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A scientometric overview of collaboration pattern in global solar cell research

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Collaborative aspects of research publications pertaining to global solar cell research as reflected in Science Citation Index-Expanded (SCI-E) for the years 1991, 1995, 2000, 2005 and 2010 have been studied. Using various bibliometric indicators, the study examined the pattern of co-authorship and nature of collaboration with respect to different types of institutions, countries and prolific institutions. It also looked into impact of collaboration in terms of citations. The study observed a peculiar behaviour wherein publication from certain prolific countries and institutions emerging from domestic collaboration resulted in higher impact than those from international collaboration.

Keywords: scientometrics; collaboration; solar cell research; photovoltaics

Introduction

The world over vigorous research in solar cell is being pursued owing to multiple reasons, like fuel crisis, environmental concerns, and the need for sustainable energy security solutions[1]. Solar cell is a key topic of research in energy technology[2]. Solar cell research is characterized by a blend of basic and applied research as well as technology[3]. For maximum power conversion the right material for the solar cells cell must be chosen to make them efficient and cost-effective[4]. The very nature of solar cell research is complex and demands an ever widening range of skills making it a potential candidate for collaborative research**.** Collaboration is a vehicle for transferring knowledge, especially tacit knowledge. A meticulous enunciation of a plethora of facets and motives for forging collaboration by Katz and Martin has been done in their seminal work on collaboration. They have also articulated that direct co-operation between two or more researchers is the basic unit of collaboration[5]. Beaver[6] too has spelled out the reasons behind forging collaboration. According to Beaver and Rosen the need for collaboration arose due to professionalization and ever increasing knowledge in science[7-9]. Collaboration may result into cross-fertilisation of ideas and clash of views which may in turn generate new perspectives or insights that the individuals working on their own would not have grasped or grasped as quickly[10-11].

International scientific collaboration is perceived as an effort in enhancing a country's scientific capabilities and is also considered as a mechanism for cost sharing[12]. It is generally accepted that international scientific collaboration is not only beneficial to less advanced countries but also to highly industrialized countries[13]. Thus adequate policy measures are required at national and supranational level in view of globalization of science[14].

Review of literature

Collaborative papers attract more citations than those without any collaboration. Also articles written in international collaboration receive more citations than articles written in domestic collaboration, which in turn receive more citations than articles written in local collaboration, thereby, suggesting that internationally co-authored articles represent a more important segment of the world science[15]. Some researchers showed that research by larger groups tends to be more influential[16-17].

The bibliometric data in scientific publications is used as a unit of analysis and dynamics of collaborative aspects could be unravelled through analysis of co-authorship[18]. Not all types of collaboration have the same effect on its impact measured by 'times cited' (TC)[19]. Frame and Carpenter suggested that "the more basic the field, the greater the proportion of international co-authorship and more basic the field, greater the probability of international co-authorship[20].

From the view point of policy perspective, collaboration can also 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[21]. Initiatives in science policy and the internal dynamics of the gamut of science have led to progressively increasing research collaborations among countries, institutions and researchers, thus, making collaboration in science a major issue in science policy. 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[22, 18].

Studies on research collaboration in the renewable energy technology field are scarce[23]. Larsen examined co-authorship networks in nanostructured solar cells to gain an insight into the knowledge diffusion in a science based technology field[23]. Huang et al conducted a study to explore collaborations in the field of solar cell science and technology which focussed on productivity and citations of publications and patents at the global and country level and found that most of the countries had higher rates of international collaboration with greater numbers in papers and patents[2]. Lei et al[24] examined technological collaboration in solar cell industry based on patent assignees and inventors as defined by the United States Patent and Trademark Office (USPTO) and found that the US had the largest number of internationally collaborative patents worldwide, however, their share was quite low in total US patents. Wang, Li, Ren et al[25] examined the growth of Chinese dye-sensitized solar cell research and the rise of collaboration between China and other countries using bibliometrics and social network analysis to explore pattern of scientific collaboration. However, there is no study reported in literature that has dealt with scientometrics pattern of collaboration in global solar cell research and this study is aimed to fill that void.

Objectives of the study

- To determine and examine the nature and pattern of collaboration in respect of different types of institutions and countries;
- To examine the co-authorship pattern over different years and in different countries; and
- To examine the nature of collaboration among prolific institutions.

Methodology

Data

Data were downloaded for five different years, i.e. 1991, 1995, 2000, 2005 and 2010 from the Web of Science (WoS) of Thomson Reuters, Philadelphia, USA using the search strategies 1 and 2 given in our earlier paper[26]. These two strategies yielded 11335 records. This comprised 10778 journal articles, 1553 proceeding papers, 355 reviews, 43 notes, 9 news items, editorial and letters 37 each, 34 meeting abstracts, 12 corrections, 17 reviews; books, 6 bibliographies, 1 book review and 1 reprint. These do not add up to 11335 as proceedings papers (1553) are, in fact, published as journal articles and included in 11335 records. This study examined only the journal articles and reviews which added up to 11133 records.

Data standardization and cleaning

Pendelbury[27] and Moed[28] have suggested that the names of the authors and their affiliations have to be standardized due to artefacts of variation. In this study, for example, certain records were incomplete in the sense that names of the country like China and the US were not mentioned and names of authors and institutions were mentioned in a variety of manners. Therefore, in view of this each record was scrutinized and standardized to make the database authentic and amenable to meaningful and reliable analysis.

On close scrutiny of the records it was observed that some irrelevant records crept into the downloaded corpus of publications owing to keywords like “OSC”, “photovoltaics”, “DSSC” etc. A few examples of these journals are, *Industrial Crops and Products*, *Journal of Medical Entomology*, *Journal of Korean Medical Science*, *Lung*, *Medical Physics*, *Oral Oncology*, *Plant Cell Reports*, *Rheumatology*, *Textile Research Journal*, *Water Research*, *Wind Energy*, etc. Therefore, these 238 irrelevant records scattered over 122 different journals were removed. After this exercise we were left with 10905 records.

Data enrichment and analysis

A database was created in Fox Pro version 2.5 comprising the following fields pertaining to all the downloaded publications.

1. Name of the authors with their affiliations and countries.
2. Type of institutions (Academic, Research, Industrial, Government, Others)
3. Number of authors
4. Number of countries
5. Types of collaboration

Domestic Collaboration (DC): At least two institutions within a country collaborate to produce a research publication.

International Collaboration (IC): At least two different countries collaborate to produce a research publication.

The citations were updated on May 15th, 2014 to allow maximum possible citation window.

The data was analysed using simple commands of FoxPro and SPSS version 20 to indentify the highly prolific countries, institutions, their total output, co-authorship and collaboration. These were used to compute different indicators like, co-authorship index, domestic collaborative index and international collaborative index, and collaboration coefficient etc.

Indicators used

The publication numbers (P) and the number of citations (C) were obtained from the downloaded records. Following indicators have been used for the analysis of data.

Citation per Paper (CPP)

Citation 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.

Co-authorship Index (CAI)

To study the shift in the pattern of co-authorship during different years CAI suggested by Garg and Padhi[29] was used. CAI is computed as follows.

$$CAI = \frac{Nij \div Nio}{Noj \div Noo} \times 100$$ 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[29], 2001 and used by Dutt, Garg and Bali[30], 2003 were used.

Domestic Collaborative Index (DCI)

$$DCI = \frac{Di \div Dio}{Do \div Doo} \times 100$$ 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

International Collaborative Index (ICI)

$$ICI = \frac{Ii \div Iio}{Io \div Ioo} \times 100$$ 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.

Collaboration Co-efficient (CC)

Ajiferuke, Burrel and Tague[31] suggested a single measure to measure collaborative research and termed it as collaboration coefficient. The method is based on fractional productivity defined by Price and Beaver[32].

The following formula used to calculate CC is explained below.

$$CC = 1 - \frac{\sum_{j=1}^{k} (1/j) f_j}{N}$$

Where fj is the number of j authored papers;
N is the total number of research papers published and
k is the greatest number of authors per paper

According to the authors, CC tends to zero as single authored papers dominate and to 1-1/j as j-authored papers dominate. This implies that higher the value of CC, higher the probability of papers with multi or mega authors. The multi authors mean papers with 3 or 4 authors and mega authors with more than 4 authors. However, inclusion of authors as multi or mega can be changed according to nature of data available for analysis.

Citation Gain (CG)

Gorraiz et al[33] have suggested that the impact gained in respect of collaborative publications can be estimated by the increase in the average citedness of internationally collaborative publication in comparison to the average value of domestically produced publication (single country) only. This is computed as follows:

$$\text{Citation Gain (CG)} = \frac{\text{CPP collaborative} - \text{CPP country only}}{\text{CPP country only}} \times 100$$

The limitation pertaining to the different field citation behaviour does not apply here as we are looking at one area of research only, i.e. solar cell research. The need for field normalized citations would have arisen if we were examining two diverse fields, for example, life sciences and physical sciences.

Results and discussion

Nature of collaboration in different type of institutions

Globally, in general four types of institutions carry out research, such as Academic Institutions (AI), Research Institutions (RI), Industrial Organizations (IO) and Government Organizations (GO). An examination of the pattern of collaboration in these types of institutions revealed almost equivalent values of DCI in respect of AI and RI but slightly higher values of ICI suggesting marginally higher proportion of output emerging out of IC (Table 1).

In respect of IO and GO there appeared a clear domination of Domestic Collaboration (DC). The institutions categorised as “Others” had higher proportion of output emerging out of International Collaboration (IC). In respect of all types of institutions IC resulted in Citation Gain (CG) in varied proportions.

Pattern of co-authorship in different years

The pattern of co-authorship over different years as reflected by the values of Co-authorship Index (CAI) revealed gradual reduction in the values of CAI in respect of single authored and two-authored papers from 1991 to 2010 thereby suggesting a general declining trend towards such publications (Table 2).

Multi-authored papers exhibited an inconsistent trend whereby the values of CAI increased gradually from 1991 and reaching the peak in the year 2000 after which they again started declining. However, mega-authored publications revealed a clear reverse trend compared to single and two-authored publications, indicating that over the years, the tendency of mega-authored publications gained momentum but the values of CAI were not as high as was the case in the single and two-authored papers which exhibited sharp decline over the years.

Pattern of co-authorship in different countries

The pattern of co-authorship in different countries was examined by distributing the output of countries with respect to the number of authors. The upward and downward arrows against some countries have been put in Table 3 which exhibited a clear rising or declining trends based on the values of CAI. Other countries without arrow markings exhibited inconsistent behaviour.

In case of USA, UK and Australia the pattern indicated decline in the values of CAI from single author to mega author publications suggesting a declining trend towards larger team sizes, whereas, in case of China, Korea and Italy, a reverse pattern was observed where the values of CAI gradually increased from single author to mega authored publications suggesting drifting away from single authored papers to those involving larger team sizes. Germany, Korea and France had the least proportion of two-authored publications while England had the highest. China, Korea, Taiwan and France showed overwhelming mega-authored work.

The values of Collaboration Co-efficient (CC) in respect of all the countries ranged from 0.61 - 0.70 indicating a general trend across all the countries towards more collaborative research and larger team sizes. China registered the highest values of CC at 0.70.

Table 1—Nature of collaboration and type of institutions

Sl. no.	Type of institute	DC(CPP)	DCI	IC(CPP)	ICI	CG	Total
1	AI	7084(29.9)	99	1614(35.8)	101	19.8	8727
2	RI	1240(25.4)	98	302(28.5)	107	12.2	1548
3	IO	407 (23.2)	111	38 (28.6)	47	23.2	446
4	GO	130 (19.8)	108	17(26.7)	64	34.8	147
5	Other	29 (26.4)	96	8 (56.75)	119	114.9	37
	Total	8890		1979			10905

Note: 36 papers were without any collaboration so the sum of breakup does not add upto 10905

Table 2—Co-authorship pattern during different years and co-authorship index

No. of authors	1991	1995	2000	2005	2010	Total
1	79(286)	94(287)	100(174)	111(95)	213(59)	597
2	133(205)	126(163)	174(128)	277(100)	698(81)	1408
3 or 4 (Multi)	186(105)	240(114)	385(248)	779(103)	2252(96)	3842
>=5 (Mega)	106(43)	136(47)	383(78)	964(97)	3469(112)	5058
	504	596	1042	2131	6632	10905

Number of countries involved

Table 4 presents the distribution of output with respect to number of countries involved in different years. It indicated that more than 80% of the output emerged out of the involvement of one country only. About 16% publication emerged from Bilateral Collaboration (BC) and about 3% from Multilateral Collaboration (MC).

From 1991 to 2010 there was a rising trend of both BC and MC, however, their proportion as total output of the respective years remained the same.

Pattern of collaboration in different aspects

To examine the shift in pattern of collaboration Domestic Collaborative Index (DCI) and International Collaborative Index (ICI) suggested by Garg and Padhi[29], (2001) and used by Dutt, Garg and Bali[30], (2003) were used.

Nature of collaboration in different years

The distribution of output in terms DC and IC in different years is presented in Table 5. The values of DCI from 1991 to 2010 showed a declining trend over the years which in turn imply that over the years the proportion of output emerging from DC was on the decline whereas the values of ICI indicated a rising trend.

Nature of collaboration in different countries

Table 6 depicts those countries that produced 2% or more of the total output. These 12 countries accounted for more than 75% of the publication output. The data was distributed among DC and IC publications with respect to different countries to examine the nature of collaboration. The values of DCI in respect of USA, China, Japan, Korea, India and Taiwan were above the world average indicating the dominance of research output emerging from DC in these countries. According to Karmalski[34] the US does not have ample opportunities for cross-national research funding and further suggests that large countries offer domestically sufficient opportunities for research collaboration, thereby implying that forging research collaboration beyond the national boundaries may not be their pressing need.

However, in case of Germany, England, Spain, France, Italy and Australia, the values of ICI were above average implying higher proportion of output originating from IC in these countries. Germany, France and Italy have structured mandate and mechanisms in their scientific agencies, like Fraunhofer[35], CNRS[36] and CNR[37] respectively which strategically forge international research collaborations. In the UK there is an almost universal

Table 3—Pattern of co-authorship in different countries (CAI)

Sl. no.	Country	Single	Two	Multi	Mega	CC	Total
1	USA ↓	143(140)	313(128)	696(104)	744(85)	0.62	1896
2	China ↑	15(18)	75(37)	430(79)	1020(143)	0.70	1540
3	Japan	52(91)	119(88)	400(109)	472(98)	0.65	1043
4	Germany	49(113)	84(82)	283(101)	378(102)	0.65	794
5	Korea ↑	18(47)	61(66)	235(94)	399(121)	0.68	713
6	India	18(70)	120(195)	214(128)	124(56)	0.62	476
7	Taiwan	20(81)	40(69)	134(85)	251(121)	0.67	445
8	England ↓	29(140)	68(138)	124(92)	160(91)	0.62	381
9	Spain	17(100)	49(121)	123(111)	123(85)	0.64	312
10	France	13(82)	25(66)	103(99)	152(112)	0.67	293
11	Italy ↑	6(40)	30(87)	92(98)	138(112)	0.67	266
12	Australia ↓	19(159)	38(133)	80(103)	83(81)	0.61	220
	Sub-total	399 (88)	1022 (94)	2914 (96)	4044(103)	0.66	8379
	Others (87 Countries)	198(166)	386(125)	928(108)	1014(77)	0.63	2526
	Total	597	1408	3842	5058		10905

Table 4—Number of countries involved in research during different periods

No. of countries	1991	1995	2000	2005	2010	Total
One	410	463	843	1774	5380	8870
Two	76	112	175	306	1047	1716
Three	15	19	20	42	164	260
Four or more	3	2	4	9	41	59
	504	596	1042	2131	6632	10905

Table 5—Nature of collaboration during different periods

Nature of collaboration	1991	1995	2000	2005	2010	Total*
DC (DCI)	489(119)	561(116)	828(97)	1678(97)	5334(99)	8890
IC (ICI)	15(16)	35(33)	214(113)	443(114)	1276(106)	1979
Total	504	596	1042	2131	6632	10905

Note: 36 papers were without any collaboration so the sum of breakup does not add upto 10905

Table 6—Nature of collaboration in different countries

Sl. no.	Country	DC	DCI	IC	ICI	CG	Total
1	USA ↓	1643	106	239	69	-0.4	1896
2	China ↑	1379	109	157	56	46.2	1540
3	Japan ≈	933	109	106	56	1.2	1043
4	Germany ↑	607	94	185	128	12.2	794
5	Korea ↑	620	106	93	72	60.9	713
6	India ↓	413	108	63	74	-0.7	476
7	Taiwan ↑	406	111	36	44	12.1	445
8	England ↓	269	86	110	159	-3.3	381
9	Spain ↑	234	92	78	138	85.2	312
10	France ↑	198	83	95	179	59.1	293
11	Italy ↑	192	88	74	153	5.7	266
12	Australia ↑	165	92	55	138	30.2	220
	Sub-total	7059		1291			8379
	Others (87 Countries)	1831	88	688	153		2526
	Total	8890		1979			10905

Note:36 papers were without any collaboration so the sum of breakup does not add upto 10905

commitment across higher education system to expand the level of international research collaboration, both institutional-level strategic partnerships and researcher-level international collaboration[38]. Australian Research Council too aims to support international research collaboration[39].

The values of Citation Gain (CG) resulting out of internationally collaborative output in respect of USA, Japan, India and England were either negative or negligible suggesting that IC had not resulted into a positive impact in terms of citations in these countries which are marked with downward arrows in Table 6. Publications resulting out of international research collaboration are twice as likely to be cited than single country publications[15]. King[40] has observed that "lack of benefits of international collaboration may also be due to the general globalization of science". He further added "as the differences have decreased between the scientific impact of nations, the effect of international collaboration may have diminished as well". The countries that attained significant CG are marked with upward arrows. The maximum CG was attained by Spain, followed by Korea, France and China. According to Glanzel et al[13] "the citation attractivity of internationally co-authored publications show that international scientific collaboration is particularly advantageous for less advanced countries, but also highly industrialized countries benefit from collaboration". This observation may not be universally valid and might have some deviations. Also some evidences provide a clue to another dimension which suggests that more distant collaborations are likely to have more citation impact[41].

In respect of USA, Japan and England it may be posited that the quality of their research output emerging out of DC and IC had little variation with each other which resulted into negative or negligible CG. However, it appeared peculiar that India too exhibited the same characteristics. This aspect needs further examination.

Nature of collaboration among prolific institutions and their impact

Those institutions that produced 0.5 % or more of the total output were termed as prolific institutions (Table 7) and their output was distributed according to nature of collaboration to understand the pattern of their research collaboration. Out of 28 institutions, in case of 16 institutions the values of DCI were above the world average indicating the dominance of output originating out of DC. Almost similar values of DCI and ICI in case of University of California, USA (UCAL) and Universidad Politecnica de Madrid, Spain (UPOS) implied almost equal proportion of output emerging out of DC and IC. Very high values of ICI were observed in respect of Imperial College of Science, Technology and Medicine, England (ICST), University of Cambridge, England (UCAM), National Research Council, Italy (CNRI), National Center for Scientific Research, France (CNRS), National University of Singapore, Singapore (NUOS) and Ecole Polytechnique Federale de Lausanne, Switzerland (EPFL), suggesting that these institutions had relatively very high proportion of output emerging out of IC.

Further examination of Table 7 revealed basically two categories of institutions, (i) one which had higher CPP in IC compared to DC and (ii) which had higher CPP in DC compared to IC. These 15 institutions in the latter category can be further broadly divided into three broad types based on range of variation of CPP in DC and IC mode, which are depicted in Figure 1. Usually, output emerging out of IC is considered to result in relatively more impact in terms of times cited than that in DC[22,42]. Contrarily, here we witnessed a reverse phenomenon where more than half of the institutions had higher values of CPP in DC mode than that in IC.

Table 7—Nature of collaboration among prolific institutions

Sl. no.	Institutions*	DC	DCI	CPP	IC	ICI	CPP	No. of papers
1	CASC, China	286	112	25.3	26	46	49.8	313(2.9)
2	UCAL, USA	139	99	185.7	31	100	91.5	171(1.6)
3	CNRS, France	111	84	27.0	50	171	40.0	161(1.5)
4	NREL, USA	135	115	48.5	6	23	47.3	143(1.3)
5	NTUT, Taiwan	81	106	23.0	11	65	49.4	93(0.8)
6	AIST, Japan	82	114	37.2	6	38	34.7	88(0.8)
7	UNSW, Australia	67	99	31.2	16	106	59.7	83(0.8)
8	OSAU, Japan	64	101	59.2	13	93	48.0	77(0.7)
9	FRAU, Germany	67	109	14.0	8	59	14.5	75(0.7)
10	RASR, Rusisa	53	94	9.3	15	120	5.0	69(0.6)
11	ICST, England	42	75	77.2	27	216	63.5	69(0.6)
12	MXPG, Germany	48	91	26.8	17	144	24.1	65(0.6)
13	IITS, India	61	115	11.4	4	34	7.2	65(0.6)
14	NAUC, China	57	114	16.1	4	36	52.2	61(0.5)
15	UPOS, Spain	49	100	12.0	11	101	29.5	60(0.5)
16	NUOS, Singapore	42	87	24.0	17	159	30.5	59(0.5)
17	ZHUC, China	49	103	19.9	9	86	14.5	58(0.5)
18	NCTU, Taiwan	55	120	27.2	1	10	139.0	56(0.5)
19	KYUJ, Japan	46	102	30.0	9	90	38.9	55(0.5)
20	HMIG, Germany	44	98	21.2	11	110	14.7	55(0.5)
21	EPFL, Switzerland	38	86	53.6	16	163	104.0	54(0.5)
22	CNRI, Italy	33	76	27.8	20	208	15.5	53(0.5)
23	STUN, USA	45	106	76.9	7	74	60.8	52(0.5)
24	KIST, Korea	44	105	18.6	7	76	22.8	51(0.5)
25	NTUS, Singapore	35	84	35.7	16	173	29.1	51(0.5)
26	CSIR, India	47	113	17.3	4	43	31.2	51(0.5)
27	UTOK, Japan	44	107	32.6	6	66	9.7	50(0.4)
28	UCAM, England	31	76	152.2	19	209	57.8	50(0.4)
	Sub-Total	1895	101		387	93		2282 (20.9)
	Others (1991 Institutions)	6995	99		1592			8623(79.1)
	Total	8890			1979			10905

** Full names of the institutions are given in Appendix I*

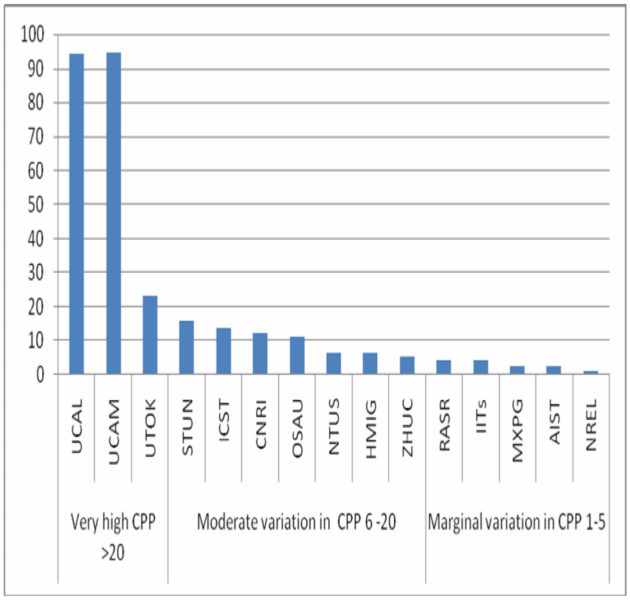

Fig. 1—Difference between CPP in DC-CPP in IC

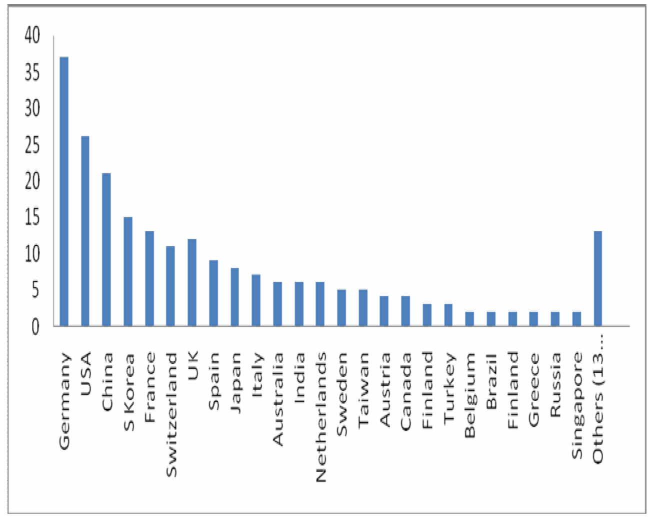

Fig. 2—Collaborating countries with 15 institutions whose CPP in DC was higher than that in IC

Of these institutions, three each were from USA and Japan, two each from England and Germany, one each from Russia, India, China, Singapore and Italy. Marginally varied values of CPP at par in case of DC and IC in respect of National Renewable Energy Laboratory, USA (NREL), National Institute of Advanced Industrial Science and Technology, Japan (AIST), Max Planck Society, Germany (MXPG), Indian Institutes of Technology, India (IITs), and Russian Academy of Sciences, Russia (RASR) may, however, be explained by surmising that research emerging out of DC had slightly more impact than IC in terms of their visibility and quality. Other types of institutions had moderately higher CPP ranging from 5-20 while University of California, USA (UCAL), University of Cambridge, England (UCAM) and University of Tokyo, Japan (UTOK) had very high range of difference in CPP (>20) in respect of the output emerging from DC compared to that in IC implying that the output emerging out of DC itself in respect of these institutions was of the highest quality and international research collaboration did not further add to its quality, visibility and impact whatsoever.

Presuming that the international collaborating partners of these institutions might be from developing countries, we looked at the data to identify the countries that collaborated with these 15 institutions and observed 39 different countries (Fig. 2) occurring at 226 different positions as collaborating partners. Majority of these collaborating countries included USA, advanced countries of Europe, China, India, South Korea, Taiwan and Singapore, etc. which cannot be termed as scientifically backward or non-performers in solar cell research. The collaboration with institutions belonging to any of these countries did not result into citation gain.

Rees[43] says "successful collaboration depends on all parties having a certain level of scientific and technological capacity". This becomes more intriguing as a majority of these countries belong to the group of 31 countries which account for more than 98% of the world's highly cited papers and the remaining 162 countries contributed less than 2% in total[40]. Thus it might be worth probing deeper who were the international institutional collaborators of such institutions to understand the dynamics of impact of international research collaboration. Thus a plausible explanation for this phenomenon is elusive and is a limitation of the present study.

Conclusions

In Academic Institutions (AI) which accounted for four fifth of the output, a slightly higher proportion of solar cell research output emerged out of International Collaboration (IC). Over the years a general tendency of increasing output contributed by larger team sizes was observed. The US and some other advanced countries of Europe indicated decline from single authored to mega authored publications while China and some other Asian countries exhibited a reverse trend. Four fifth of the research output emerged out of single country and the quantum of publications gradually decreased with increase in the number of countries involved. Over a period of time the output emerging out of IC increased gradually. In USA, China, Japan, Korea, India and Taiwan publications emerging out of Domestic Collaboration (DC) dominated whereas in case of Germany, England, Spain, France, Italy and Australia those from IC dominated. Of the 28 prolific institutions slightly more than half emphasised on DC while the other half on IC. The institutions that had higher research output emerging out of DC belonged to the US and Asian countries whereas institutions from the advanced countries of Europe had dominance of output emerging out of IC. About half the prolific institutions displayed a strange characteristic whereby their output emerging out of DC had higher CPP compared with that from IC. It is possible that "other institutions" not displayed in the table might also bear the similar characteristics.

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Appendix I - Abbreviations of institutes and their full names

Sl. no.	Abbreviation	Full name of Institution / Organization
1	CASC	Chinese Academy of Sciences, China
2	UCAL	University of California, USA
3	CNRS	National Center for Scientific Research, France
4	NREL	National Renewable Energy Laboratory, USA
5	NTUT	National Taiwan University, Taiwan
6	AIST	National Institute of Advanced Industrial Science and Technology, Japan
7	UNSW	University of New South Wales, Australia
8	OSAU	Osaka University, Japan
9	FRAU	Fraunhofer, Germany
10	RASR	Russian Academy of Sciences, Russia
11	ICST	Imperial College of Science, Technology and Medicine, England
12	MXPG	Max Planck Society, Germany
13	IITS	Indian Institutes of Technology, India
14	NAUC	Nankai University, China
15	UPOS	Universidad Politecnica de Madrid, Spain
16	NUOS	National University of Singapore, Singapore
17	ZHUC	Zhejiang University, China
18	NCTU	National Chiao Tung University, Taiwan
19	KYUJ	Kyoto University, Japan
20	HMIG	Hahn Meitner Insttute, Germany
21	EPFL	Ecole Polytechnique Federale de Lausanne, Switzerland
22	CNRI	National Research Council, Italy
23	STUN	Stanford University, USA
24	KIST	Korea Advanced Institute Science & Technology, Korea
25	NTUS	Nanyang Technological University, Singapore
26	CSIR	Council of Scientific and Industrial Research, India
27	UTOK	University of Tokyo, Japan
28	UCAM	University of Cambridge, England