Photoelectrochemical solar cell was the only type which witnessed continuous research activity right from the beginning and gaining momentum in the later periods. It also indicated that more emphasis was being given to crystalline silicon solar cell as compared to amorphous silicon solar cell.

Impact of research output

The assessment about the impact of research output could be made from three different parameters i.e. (a) impact factor of the journals where the research work was published, (b) country of origin of these journals and (c) citations of research output.

Distribution of research output according to impact factor of journals

Impact factor of the journal is one of the established indicators to evaluate the prestige or

Table 3—WoS publications output based on keywords

Sl. no.	Keywords	1991	1995	2000	2005	2010	2011	Total
1	amorphous silicon photovoltaic cell	2	1	0	1	0	2	7
2	bulk heterojunction solar cell	0	0	0	1	20	25	46
3	cadmium telluride solar cell	10	9	8	5	8	18	58
4	carbon based solar cell	0	0	0	0	4	7	11
5	conjugated polymer solar cell	0	0	0	1	25	31	57
6	copper indium diselenide solar cell	0	0	2	2	5	5	14
7	copper indium gallium diselenide solar cell	0	0	0	0	7	4	11
8	dye sensitized solar cell	1	0	0	7	76	106	190
9	foil solar cell	0	0	0	0	3	2	5
10	gallium arsenide solar cell	1	0	9	8	3	3	24
11	hybrid inorganic solar cell	0	0	0	0	5	5	10
12	hybrid organic solar cell	0	0	0	0	8	10	18
13	hybrid silicon solar cell	0	0	0	0	4	2	6
14	indium phosphide solar cell	0	2	2	2	2	0	8
15	microcrystalline silicon solar cell	0	2	4	3	6	10	25
16	monocrystalline silicon solar cell	0	0	0	3	1	1	5
17	nano / nano wire solar cell	0	0	2	1	20	35	58
18	organic and polymer solar cell	5	7	4	26	209	228	235
19	polycrystalline silicon solar cell	3	4	3	6	7	5	28
20	plastic solar cell	0	0	0	2	1	4	7
21	quantum dot solar cell	0	0	0	0	15	47	62
22	self assembling solar cell	0	0	0	0	4	8	12
23	silicon wafer solar cell	2	0	0	1	11	6	18
24	photoelectrochemical solar cell	10	14	16	10	43	50	143

relative influence of the scholarly journal. Hoeffel[24] stated that…'experience has shown that in each specialty the best journals are those in which it is most difficult to have an article accepted, and these are the journals that have a high impact factor'. Several studies have been reported in the literature that have applied journal impact factors and related citation measures to assess the research performance of individual scientists, institutions and countries Thus impact factor is a credible indicator for evaluating the research output[25].

The entire output of Indian scientists in solar cell research was divided into four quartiles for ease of analysis. The distribution is depicted in Table 4.

Table 4—Distribution of research output according to impact factor

Quartile	Category (value of I.F.)	No. of papers	% of papers
Q1	Low (1.25)	487	24.1
Q2	Medium (1.9)	522	25.8
Q3	High (3.17)	497	24.5
Q4	Very High (>3.17)	498	24.6
	IF not available	20	0.98
	Total	2024	~99.99

The above categorization revealed that almost half of the research output in solar cell research appeared in journals of impact factors above the range of 1.9, i.e. categorized as of high and very high quality. One fourth of papers have been published in journals having high impact factor lying between 1.9 and 3.17. The remaining almost one fourth appeared in journals having very high impact factor, i.e above 3.17. The overall distribution of output according to journal impact factors suggest that substantial proportion (~75%) of Indian output has medium or high or very high visibility thereby implying that solar cell research work carried out by Indian researchers was connected to the international trends and had international visibility.

Country of journals

The research output has been published in 168 journals originating from various parts of the world including India. The major proportion of the research output has been published in journals emanating from the advanced countries of Europe and USA. Table 5 indicates that about 90 per cent of the output was published in journals originating from these countries. This suggested that the research being performed on solar cell in India was well connected to the mainstream research in the area.

Citation trend of research output

In addition to the impact factor and publishing country of journal the other indicator taken into consideration for evaluation of quality of research was Citation analysis This would essentially supplement the inferences drawn out from the impact factor analysis of the research output**.** The quality and visibility of a research publication is indicated by the citations received by the scientific work. Quality papers are frequently cited which in turn helps them to acquire greater visibility and publicity in academic circles[26].

The citations analysis revealed that 2024 research publications drew 22086 citations (Table 6). The citation per paper (CPP) for the research output in solar cell was about 10.91. At the same time about 11 per cent papers remained uncited. Proportion of papers that received 1 to 5 citations was about 38 per cent. About 19 per cent papers received 6-10 citations. After this the proportion of papers gradually declined with the higher number (groups) of citations. Only 2.1 per cent papers got 51-100 citations and 0.6 per cent received 101-600 citations. Overall distribution of research output according to citation ranges suggested that half the output had received six or more than six citations.

An analysis of the output with respect to the nature of collaboration and the citation received revealed that papers with international collaboration had more citation (13.21) per paper compared to domestic collaboration for which this value was 8.07. According to Moed[27], international collaboration with advanced countries is beneficial in terms of their citation impact compared to purely domestic publication output.

Table 5—Country of journals where Indian research work was published

SI. No.	Country of journal	No. of papers	% age	Cumulative % age
1	Netherlands	564	27.9	27.9
2	England	506	25.0	52.9
3	USA	356	17.6	70.5
4	Switzerland	288	14.2	84.7
5	India	138	6.8	91.5
6	Germany	61	3.0	94.5
7	Romania	49	2.4	96.9
8	Japan	22	1.1	98.0
9	Others (16 countries)	40	2.0	100.0
	Total	2024	100.0	

Table 6—Distribution of output according to citations received

SI. No.	Citations	No. of papers	% age of papers	Citations
1	0	235	11.6	0
2	1	185	9.1	185
3	2	180	8.9	360
4	3-5	416	20.6	1622
5	6-10	395	19.5	3012
6	11-20	327	16.2	4744
7	21-30	157	7.8	3933
8	31-50	74	3.7	2767
9	51-100	42	2.1	2707
10	101-600	13	0.6	2756
		2024		22086

Collaboration pattern

Gone are the days when science was the pursuit of individual scientists. In today's world a large body scientific research involves team work. Governments in many countries through various policy initiatives facilitate enhanced contacts among scientists through collaborative research programmes. Collaboration issue can be looked upon as a consequence of science reaching a "steady state" at which synergistic effects will play an increasingly important role for the production of scientific knowledge[28]. Collaboration can thus be seen as one of a set of science policy tools that is needed in a situation when scientific growth can no longer be based on an ever increasing expansion of manpower[29]. These initiatives manifest themselves in various forms of collaboration at the local, national and international level. Beaver[30] has delineated several reasons for entering into collaboration. This paper examined the collaboration trends in solar cell research in two different ways: (a) change in the pattern of co-authorship during the two blocks of ten years, i.e. 1991-2000 and 2001-2010, (b) change in the pattern of nature of collaboration during the two blocks mentioned above.

Pattern of co-authorship

To examine the pattern of co-authorship the entire data was divided into two blocks of ten years in single author, two authors, multi authors (3 or 4 authors) and mega authors (>=5 authors). CAI was calculated as suggested by Garg and Padhi[20]. The results of CAI are presented in parentheses in Table 7.

The value of CAI in the first block of 1991-2000 was the highest for single authored papers which gradually declined in respect of two, multi and mega authored papers. This implied that during the first decade, single authored papers dominated the scenario. The second block indicated that the values of CAI gradually rose from the single authored papers to mega authored papers suggesting the trend in the later decade was marked with more research papers with larger team sizes. This trend was almost a reversal of the co-authorship trend in the first decade.

Nature of collaboration

Two forms of collaboration have been looked into. Collaboration was categorized on an institutional basis. Significantly, larger number of papers have been observed as having several addresses within India and those from outside. Bordons[31] et al have defined forms of collaboration in a similar manner.

Domestic collaboration (DC) between different institutions within India. The papers with different addresses within India were classified as DC.

International collaboration (IC) at least one foreign address. The papers that had at least one foreign address were classified as IC.

The research output included collaborative research work contributed by researchers from 31 other countries from almost all the regions of the world. The most dominating international collaborating countries were South Korea followed by USA and Japan. About half of the output has originated as a result of collaborative research between two or more than two institutions within and outside India.

Table 8 suggests that during the first block approximately 80 per cent research papers were produced without any kind of collaboration. Among the remaining, domestic collaboration dominated followed by international collaboration, however, the values of indices indicated below average collaborative activity in both the types of collaboration. During the later block only about 37 per cent papers emerged without any collaboration which was a substantial change. The absolute values of papers originating out of domestic and international collaboration were very close to each other, however, the values of DCI and ICI suggested predominance of domestic collaborative research activity over international collaboration. Further analysis of data on collaboration indicates that more than half of the domestic and international collaborations were from AI. DST and PVT had more international collaborative work. Among the prolific institutions IACS, SVU, CUST, CSIR-IICT, IIT Kanpur and Bombay and KASC-Coimbatore, had relatively more papers in international collaboration compared to domestic collaboration.

Prolific authors, highly cited papers and most commonly used journals

Total output was produced by 1162 authors, which were scattered in 31 countries other than India. Authors who produced 0.5 per cent or more of the total output were termed as most prolific authors. Eight authors fell in the category as listed in Table 9. Of these, five belonged to state universities and two from CSIR and one from DRDO.

Highly cited papers

Papers that had received 100 or more citations were designated as highly cited papers which are listed in Table 10. Of these, three were from state universities and three were from CSIR. The topper among these was from IISc getting 84 citations per year.

Table 8—Distribution of output according to nature of collaboration

Ten year block	Nature of collaboration		Total papers
	DC (DCI)	IC (ICI)	
1991-2000	78 (53)	36 (27)	539
2001-2010	471 (371)	457 (126)	1485
	549	493	2024

Table 7—Distribution of output according to number of authors

Ten Year Block	Number of Authors				Total
	Single	Two	Multi*	Mega*	
1991-2000	39 (185)	163 (133)	260 (105)	77 (51)	539
2001-2010	40 (69)	296 (88)	661 (98)	488 (117)	1485
Total	79	459	921	565	2024

*Multi = 3 or 4 authors, Mega = 5 authors or above

Table 9—Prolific authors and their citations per paper

SI. No.	Author	Affiliation	No. of papers	Citations / Paper
1	G.D. Sharma	Jai Narain Vyas Univ, Jodhpur	49	10.61
2	K.R.Murali	CSIR-CECRI, Karaikudi	21	3.23
3	K.T.R. Reddy	Sri Venkateswara Univ, Tirupati	15	15.06
4	B.M. Reddy	CSIR-IICT, Hyderabad	13	30.76
5	T. Mahalingam	Alagappa Univ, Karaikudi	13	14.92
6	L.P. Deshmukh	Shivaji Univ, Kolahpur	13	12.46
7	K. Ramamoorthy	Alagappa Univ, Kairakudi	10	14.7
8	M.S. Roy	DRDO-Def Lab, Jodhpur	10	5.2

Table 10—Highly cited papers that received 100 or more citations

SI. No.	Paper	Affiliation
1.	Sangetha NM, Maitra, U, Supermolecular gels: functions and uses, *Chemical Society Reviews*, 34(10), 2005, 821-836. Citations = 588.	IISc, Bangalore
2	Thomas, K.G. and Kamat, P.V., Chromophore-functionalised gold nanoparticles, *Accounts of Chemical Research*, 36(12), 2003, 888-898. Citations = 382.	CSIR-NIIST, Trivandrum
3.	Mane R.S. and Lokahnde, C.D., Chemical deposition method for metal chalcogenide thin films, *Materials Chemistry and Physics, 65(1),* 2000, 1-31. Citations = 330	Shivaji Univ, Kolhapur
4.	Kumar, S., Self-organisation of disc-like molecules: chemical aspects, *Chemical Society Reviews*, 35(1), 2006, 83-109. Citations = 200.	Raman Res Instt, Bangalore
5.	Chopra, K.L., Paulson, P.D. and Dutta, V., Thin film solar cells: An Overview, *Progress in Photovoltaics,* 12(2-3), 2004, 69-92.Citations = 169.	IIT, Delhi
6	Lakshmikumar, S.T and Rastogi, A.C., Selenization of CU and IN thin films for the preparation of selenide photo-absorber layers on solar cell, *Solar Energy Materials and Solar Cells*, 32(1), 1994, 7-19. Citations = 163.	CSIR-NPL, Delhi
7.	Deb, S.K. et al, Pressure induced amorphization and an amorphous-amorphous tension in densified porous silicon, *Nature*, 414(6863), 2001, 528-530. Citations = 153	DAE-BARC
8.	Gurunathan, K. et al, Electrochemically synthesized conducting polymeric materials for application towards technology in electronics, optoelectronics, *Materials Chemistry & Physics,* 61(3), 1999, 173-191. Citations = 153	MIT-CMET, Pune
9.	Reddy, P.Y., et al, Efficient sensitization of non-crystalline TIo2 films by a ear-IR-absorbing unsymmetrical zinc phthalcoyamine, *Angewandte Chemie-Int Ed*. 46(3), 2007, 373-376. Citations= 150.	CSIR-IICT, Hyderabad
10.	Kumar, S., Recent developments in the chemistry of triphenyl based discotic liquid crystals, *Liquid Crystals*, 31(8), 2004, 1037-1059. Citations=149	Raman Res Instt, Bangalore
11	Pathan H.M. and Lokhande, C.D., Deposition of metal chalcogenide thin films by successive ionic layers absorption and reaction (SILAR) method, *Bulletin of Materials Science*, 27(2), 2004, 85-111. Citations=109	Shivaji Univ, Kolhapur
12.	Balamurugan, B and Mehta, B.R., Optical structural properties of nanocrystalline copper oxide thin films prepared by activated reactive evaporation, T*hin Solid Films*, 396(1-2), 2001, 90-96. Citations=106	IIT, Delhi
13.	Lokhande, C.D., Chemical deposition of metal chalcogenide thin films, *Materials Chemistry & Physics,* 27(1), 1991, 1-43. Citations = 104	Shivaji Univ, Kolhapur

Most commonly used journals

The total output was scattered in 168 journals published from 23 countries other than India. The journals that published one per cent or more of the research output along with their impact factor have been listed in Table 11. More than half of the output has been published in these 24 journals while the rest of the half is covered in more than 144 journals.

Table 11—Top journals publishing one per cent or more of the research output

SI. No.	Journal	No. of papers	Country	I.F.
1	*Solar Energy Materials and Solar Cells*	247	Netherlands	4.59
2	*Thin Solid Films*	86	Switzerland	1.90
3	*Journal of Applied Physics*	66	USA	2.06
4	*Materials Chemistry and Physics*	55	Switzerland	2.35
5	*Journal of Physics D Applied Physics*	53	UK	2.10
6	*Indian Journal of Pure & Applied Physics*	45	India	0.51
7	*Solar Energy*	40	UK	2.13
8	*Semiconductor Science and Technology*	39	UK	1.32
9	*J of Materials Science- Materials in Electronics*	38	Netherlands	0.92
10	*Applied Surface Science*	34	Netherlands	1.79
11	*Journal of Alloys and Compounds*	32	Switzerland	2.13
12	*Synthetic Metals*	32	Switzerland	1.87
13	*Journal of Crystal Growth*	30	Netherlands	1.73
14	*Applied Physics Letters*	29	USA	3.82
15	*Journal of Physical Chemistry C*	29	USA	4.52
16	*Renewable Energy*	28	UK	2.55
17	*Journal of Non Crystalline Solids*	27	Netherlands	1.48
18	*Journal of Materials Science*	27	USA	1.85
19	*Materials Letters*	26	Netherlands	2.11
20	*Bulletin of Materials Science*	23	India	0.94
21	*Materials Science and Engg B Solid State Materials for Advanced Technology*	23	Switzerland	1.56
22	*Vacuum*	21	UK	1.04
23	*Journal of Physics and Chemistry of Solids*	20	UK	1.38
24	*Materials Research Bulletin*	20	UK	2.14
	Sub-total	1070		
	Others (144 Journals)	954		

Conclusions

The study based on 20 years data (1991-2010) revealed that solar cell research in India received an impetus during the last decade i.e., 2001-2010. Academic Institutions (AI), Indian Institutes of Technology (IITs), Council of Scientific and Industrial Research (CSIR), Department of Science and Technology (DST) and Engineering Colleges (EC) accounted for more than 90 per cent of the output whereas Public Sector Undertakings (PSUs) had an almost negligible contribution. Despite the fact that AI outperformed all other performing sectors in terms of quantum of publications yet the visibility of their work was quite lower than that of Private Organization (PVT), Department of Atomic Energy (DAE), Department of Scientific and Industrial Research and other Ministries (DSIR&M) and CSIR. Seven state universities figured among the top 22 institutions which included Indian Institute of Science (IISc), a few IITs and CSIR institutions. CSIR-Indian Institute of Chemical Technology (CSIR-IICT), IISc, Shivaji University (SU) and Alagappa University (AU) had the highest citation rate and citation per paper. Some of the top institutions became active only in the later decade. The first decade was marked by dominance of single authored research while the later decade witnessed larger team sizes as well as relatively more domestic and international collaborative work. The solar cell research of Indian scientists appeared to be well connected to the international research trends as more than 90 percent of the research work was published in the journals originating from the US, UK and the other advanced countries of Europe. Not only this, three fourth of Indian solar cell research appeared in journals having medium, high or very high impact factor. Among all the types of solar cells, organic and polymer solar cell, dye-sensitized solar cell, photoelectrochemical solar cell and quantum dot solar cell were the recent focus of research of Indian scientists. Also, crystalline silicon based research is getting more emphasis than that based on amorphous silicon.

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Appendix I

Search strategy 1

ts=("solar cell*" or "photovoltaic*" or "amorphous silicon photovoltaic cell*" or "amorphous si pv cell*" or "bulk heterojunction solar cell*" or "cadmium telluride solar cell*" or "cdte solar cell*" or "carbon based solar cell*" or "conjugated polymer solar cell*" or "concentrating photovoltaic cell*" or "concentrating pv cell*" or "copper indium dieselenide solar cell*" or "cis solar cell*" or "copper indium gallium selenide solar cell*" or "copper indium gallium diselenide solar cell*" or "cigs solar cell*" or "crystalline silicon photovoltaic cell*" or "crystalline si pv cell*" or "dye sensitized solar cell*" or "dssc" or "fibre shaped flexible solar cell*" or "foil solar cell*" or "gallium arsenide solar cell*" or "gaas solar cell*" or "hybrid inorganic solar cell*" or "hybrid organic solar cell*" or "hybrid silicon solar cell*" or "hybrid si solar cell*" or "hybrid solar cell*" or "indium phosphide solar cell*" or "inp solar cell*" or "liquid junction solar cell*") and (cu=India)

Search strategy 2

ts=("microcrystalline silicon solar cell*" or "microcrystalline si solar cell*" or "monocrystalline silicon solar cell*" or "monocrystalline si solar cell*" or "multijunction silicon photovoltaic cell*" or "multijunction si pv cell*" or "nano crystal solar cell*" or "nano particle photovoltaic cell*" or "nano particle pv cell*" or "nano solar cell*" or "nanowire solar cell*" or "organic solar cell*" or "osc" or "organic photovoltaic cell*" or "organic pv cell*" or "polycrystalline silicon solar cell*" or "polycrystalline si solar cell*" or "polymer photovoltaic cell*" or "polymer pv cell*" or "polymer solar cell*" or "plastic solar cell*" or "quantum dot solar cell*" or "quantum dot sensitized solar cell*" or "self assembling solar cell*" or "silicon wafer solar cell*" or "thin film solar cell*" or "tandem silicon photovoltaic cell*" or "tandem si pv cell*") and (cu=India)

Appendix II – Full names of institutions

IACS - Indian Association for Cultivation of Science, Kolkata

IITD - Indian Institute of Technology, Delhi

NPLNational Physical Laboratory, Delhi

SU - Shivaji University, Kolhapur

SVU - Sri Venkateswara University, Tirupati

IISc - Indian Institute of Science, Bangalore

JNVU - Jai Narain Vyas University, Jodhpur

JU - Jadavpur University, Kolkata

IITB - Indian Institute of Technology, Bombay

BHU - Banaras Hindu University, Banaras

DU - Delhi University, Delhi

AU - Alagappa University, Karaikudi

CUST - Cochin University of Science & Technology, Cochin

IITM - Indian Institute of Technology, Madras

CECRI - Central Electrochemical Research Institute, Karaikudi

IICT - Indian Institute of Chemical Technology, Hyderabad

SSPL - Solid State Physics Laboratory, Delhi

IITK - Indian Institute of Technology, Kanpur

KASC - Kongunadu Arts & Science College, Coimbatore

IITKH - Indian Institute of Technology, Kharagpur

DL - Defence Laboratory, Jodhpur

BU- Bharathidasan University, Tiruchirapalli

CSIR - Council of Scientific and Industrial Research

DRDO - Defence Research and Development Organisation

MIT-CMET - Ministry of Communications & Information Technology - Centre for Materials for Electronics Technology