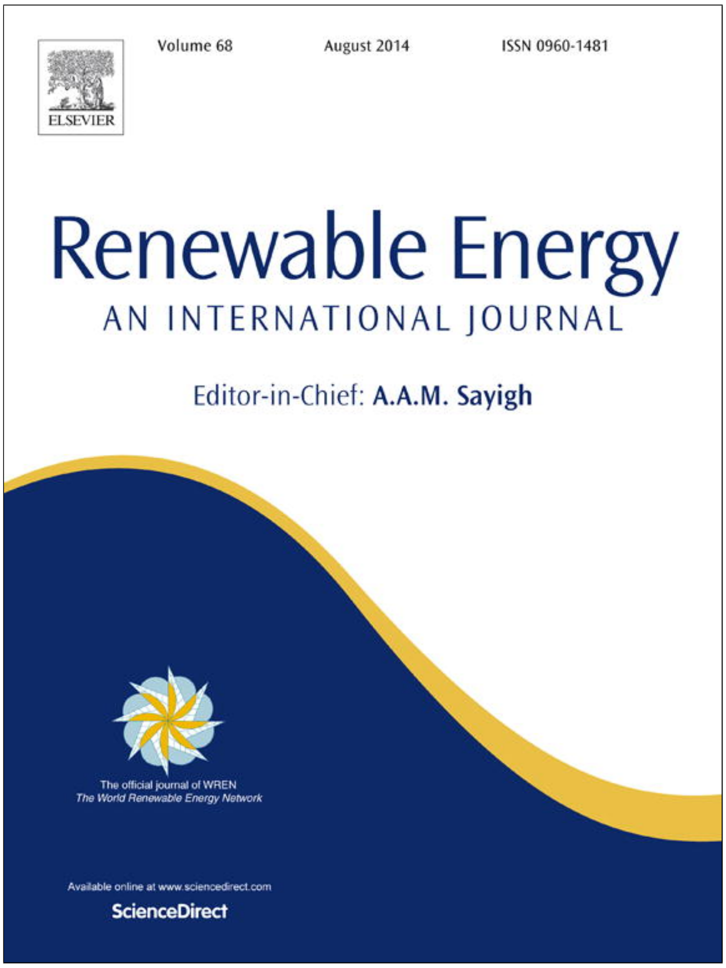
Volume 68
August 2014
ISSN 0960-1481
ELSEVIER
Renewable Energy
AN INTERNATIONAL JOURNAL
Editor-in-Chief: A.A.M. Sayigh
The official journal of WREN
The World Renewable Energy Network
Available online at www.sciencedirect.com
ScienceDirect

Renewable Energy 68 (2014) 733–744

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

# Production, consumption and research on solar energy: The Spanish and German case

Elias Sanz-Casado [a], Maria Luisa Lascurain-Sánchez [a], Antonio Eleazar Serrano-Lopez [a], Birger Larsen [b], Peter Ingwersen [c,*]

[a] *University Carlos III, Madrid, Department of Library Science and Documentation, Laboratorio de Estudios Métricos de Información (LEMI), C/Madrid 126, Getafe Madrid 28903, Spain*
[b] *Department of Communication and Psychology, Aalborg University Copenhagen, A.C. Meyers Vænge 15, DK-2450 Copenhagen SV, Denmark*
[c] *Royal School of Library and Information Science, University of Copenhagen, Birketinget 6, DK-2300 Copenhagen S, Denmark*

ARTICLE INFO

*Article history:*
Received 17 October 2013
Accepted 3 March 2014
Available online 25 March 2014

*Keywords:*
Bibliometric analysis
Renewable energy
Solar energy
Spain and Germany

ABSTRACT

An analysis of scientific publications on solar energy was conducted to determine whether public interest in the subject is mirrored by more intense research in the area. To this end, the research published by Spain and Germany, the two EU countries with the highest installed photovoltaic capacity, was analyzed based on Web of Science data. The results show that: solar output has risen substantially; solar research has a greater impact (measured in terms of citations) than publications on other renewables such as wind power; scientific production on solar energy is high in Germany and Spain, which together account for 51% of the total in the EU-27; the pattern of topics researched in the two countries is very similar; and their international collaboration is more intense than the world average and higher than in countries such as the USA, China or Japan. Collaboration between them is likewise intense. The main conclusion is the divergence in Germany and Spain between solar energy demand/output growth, being exponential, and the growth of research papers on the subject, which is linear.



## 1. Introduction

Research, development and innovation in the field of renewable energy, is closely related to investment and national policies, especially in regard to obtaining sustainable resources [1]. In this respect, countries and institutions are the main actors of research on this type of energy production.

The countries in the European Union have a huge interest in the promotion of the use of renewable energy sources. By developing less dependence on fossil fuels from countries outside the EU the emission of $CO_2$ is reduced, which is an advantage from both energy, environmental and economic perspectives. This interest is specified in legislation with Directive 2009/28/EC [2] from the European Parliament on promotion of the use of energy from renewable energy sources which outlines a set of goals to be achieved by 2020.

* Corresponding author.
*E-mail addresses:* clb798@iva.ku.dk, peteringwersen@yahoo.com (P. Ingwersen).

http://dx.doi.org/10.1016/j.renene.2014.03.013
0960-1481/

Moreover, the OECD raises an awareness related to the importance of sustainable developments through various programs that enhance their study and promotion, especially in the field of sustainable growth and so-called "Green growth" [3,4].

Political decisions on renewable energy in the EU are becoming increasingly important, as evidenced by the increased generation and consumption of energy from alternative sources, with continued growth in recent years, although they are still far from reaching the goal set for the year 2020, where 20% of energy production should come from renewable energy sources (Fig. 1) [5]. The target of 20% is an overall target for the entire EU, and individual countries have their own targets.

An analysis of the evolution of this energy consumption by country (Table 1), indicates that primarily in Scandinavia and Eastern Europe the percentage of energy produced by alternative sources exceeds the overall 2020 target reaching well above the countries of the Central European region and the Mediterranean [5].

Among the renewable energy sources, the largest share of energy production capacity derives from wind and solar energies. As shown in Fig. 2, especially wind power demonstrates a remarkable growth in the EU since the 90s [6], while a similar boost of solar energy production initiates in the middle of the last decade (2005–2006).

Energy production from solar sources as such already started in the mid-90s. Germany and Spain are the two European countries that are making the greatest effort with respect to this type of energy (Fig. 3), which contributes to reducing emissions of significant amounts of $CO_2$ to the atmosphere, as well as creating so-called “green jobs”, largely related to the development, production and installation of photovoltaic systems.

When looking at the data on the installed photovoltaic capacity in the 27 EU countries at the end of 2009 Germany and Spain top the list, followed by Italy, the Czech Republic and Belgium (Fig. 3). The same top position applies in relation to the photovoltaic capacity per capita (Table 2), but with Italy at a lower ranking. Furthermore, the Eurostat data (Table 3) show that Spain and Germany have a much higher growth in production of solar energy than the EU overall. While the production in the EU has increased by a factor of 21 1995–2011, it has increased by factors of 52 and 58 in Spain and Germany, respectively [7].

From a bibliometric and scientometric perspective several studies have been conducted that analyze different papers have studied the literature on renewable energy in general and solar energy in particular. For example, Garg and Sharma [8] observed the great growth of publications on collectors and solar cells after the 1973 energy crisis. Tijssen [9], based on co-classification analysis shows the interdisciplinary structure and sources of renewable energy research in the Netherlands. Celiktas et al. [10] analyzed the different trends in renewable energy research in Turkey and showed the important role played by solar energy within them. Recent bibliometric research on India highlights the importance of solar energy in this country, and the significant weight of its scientific production on the global scene [11,12].

Dong et al. [13] analyzed the literature on solar energy and also observed an important growth of publications between 1991 and 2010 and concluded emphasizing the importance that research on solar cells will have in the 21st century. Romo-Fernández et al. [14] discuss research on renewable energy in different European countries. They show the leading role of European institutions in this field, with a large scientific production and a higher impact than the world average. In a later article [15] they focus their analysis on production of renewable energy research in Spain compared to a global context. They point to the increasing presence of publications authored by Spanish institutions in the area of renewable energy and in particular to the increase in solar energy research.

The overall aim of this paper is to determine whether the increase in the societal interest in solar energy is reflected in an increase of research on this type of energy, measured primarily by analyses of publications. To do this, we have analyzed the publications of the research institutions in Spain and Germany, as they are the two EU countries with the highest installed photovoltaic capacity. The analyses will establish the publication patterns in terms of temporal evolution, the main subjects, the publication sources, the most productive institutions as well as international scientific collaboration in the field of solar energy research.

The article is structured as follows. First, a methodological section describes the data collection, including the retrieval profiles, and the means of data analysis in the form of indicators used. This is followed by result sections that first provide findings on renewable energy as such, followed by findings on solar energy research, particular topics, central journals, major research institutions in Spain and Germany, and international collaboration patterns. The article ends with a discussion of perspectives and conclusions.

**Table 1**
Percentage of consumption from renewable energy sources by country (2004–2010).

| | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2020 target |
|---|---|---|---|---|---|---|---|---|
| EU-27 | 8.1 | 8.5 | 9.0 | 9.9 | 10.5 | 11.7 | 12.5 | 20 |
| Belgium | 1.9 | 2.3 | 2.6 | 2.9 | 3.3 | 4.5 | 5.1 | 13 |
| Bulgaria | 9.6 | 9.5 | 9.6 | 9.3 | 9.8 | 11.9 | 13.8 | 16 |
| Czech Republic | 6.1 | 6.1 | 6.5 | 7.4 | 7.6 | 8.5 | 9.2 | 13 |
| Denmark | 15.1 | 16.2 | 16.5 | 18.0 | 18.8 | 20.2 | 22.2 | 30 |
| Germany | 5.1 | 5.9 | 6.9 | 9.0 | 9.1 | 9.5 | 11.0 | 18 |
| Estonia | 18.4 | 17.5 | 16.1 | 17.1 | 18.9 | 23.0 | 24.3 | 25 |
| Ireland | 2.2 | 2.7 | 2.9 | 3.3 | 3.9 | 5.1 | 5.5 | 16 |
| Greece | 6.9 | 7.0 | 7.0 | 8.1 | 8.0 | 8.1 | 9.2 | 18 |
| Spain | 8.2 | 8.3 | 9.0 | 9.5 | 10.6 | 12.8 | 13.8 | 20 |
| France | 9.3 | 9.5 | 9.6 | 10.2 | 11.3 | 12.3 | 12.9 | 23 |
| Italy | 5.3 | 5.3 | 5.8 | 5.7 | 7.1 | 8.9 | 10.1 | 17 |
| Cyprus | 2.4 | 2.4 | 2.5 | 3.1 | 4.1 | 4.6 | 4.8 | 13 |
| Latvia | 32.8 | 32.3 | 31.1 | 29.6 | 29.8 | 34.3 | 32.6 | 40 |
| Lithuania | 17.1 | 16.9 | 16.9 | 16.6 | 17.9 | 20.0 | 19.7 | 23 |
| Luxembourg | 0.9 | 1.4 | 1.4 | 2.7 | 2.8 | 2.8 | 2.8 | 11 |
| Hungary | 4.4 | 4.5 | 5.1 | 5.9 | 6.6 | 8.1 | 8.7 | 13 |
| Malta | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 | 0.2 | 0.4 | 10 |
| Netherlands | 1.9 | 2.3 | 2.7 | 3.1 | 3.4 | 4.1 | 3.8 | 14 |
| Austria | 22.9 | 25.0 | 26.6 | 28.9 | 29.2 | 31.0 | 30.1 | 34 |
| Poland | 7.0 | 7.0 | 7.0 | 7.0 | 7.9 | 8.9 | 9.4 | 15 |
| Portugal | 19.2 | 19.6 | 20.8 | 22.0 | 23.0 | 24.6 | 24.6 | 31 |
| Romania | 16.8 | 17.6 | 17.1 | 18.3 | 20.3 | 22.4 | 23.4 | 24 |
| Slovenia | 16.2 | 16.0 | 15.5 | 15.6 | 15.1 | 18.9 | 19.8 | 25 |
| Slovakia | 6.1 | 6.2 | 6.6 | 8.2 | 8.4 | 10.4 | 9.0 | 14 |
| Finland | 29.1 | 28.7 | 29.9 | 29.5 | 31.1 | 31.1 | 32.2 | 38 |
| Sweden | 38.7 | 40.6 | 42.7 | 44.2 | 45.2 | 48.1 | 47.9 | 49 |
| United Kingdom | 1.1 | 1.3 | 1.5 | 1.8 | 2.3 | 2.9 | 3.2 | 15 |
| Norway | 58.4 | 60.1 | 60.6 | 60.5 | 62.0 | 66.1 | 61.1 | 67.5 |
| Croatia | 15.2 | 14.1 | 13.8 | 12.4 | 12.2 | 13.2 | 14.6 | 20 |

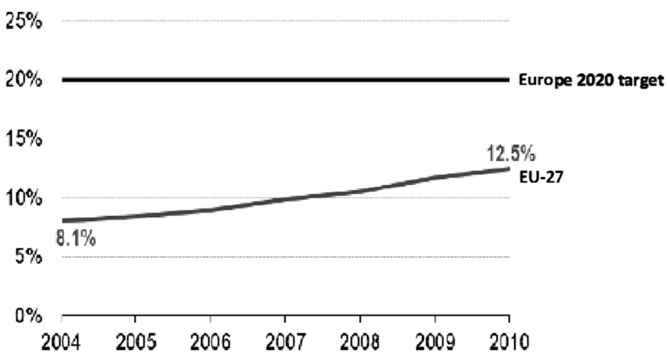


**Fig. 1.** Percentage of consumption from renewable energy sources (2004–2010).

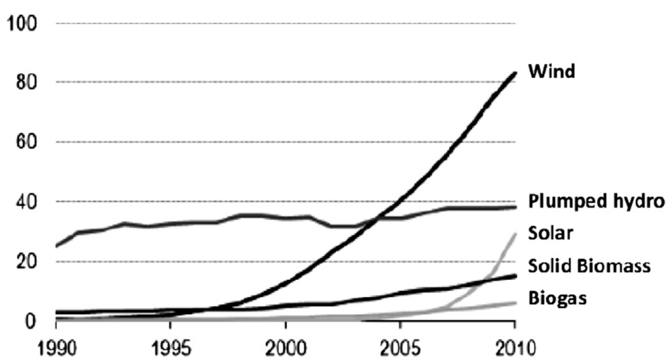


**Fig. 2.** Renewable energy production capacity (in gigawatts) by energy type in the EU. (1990–2010).

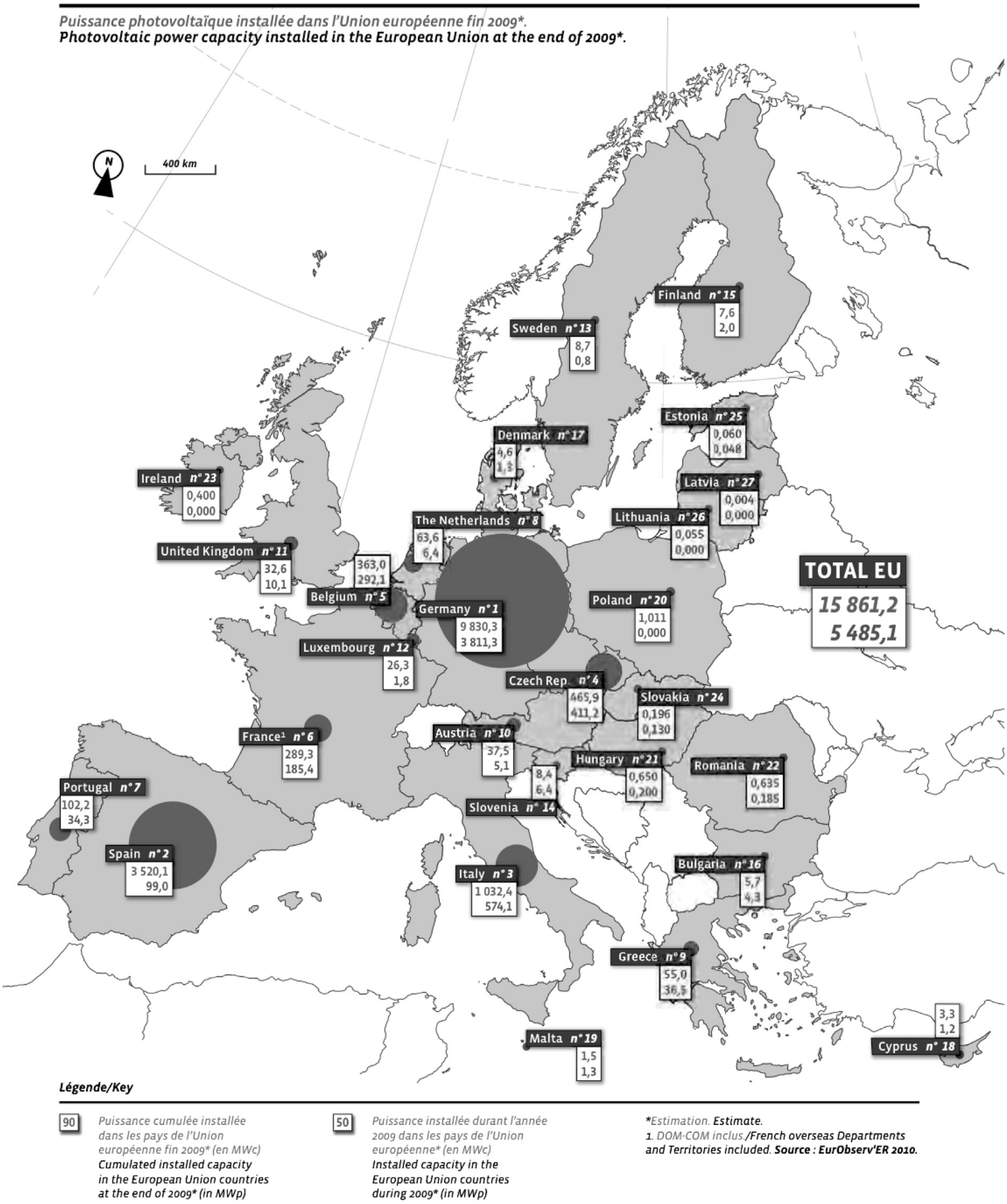


**Fig. 3.** Photovoltaic capacity installed in the EU at the end of 2009 (Source: EurObserv'ER).

## 2. Methodology

The study of scientific production is based on the records included in the database of Web of Science (Science Citation Index, Social Science Citation Index and the Proceedings databases) accessible through the Web of Knowledge [16]. The period analyzed covers 1995 to 2009 and all documents containing an "Address" including at least one Spanish or German institution are collected.

The thematic delimitation was discussed with renewable energy experts [6]. We designed a search strategy to identify research publications in areas related to "Renewable energy generation", which includes the subfields of "Renewable Energy", "Wind Power", "Solar Energy", "Geothermal Energy" and "Wave (Marine/Ocean) Energy". The following search strategy was used for collecting the documents on solar energy in the Science Citation Index Expanded part of the Web of Science:

**Table 2**
Photovoltaic power per capita in the EU (Wp = Watts peak).

| Country | Wp/inhab. |
|---|---|
| **Germany** | **120.2** |
| **Spain** | **76.4** |
| Luxembourg | 52.4 |
| Czech Rep | 44.3 |
| Belgium | 33.5 |
| Italy | 17.1 |
| Portugal | 9.6 |
| Greece | 4.9 |
| Austria | 4.5 |
| France | 4.5 |
| Cyprus | 4.2 |
| Slovenia | 4.1 |
| Netherlands | 3.8 |
| Malta | 3.7 |
| Finland | 1.4 |
| Sweden | 0.9 |
| Denmark | 0.8 |
| Bulgaria | 0.8 |
| United Kingdom | 0.5 |
| Ireland | 0.1 |
| Hungary | 0.1 |
| Slovakia | 0 |
| Estonia | 0 |
| Romania | 0 |
| Poland | 0 |
| Lithuania | 0 |
| Latvia | 0 |
| **Total EU-27** | **31,6** |

Source: EurObserv'ER 2010

*TS=("solar energy*" OR "solar radiation" OR "solar cell*" OR "solar photovoltaic*" OR "solar power" OR "solar heat*" OR "solar plant*" OR "solar concentrate*" OR "solar thermal" OR "solar collect*" OR "solar technolog*") AND PY=(1995–2009)*
*Refined by: Document Type=(ARTICLE OR PROCEEDINGS PAPER OR REVIEW) AND [excluding] Web of Science Categories=(HORTICULTURE OR PLANT SCIENCES OR FORESTRY)*

The records retrieved were downloaded and processed in Perl, with the goal of treating the text and insert records into a relational MySQL database. Institutional name forms were cleaned up post retrieval; country names as well as topical descriptors are controlled at indexing time in the Web of Science (WoS) database.

We have obtained a series of one-dimensional and multidimensional indicators to achieve the proposed analysis objectives:

- Global Scientific Production about renewable energy in WoS.
- Scientific Production on solar energy in Spain and Germany during the period 1995–2009.
- Main topics of publications on solar energy and their relationships (both countries)
- Central Sources of publications on solar energy (both countries)
- Central research Institutions on solar energy (both countries)
- International Scientific Collaboration on solar energy research in percentage of total national publication volume

## 3. Results

Below we present the results of our analysis of the overall present situation of research on renewable energies, the scientific production in solar energy in Spain and Germany as well as the relation between solar energy research and energy production. The publication sources and topics are also analyzed along with the predominant institutions and patterns of international collaboration.

### 3.1. Present situation of research on renewable energies 1995–2009

Table 4 shows the global evolution of research in renewable energy included in WoS 1995–2009. The documents have been grouped according to the main renewable energy types (wind, solar, geo-thermal and wave) and into three time periods. They consist of research and review articles published in journals and conference proceedings papers; meeting abstracts as well as editorial materials are excluded from the analyses. It should be noted that there is some overlap between the documents considered in Table 4 because a publication may refer to one or more of renewable energy types in which the results are broken down. This overlap ranges in the three periods analyzed between 4% and 7%.

The table demonstrates how renewable energy production has grown significantly since the first study period (1995–1999), especially in the case of wind and solar energies. This growth can be explained by the significant renewable energy penetration in academia and research, due to societal recognition and development and promotion policies that have been carried out in different

**Table 3**
Supply, transformation, consumption – renewables and wastes (total, solar heat, biomass, geothermal, wastes) – annual data (Tonne of Oil Equivalent – TOE).

| Time\GEO | Solar energy | | | Renewable energies | | |
|---|---|---|---|---|---|---|
| | European Union (27 countries) | Germany (including former GDR from 1991) | Spain | European Union (27 countries) | Germany (including former GDR from 1991) | Spain |
| 1995 | 282 | 38 | 26 | 82631 | 6095 | 5510 |
| 1996 | 305 | 48 | 26 | 86139 | 6278 | 6986 |
| 1997 | 329 | 61 | 24 | 89754 | 7228 | 6646 |
| 1998 | 362 | 77 | 27 | 92353 | 7795 | 6783 |
| 1999 | 391 | 92 | 29 | 92681 | 8069 | 6031 |
| 2000 | 430 | 115 | 33 | 96650 | 9094 | 6928 |
| 2001 | 482 | 150 | 38 | 99637 | 9747 | 8169 |
| 2002 | 533 | 184 | 43 | 97505 | 10898 | 7040 |
| 2003 | 594 | 216 | 48 | 103906 | 12969 | 9245 |
| 2004 | 683 | 262 | 58 | 111843 | 15780 | 8866 |
| 2005 | 806 | 353 | 65 | 115891 | 17502 | 8353 |
| 2006 | 988 | 472 | 83 | 123507 | 21678 | 9158 |
| 2007 | 1264 | 580 | 137 | 134057 | 27964 | 9996 |
| 2008 | 1730 | 735 | 352 | 142037 | 27968 | 10334 |
| 2009 | 2498 | 973 | 711 | 148776 | 27777 | 12158 |
| 2010 | 3720 | 1452 | 1035 | 166844 | 32746 | 14503 |
| 2011 | 6062 | 2218 | 1348 | 162559 | 31291 | 13762 |

**Table 4**
Global publication, citation and impact trends 1995-2009, cited 1995-2011 with up to 7-year citation windows, Renewable Energy Generation research.

| | | 1995–1999 | 2000–2004 | 2005–2009 | Total 1995–2009 |
|---|---|---|---|---|---|
| Renewable energy (general) | Publ. | 1583 | 2197 | 7104 | 10884 |
| | Cits. | 2296 | 6947 | 52145 | 61388 |
| | c/p | 1.5 | 3.2 | 7.3 | 5.6 |
| Solar Energy | Publ. | 8622 | 12619 | 26585 | 47826 |
| | Cits. | 38310 | 92578 | 369890 | 500778 |
| | c/p | 4.4 | 7.3 | 13.9 | 10.5 |
| Wind Power | Publ. | 1107 | 1650 | 7018 | 9775 |
| | Cits. | 1518 | 4571 | 30693 | 36782 |
| | c/p | 1.4 | 2.8 | 4.4 | 3.8 |
| Geo-thermal | Publ. | 1743 | 1875 | 2615 | 6233 |
| | Cits. | 7028 | 10535 | 18281 | 35844 |
| | c/p | 4.0 | 5.6 | 7.0 | 5.8 |
| Wave Energy | Publ. | 770 | 895 | 1444 | 3109 |
| | Cits. | 3222 | 3673 | 6859 | 13754 |
| | c/p | 4.2 | 4.1 | 4.8 | 4.4 |
| Total | Publ. | 13825 | 19236 | 44766 | 77827 |
| | Cits. | 52374 | 118304 | 477868 | 648546 |
| | c/p | 3.8 | 6.2 | 10.7 | 8.3 |

countries. Moreover, solar energy publications demonstrate significantly higher citation impact, than other groups of renewable energy areas: the citations per paper on solar energy are 10.5, whilst in wind power it is 3.8, geo-thermal is 5.8 and in wave energy 4.4 as shown in Table 4 [6].

### 3.2. Scientific production on solar energy in Spain and Germany

In the period studied, the scientific production on solar energy in all 27 EU countries amounted to 11672 publications, 5136 of which have at least one author with a German affiliation, and 1813 having at least one author with an affiliation at a Spanish institution.

Fig. 4 shows index numbers starting in 1995 for the scientific production on solar energy of Spain and Germany, showing a similar distribution in both countries, with a significant growth in recent years in the case of Spain. The production of Spain has a higher cumulative average growth (26.7%) followed by Germany (26.1%) and EU-27 (16.9%).

Table 5 shows the distribution of solar energy production by countries and the percentage of world production they represent in this area. Germany appears in the first two periods as the second country (behind USA); during the last period (2005–2009) Germany drops to fourth place, decreasing its world share from 11.3% to 13% in the first and second periods to 9.3% in the third. In the case of Spain the situation is the opposite. The highest share of publications is found in the third period (4.0% versus 2.8% and 3.7% of the previous periods). Spain raises its ranking position on the list of countries to be ranked seventh in the world and second among the European countries.

Fig. 5 shows the evolution of five selected countries with different growth rates. Thus, countries with higher growth, especially in the last period, are USA, China and to a lesser degree Spain, while Japan and Germany maintains a much more stable linear growth. For China the recent growth is in particular caused by an increased production of conference proceedings papers on solar energy.

### 3.3. Relation between solar energy research and energy production

Fig. 6 shows the evolution of scientific publications on solar energy in Spain and Germany as well as solar energy production in both countries. It is noticeable that while the number of scientific publications grows linearly, energy production grows exponentially in both countries.

Fig. 7 shows the combined data on energy production and scientific publications grouped in two different periods for each country (1995–2001 and 2002–2009). We observe that the former period corresponds in each case to a linear growth and the second corresponds to exponential growth for energy production.

The coefficient of determination obtained (Table 6) shows very high values, being higher in the second period for both countries, corresponding to the recent exponential growth phase of energy production. These data also indicate that in this period the scientific activity also experiences greater momentum and the growth model is closer to exponential than compared to the linear development in the previous period for Germany.

Although productivity in Germany is significantly higher than that of Spain, these differences are reduced over the time period

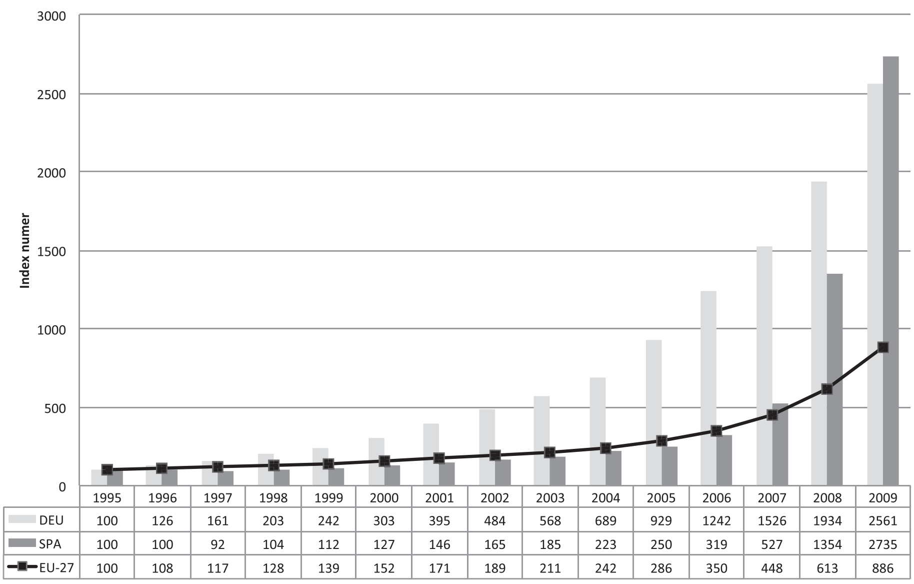


**Fig. 4.** Scientific production of solar energy EU27, Germany and Spain (Index numbers).

**Table 5**
Top-20 countries producing research on solar energy research (1995–2009). German and Spanish rank position in bold.

| 1995–1999 | | | 2000–2004 | | | 2005–2009 | | |
|---|---|---|---|---|---|---|---|---|
| Country | Publ. | % | Country | Publ. | % | Country | Publ. | % |
| USA | 2526 | 28.8 | USA | 3021 | 23.8 | USA | 5990 | 22.3 |
| **Germany** | **988** | **11.3** | **Germany** | **1660** | 13.0 | China | 3524 | 13.1 |
| Japan | 836 | 9.5 | Japan | 1635 | 12.9 | Japan | 2627 | 9.8 |
| India | 483 | 5.5 | China | 635 | 5.0 | **Germany** | **2488** | **9.3** |
| England | 437 | 5.0 | England | 599 | 4.7 | South Korea | 1238 | 4.6 |
| France | 402 | 4.6 | France | 560 | 4.4 | India | 1215 | 4.5 |
| Australia | 329 | 3.7 | India | 506 | 4.0 | **Spain** | **1086** | **4.0** |
| **Spain** | **250** | **2.8** | **Spain** | **477** | **3.7** | France | 1068 | 4.0 |
| Canada | 244 | 2.8 | Netherlands | 458 | 3.6 | England | 1025 | 3.8 |
| Italy | 241 | 2.7 | Australia | 438 | 3.4 | Italy | 798 | 3.0 |
| Russia | 239 | 2.7 | Italy | 375 | 2.9 | Taiwan | 787 | 2.9 |
| Switzerland | 210 | 2.4 | Switzerland | 334 | 2.6 | Australia | 698 | 2.6 |
| Israel | 199 | 2.3 | Canada | 295 | 2.3 | Netherlands | 683 | 2.5 |
| Netherlands | 165 | 1.9 | Russia | 278 | 2.2 | Switzerland | 672 | 2.5 |
| China | 144 | 1.6 | Sweden | 276 | 2.2 | Canada | 635 | 2.4 |
| Sweden | 123 | 1.4 | South Korea | 252 | 2 | Sweden | 430 | 1.6 |
| Mexico | 117 | 1.3 | Israel | 223 | 1.7 | Turkey | 421 | 1.6 |
| Greece | 103 | 1.17 | Brazil | 194 | 1.5 | Russia | 368 | 1.4 |
| Egypt | 94 | 1.1 | Mexico | 188 | 1.5 | Brazil | 345 | 1.3 |
| Turkey | 90 | 1.0 | Belgium | 181 | 1.4 | Greece | 331 | 1.2 |
| Total countries | 128 | | Total countries | 130 | | Total countries | 143 | |
| Total docs. | 8768 | | Total docs. | 12717 | | Total docs. | 26858 | |

analyzed. In the first period Germany publishes almost 4 times more than Spain, but in the second this difference is reduced to 3.5 times, and in the third to 2.3. Analyzing the citedness, i.e. the share of publications receiving one or more citations, we see that this is quite stable over time and of a similar, and high, level for both Germany and Spain (see Table 7).

### 3.4. Publication topics

Fig. 8 shows the most published topics by Spanish and German institutions. This representation is based on a dendrogram constructed using cluster analysis techniques following Ward's method [17], from the keywords of the publications themselves. Due to the volume of keywords we have excluded keywords that appear 40 times or less to facilitate the presentation.

In the distribution of the dendrogram two groups of topics are clearly distinguishable. To the left of the figure, the group is composed of three large clusters, in which the keywords relate to solar cells and collection techniques of this type of energy. Furthermore, in the right group, much more cohesive, are located topics relative to the storage of the energy captured by the solar cells - more related to the topic of materials physics.

We have also analyzed the WoS categories of publications retrieved as "solar energy" by our search strategy (see Section 2). Table 8 shows the Top-10 categories in each of the two countries and their percentage of total documents. There is a match between Spain and Germany in the order and preference of the five core subjects (Physics, Material Science, Energy & Fuels, Engineering and Chemistry) although the concentration of papers on Physics and Material Science is higher in the case of Germany.

Comparing the publication profiles of solar energy research in Spain and Germany with the EU-27 countries as a whole they are overall quite similar, focusing the main research efforts in the same subjects (Fig. 9). We see that Germany has a larger focus on research in the Physics and Materials Science aspects of solar research, while Spain focusses on a broader set of subjects.

### 3.5. Publication sources

Table 9 shows the top 10 sources of publications (journals and conferences) on solar energy of the two countries analyzed. The table shows the matches and differences in publication profiles in both countries; for instance, 50% of the journals are the same in two countries. However, for Germany we also observe a tendency to publish in proceedings with two of the ten top sources being

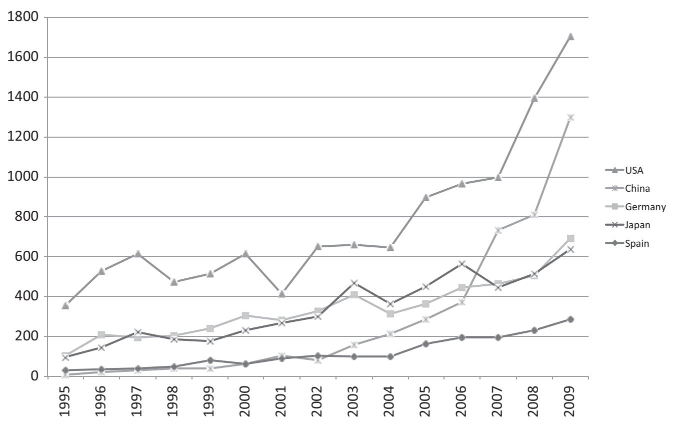


**Fig. 5.** Research publications on solar energy in five countries 1995–2009.

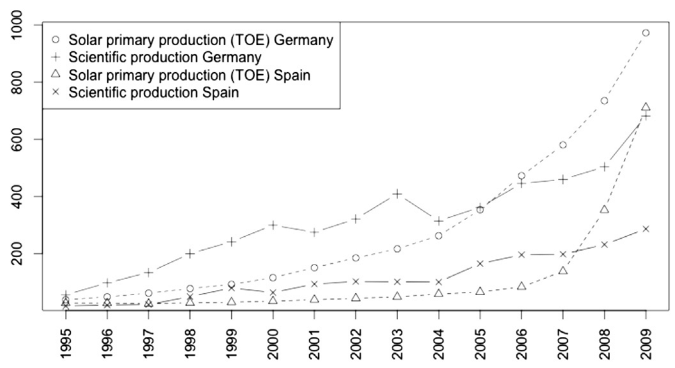


**Fig. 6.** Scientific publications and energy production on solar energy.

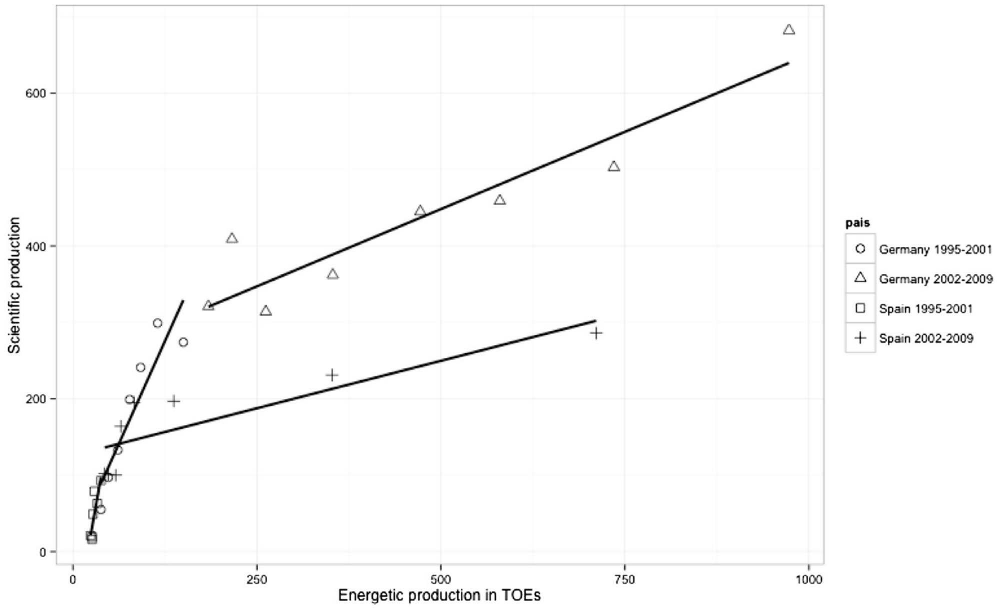


**Fig. 7.** Relationship between scientific production and energy production on solar energy in two periods (1995–2001 and 2002–2009).

conference proceedings, while in Spain all the main publications are journals.

### 3.6. Institutions

The most productive institutions in both countries in solar energy are shown in Table 10. Both in Spain and in Germany the universities have a strong scientific activity in this research field.

### 3.7. Patterns of international collaboration

In almost all the periods analyzed in the two countries, international collaboration shows similar trends in most of the indicators (Table 11, Figs. 10 and 11). However, the percentage of international collaborative papers presents different trends in the last period during which Spain decreased and Germany continued to increase their international collaboration efforts.

The profile of international collaboration in Table 12 shows that the major collaborators for Spain and Germany are identical. The intense direct collaboration observed between both countries is very important; in the case of Spain the first country in collaborative publications is Germany, while for Germany the collaboration with Spain occupied the second place on par with France.

## 4. Discussion

The production and consumption of energy is increasing in all countries, but this trend is further reinforced in industrialized nations, because as shown in this paper the growth is following an exponential model. This trend, far from diminishing, is expected to continue to rise, since according to the World Energy Outlook [18] in the New Policies Scenario, the world's primary energy demand is predicted to increase by 36% between 2008 and 2035, from around 12,300 Million Tons of Oil equivalent (MTOE) to over 16,700 MTOE, or by 1.2% per year on average. Most of the energy thus produced as consumed comes from fossil fuels (80%), and within these, oil is the most important one. However, this heavy reliance on one type of resources that has an expiration date and is extremely harmful to the environment shows the fragility of the current system of energy production on which the development of human activities depend. Therefore, various international agencies recommend finding alternative energy sources to eliminate problems caused by traditional sources and in turn ensure an unlimited supply at a lower cost.

Renewable energy is seen by many as the best alternative source, and many countries are devoting considerable efforts in economic development and human resources to meet its energy needs in a sustainable way and, in turn, occupy privileged positions in the research and production of technologies that insure that their business sectors maintain their competitive position in the global energy market. To this end, the EU-27 countries are making a major effort with the expected result that by 2020 at least 20% of the energy produced and consumed in the countries of the region come from renewable sources [5]. However, it should be noted that the situation across the EU countries is very different in terms of achieving this goal, since there are countries where the goal already currently is being met and even exceeded. Such is the case of the Scandinavian countries, Lithuania and Austria, while others are still far away from their goals, as in the case of United Kingdom, Ireland, The Netherlands and France [5].

Wind and solar energy are the types of renewables that demonstrate the largest growth in development and production capacity. The wind power industry has grown considerably over the past 15 years. In 1997 there were 4.8 GW of installed wind power capacity in the EU. By the end of 2011 this figure had risen to 94 GW, able to produce 204 TWh of electricity and meet 6.3% of the EU's overall electricity demand [19]. The generation of electricity from solar energy has increased 10-fold in the last 20 years, but only contributed 3% of total energy produced. Germany and Spain are

**Table 6**
Coefficient of determination between solar energy production and scientific production on solar energy.

| Country (period) | $R^2$ |
|---|---|
| GER1 (1995–2001) | 0.91467 |
| GER2 (2002–2009) | 0.93890 |
| SPA1 (1995–2001) | 0.85431 |
| SPA2 (2002–2009) | 0.85252 |


**Fig. 8.** Cluster analysis of WoS author keywords ($N > 40$) from documents on solar energy (1995–2009) (Following Ward's method, 1963).

the two EU countries that make the largest effort in the generation of this type of energy. In Spain solar energy already accounts for 9.8% of the total production of renewable energy, while in Germany it is 7.1%. The increase in production and consumption of solar energy in these two countries has been quite substantial, since from 1995 to 2011 it has increased by 58 times in Germany and by 52 times in Spain [5], notwithstanding the economic crisis.

In terms of scientific production in renewable energies a sharp increase occurs worldwide in the last period (2005–2009), with 65.3% of all documents published in this period which is threefold the number of publications published in the previous period (2000–2004). Similar results were obtained by Romo-Fernández et al. [14], which considered that the increase occurring after 2005 may be due to the entry into force in 2005 of the United Nations Framework Convention on Climate Change, as stated by Tsay [20], as well as the strong commitment by the EU promoting renewable energy research within their Framework Programs. However, we observed the volume of papers published in renewable energies in Web of Science over a similar period had a more linear increase.

The effort made in research on solar energy is higher than other renewable sources and means that 60% of the publications on renewables are on this type of energy in the period studied. Compared to the share of publications on wind power, which was 12% in renewable energy research in 1995–2009, one obtains an impression of the magnitude of the effort in solar energy research. Similarly, it is necessary to consider the impact of solar energy research on the scientific community, which dominates the whole area with 77.2% of all citations received by all publications on renewable energy. The relative impact of solar energy research (10.5 citations/doc.) is also significantly higher than those received by any other type of renewable energy (3.8 citations/doc. in wind power, or 5.8 in geo-thermal). Finally, although aggregate wind power generation in major countries exceeds that of solar energy, the total number of research papers and citations is far greater for the latter [18,21].

The scientific production of Spain and Germany in solar energy represents 51% of the total published in the EU-27 countries on this topic, with Germany contributing 37% and Spain 14%. In an international context, Germany is one of the leading countries in terms

**Table 7**
Publications and their citedness ratio on solar energy research.

| | 1995–1999 | | 2000–2004 | | 2005–2009 | |
|---|---|---|---|---|---|---|
| | Publications | Citeness | Publications | Citeness | Publications | Citeness |
| Germany | 988 | 0.83 | 1660 | 0.86 | 2488 | 0.84 |
| Spain | 250 | 0.87 | 477 | 0.88 | 1086 | 0.84 |

**Table 8**
Top-10 WoS categories (1995–2009). Note that percentages add up to more than 100% as each paper can have more than one associated category.

| Spain | | | Germany | | |
|---|---|---|---|---|---|
| WoS categories | Total docs. | % Of total docs | WoS categories | Total docs. | % Of total docs |
| Physics | 438 | 25.76 | Physics | 1876 | 43.07 |
| Materials science | 401 | 23.59 | Materials science | 1575 | 36.16 |
| Energy & fuels | 359 | 21.12 | Energy & fuels | 1024 | 23.51 |
| Engineering | 279 | 16.41 | Engineering | 592 | 13.59 |
| Chemistry | 262 | 15.41 | Chemistry | 579 | 13.29 |
| Science & technology - other topics | 86 | 5.06 | Meteorology & atmospheric sciences | 212 | 4.87 |
| Optics | 85 | 5.00 | Optics | 191 | 4.38 |
| Environmental sciences & ecology | 80 | 4.71 | Science & technology - other topics | 187 | 4.29 |
| Meteorology & atmospheric sciences | 79 | 4.65 | Astronomy & astrophysics | 117 | 2.69 |
| Marine & freshwater biology | 46 | 2.71 | Polymer science | 97 | 2.23 |

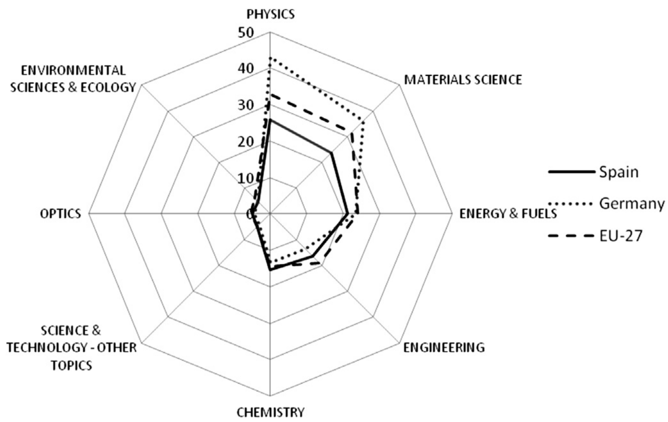


**Fig. 9.** Distribution in percent of WoS categories on Solar Energy research for Spain, Germany and EU-27 (1995–2009).

**Table 10**
Most productive Spanish and German institutions on solar energy 1995–2009.

| Spain | | Germany | |
|---|---|---|---|
| **Institution** | **Docs.** | **Institution** | **Docs.** |
| Univ Politecn Madrid | 189 | Hahn Meitner Inst Berlin GMBH | 514 |
| Ciemat | 178 | Fraunhofer Inst Solar Energy Syst | 349 |
| CSIC | 163 | Univ Stuttgart | 284 |
| Univ Barcelona | 99 | Forschungszentrum Julich | 229 |
| Univ Autonoma Madrid | 82 | Univ Erlangen Nurnberg | 181 |
| Univ Jaume I | 75 | Univ Konstanz | 128 |
| Univ Malaga | 67 | Univ Bayreuth | 88 |
| Univ Almeria | 64 | Univ Jena | 84 |
| Univ Valencia | 50 | Univ Bremen | 79 |
| Univ La Laguna | 44 | Univ Wurzburg | 78 |
| Univ Complutense Madrid | 44 | Univ Oldenburg | 77 |

of number of publications, however, its influence is decreasing compared to countries such as Japan or China. Specifically the latter moves into second place in the world in the period 2005-2009, which shows the significant efforts being made to achieve production that place China among the world leaders in this field of science, although the main part of this production are conference papers.

When comparing the scientific production with the primary energy production from solar power we find an initial linear growth followed by a strong exponential growth in both countries, especially as regards energy production. This significant increase in the second period is most likely related to the large increase in funding for renewable energy worldwide which has grown sevenfold over the period 2004–2008, from $ 17 billion to $ 126 billion (IEA, 2010). In the paper we show that the funding effort being made by countries in the European Union with its framework programs [5], as well as China, Korea, Japan, etc., is responding to the energy needs, multiplying the production of renewable energy [22,18]. This has led to further research producing a larger number of scientific publications in these countries in both periods analyzed.

Regarding research topics, there is a great similarity in the profiles of Germany and Spain for the top-10 topics. However, the high concentration of papers observed in the German institutions in the first two topics (Physics and Material Science) is noteworthy as it represents almost 80% of the publications, while in the case of Spain this percentage is only 60%. Comparing the German profile with the EU-27 countries as a whole, the topics of greatest interest are the same, but the percentages of Physics and Material Science are still much higher in the German case. The high number of German publications on these two topics would mean greater industrial use of research generated, because in general, the development of new solar cell technology and applied devices, partly justify the large number of publications related to Materials Sciences [23].

The main sources of publication present some differences in the two countries. Although 50% of the sources are the same journals in both countries Germany also have several publications appearing in proceedings, while for Spain all the top 10 publications sources are journals.

The most productive institutions in both countries are universities, companies have a low representation. Obviously, this result does not mean that companies do not investigate solar energy, but it rather indicates that the primary purpose of companies is achieving competitive advantage in the market based on the development of innovative products or processes instead of publishing results through scientific channels.

Scientific collaboration on research in solar energy is another aspect that should be highlighted. Collaboration is nowadays essential for the development of science and technology, and research increasingly requires financial and human efforts, involving knowledge from different specialties. In this sense, the international science and technology collaboration is an efficient method of combining the advantages of multiple participants and of increasing the output of research and development [22]. In solar energy there is strong international collaboration; in general it is estimated that on average it reaches a percentage of 27.3% [13]. We found that the average collaboration by the German and Spanish institutions is slightly higher than this percentage (33.7% for

**Table 9**
Top-10 sources of publications WoS (1995–2009).

| Spain | | Germany | |
|---|---|---|---|
| Source | Docs. | Source | Docs. |
| Solar energy | 89 | Thin solid films | 427 |
| Thin solid films | 84 | Solar energy materials and solar cells | 290 |
| Solar energy materials and solar cells | 73 | Applied physics letters | 185 |
| Progress in photovoltaics | 39 | Journal of applied physics | 179 |
| Journal of applied physics | 35 | Progress in photovoltaics | 167 |
| Journal of solar energy engineering-transactions of the ASME | 34 | Solar energy | 111 |
| Renewable energy | 34 | Proceedings of 3rd world conference on photovoltaic energy conversion, vols a-c | 92 |
| Journal of physical chemistry B | 27 | Conference record of the 2006 IEEE 4 th world conference on photovoltaic energy conversion, vols 1 and 2 | 65 |
| Energy conversion and management | 25 | Journal of crystal growth | 59 |
| Desalination | 22 | Journal of geophysical research-atmospheres | 52 |

**Table 11**
International collaboration patterns.

| | Germany | | | Spain | | |
|---|---|---|---|---|---|---|
| | 1995–1999 | 2000–2004 | 2005–2009 | 1995–1999 | 2000–2004 | 2005–2009 |
| International Col. | 25.9% | 36.2% | 39.0% | 27.7% | 38.1% | 35.9% |
| No. of countries/doc | 1.36 | 1.53 | 1.57 | 1.32 | 1.52 | 1.55 |
| No. of institutions/doc | 2.02 | 2.24 | 2.61 | 2.04 | 2.31 | 2.89 |
| No. of authors/doc | 4.96 | 5.19 | 6.02 | 4.52 | 5.05 | 6.17 |

Germany and 33.9% for Spain), but these values are very far away from those found in other European countries like UK, France and Switzerland, where more than half of the articles published in solar energy research were published in international collaboration. These values are significantly higher than those observed in other countries such as the USA (28%), China (20.9%) and Japan (21.6%) [13].

Likewise, the number of countries collaborating with Spain and Germany in solar energy follows a very similar pattern in both countries, with increased collaboration in all periods analyzed, and with the final increase higher for Spain (17%) than for Germany (15%). Also the number of institutions collaborating in research increases in the 3 periods analyzed in the two countries, and in the last period this increase is also higher in Spain than in Germany. A similar situation to the Spanish case has been observed by Dong et al. [13] in their bibliometric study of solar energy where international collaboration decreases, while the number of institutions involved in the research increases.

Something similar happens with the average number of authors per document. Spanish institutions are reaching higher values in the last period (6.2 authors/doc.). However, in both countries this indicator shows very high average values during the entire period (5.4 authors/doc. in Germany and 5.2 authors/doc. in Spain), as well as a significant increase of the number of authors in the whole period, 21.5% in Germany and 36.5% in Spain. Globally, the collaboration among authors in solar energy is significantly lower than that of the two countries analyzed, as it shows an average value for the same period of 3.9 Authors/doc [13].

The international collaboration profile of Germany and Spain in solar energy is very similar, as they not only share 6 of the 10 countries with whom they collaborate most, but in the case of Germany, Spain is the second most collaborating country behind USA. For Spain Germany is the first chosen country for collaboration, while USA holds the second position.

The collaboration phenomena by Germany and Spain observed in this work, where USA and EU countries are the most frequent collaborators, is very similar to that observed by other authors [22]. For example, in the case of China collaboration focuses on USA, EU countries such as France, UK, Italy, Sweden, and other countries outside the EU such as Japan. The strong collaboration that occurs in Germany and Spain with these countries can be explained by the aid they have received the European institutions from different EU framework programs (FP5, FP6) for research grants and fostering collaboration with Asian countries like China [21]. Of course, without the support of the EU, the situation of solar energy would most likely have been quite different, with less competition.

## 5. Conclusions

Some of the conclusions from the results of this work are related to the effort made by a large number of EU countries to adapt to a new friendly environment and sustainable energy production, since many of them have already reached the target of the European Commission to produce 20% of the energy consumed from renewable sources.

Solar energy, despite not being the biggest contributor to the production of energy from renewable sources in the EU, has increased more than 20 times in the last 15 years. Solar energy is also the most active field of scientific production and the one with greater impact in published research, attracting nearly 80% of the citations of all publications of renewable energy.

The two European countries with the greatest installed capacity and scientific production in solar energy are Germany and Spain. In both countries, the growth in production and demand for solar energy is completely different from the research publications on this topic. In the first case, energy production shows an exponential increase due to growing energy needs of today's society, while for research productivity this growth is linear and would be affected, in

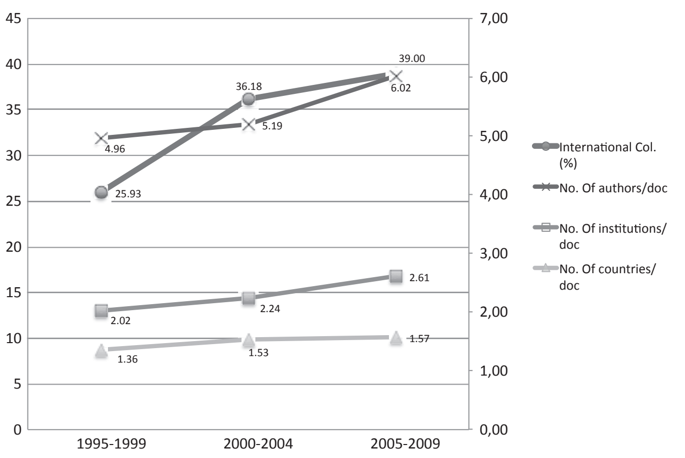


**Fig. 10.** Patterns of German collaboration.

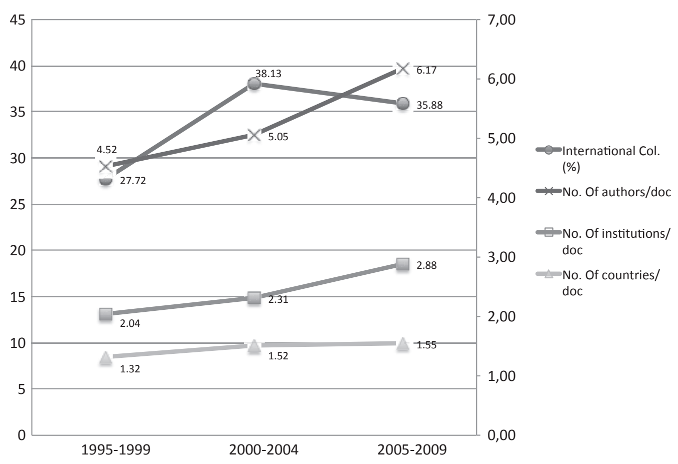


**Fig. 11.** Patterns of Spanish collaboration.

**Table 12**
Countries (≥20 documents) collaborating with Spain and Germany in research on Solar energy 1995–2009. (WoS, 2013).

| Spain | | Germany | |
|---|---|---|---|
| No. countries | No. Docs | No. countries | No. docs |
| 61 | 1716 | 81 | 4793 |
| Germany | 175 | USA | 411 |
| Usa | 103 | France | 175 |
| France | 78 | Spain | 175 |
| England | 67 | England | 169 |
| Italy | 47 | Switzerland | 155 |
| Switzerland | 44 | Netherlands | 153 |
| Portugal | 37 | Japan | 132 |
| Mexico | 29 | Australia | 114 |
| Netherlands | 26 | Italy | 104 |
| Israel | 24 | Russia | 98 |
| Sweden | 23 | Austria | 93 |
| Austria | 20 | Sweden | 71 |
| | | Israel | 70 |
| | | China | 62 |
| | | India | 53 |
| | | Belgium | 49 |
| | | Canada | 48 |
| | | Greece | 44 |
| | | Brazil | 38 |
| | | Poland | 38 |
| | | Czech Republic | 31 |
| | | Finland | 28 |
| | | Norway | 25 |
| | | Argentina | 24 |
| | | Portugal | 24 |
| | | Bulgaria | 23 |
| | | Denmark | 23 |
| | | South africa | 21 |

part, by the ability of countries to increase funding for research groups working in this topic.

In the international arena an interesting result is the observation that the evolution of scientific production in certain countries such as China demonstrates a significant increase in scientific productivity. Also Germany and Spain increase their production, but do so at a more moderate pace than some Asian countries.

It should also be pointed out that there are great similarities in both countries regarding research topics and the type of institutions with the highest research activity. In the first case Physics and Materials Science account for the majority of publications in both countries. This profile matches the one shown in EU-27 as a whole. In terms of institutions, the universities are the main producers. The lack of companies among the top producers reflects their lack of interest in the publication of their research and development effort.

More than a third of the papers published by Spain and Germany are made in international collaboration. This proportion is higher than that observed globally or in other countries with great research efforts in solar energy such as USA, China and Japan. Finally, the intense scientific collaboration that occurs between German and Spanish institutions in solar energy is noteworthy – with Germany being the top collaborator for Spain, and Spain the second most occurring collaborator for Germany.

## Acknowledgments

This research was funded by the Spanish Ministry of Economy and Competitiveness under the project CSO2010-21759-C02-01 titled "Análisis de las capacidades científicas y tecnológicas de la eco-economía en España a partir de indicadores cuantitativos y cualitativos de I + D + i, and by Carlos III University of Madrid-Banco de Santander Chairs of Excellence Program for 2011/2012 academic year and also by Carlos III University of Madrid, Programme of Doctoral Mobility for 2011/2012 academic year.

## Appendix A. Retrieval profiles

**Block A: Renewable Energy Generation**
**Renewable Energy Sub-field:**

# 2 7,104 TS = ("renew* energ*" OR "alternative energ*" OR "green energ*" OR "energy polic*") AND PY = (2005–2009)

Refined by: Document Type = (ARTICLE OR PROCEEDINGS PAPER OR REVIEW)

Databases = SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH Timespan = 1995–2011.

Lemmatization = On

**Wind Power sub-field:**

# 5 7,018 TS=("wind power" OR "wind turbine*" OR "wind energy*" OR "wind farm*" OR "wind generation" OR "wind systems") AND PY = (2005–2009)

Refined by: Document Type = (PROCEEDINGS PAPER OR ARTICLE OR REVIEW) AND [excluding] Web of Science Categories=(ASTRONOMY ASTROPHYSICS)

Databases = SCI-EXPANDED, SSCI, CPCI–S, CPCI-SSH Timespan = 1995–2011

Lemmatization = On

**Solar Energy sub-field:**

# 8 26,585 TS = ("solar energy*" OR "solar radiation" OR "solar cell*" OR "solar photovoltaic*" OR "solar power" OR "solar heat*" OR "solar plant*" OR "solar concentrate*" OR "solar thermal" OR "solar collect*" OR "solar technolog*") AND PY = (2005–2009)

Refined by: Document Type = (ARTICLE OR PROCEEDINGS PAPER OR REVIEW) AND [excluding] Web of Science Categories = (HORTICULTURE OR PLANT SCIENCES OR FORESTRY)

Databases = SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH Timespan = 1995–2011.

Lemmatization = On

**Geothermal Energy sub-field:**

# 10 2,615 TS = geothermal AND PY=(2005–2009)

Refined by: Document Type=(ARTICLE OR PROCEEDINGS PAPER OR REVIEW)

Databases = SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH Timespan = 1995–2011.

Lemmatization = On

**Ocean Wave Power Energy sub-field:**

# 14 1554 TS = ("wave power" OR "wave energy*" OR "wave convers*" OR "marine energy" OR "ocean energy") AND PY = (2005–2009)

Refined by: Document Type = (ARTICLE OR PROCEEDINGS PAPER OR REVIEW) AND [excluding] Web of Science Categor ies = (ASTRONOMY ASTROPHYSICS OR REMOTE SENSING OR PHYSICS APPLIED OR PHYSICS FLUIDS PLASMAS OR NANOSCIENCE NANOTECHNOLOGY OR OPTICS OR CLINICAL NEUROLOGY OR MATERIALS SCIENCE COATINGS FILMS OR TELECOMMUNICATIONS OR ACOUSTICS OR CHEMISTRY PHYSICAL OR PHYSICS CONDENSED MATTER OR RADIOLOGY NUCLEAR MEDICINE MEDICAL IMAGING OR PHYSICS PARTICLES FIELDS) AND [excluding] Web of Science Categories=(HEMATOLOGY OR IMAGING SCIENCE PHOTOGRAPHIC TECHNOLOGY OR ENGINEERING BIOMEDICAL OR TOXICOLOGY OR BIOLOGY OR BIOPHYSICS OR CRITICAL CARE MEDICINE OR PHYSIOLOGY OR CARDIAC CARDIOVASCULAR SYSTEMS OR FORESTRY OR GASTROENTEROLOGY HEPATOLOGY OR ENGINEERING AEROSPACE OR HORTICULTURE OR MEDICINE GENERAL INTERNAL OR PERIPHERAL VASCULAR DISEASE OR MEDICINE RESEARCH EXPERIMENTAL OR UROLOGY NEPHROLOGY OR PHARMACOLOGY PHARMACY OR ELECTROCHEMISTRY OR PSYCHIATRY OR REHABILITATION OR NEUROSCIENCES OR SPECTROSCOPY)

Databases = SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH Timespan = =1995–2011

Lemmatization = On

*Topics to be excluded from* "*Ocean Wave Power Energy*" *sub-field:*# 15 414,737 TS=("micro wave*" OR microwave* OR electromagnetic OR laser* OR quantum OR radio) AND PY = (2005–2009)

Databases = SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH Timespan = 1995–2011

Lemmatization = On

**Ocean Wave Power Energy sub-field - final:**

# 16 1,444 #14 NOT #15

***Renewable Energy Generation Block:***

# 17 41,797 #16 OR #10 OR #8 OR #5 OR #2

## References


[1] Walz R, Schleich J, Ragwitz M. Regulation, innovation and wind power technologies—an empirical analysis for OECD countries. In: DIME final conference in Maastricht, The Netherlands; 2011 (6–8 April).

[2] Europea Unión. Directiva 2009/28/CE del Parlamento Europeo y del Consejo de 23 de abril de 2009 relativa al fomento del uso de energía procedente de fuentes renovables. Diario Oficial de la Unión Europea, 5 de junio de 2009 2009;L 140:16–62.

[3] OECD. Towards green growth. Paris: OECD; 2011.

[4] OECD. Greening development: enhancing capacity for environmental management and governance. Paris: OECD; 2012.

[5] Eurostat. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/ [accessed Nov 2012].

[6] Sanz-Casado E, García-Zorita JC, Serrano-López AE, Larsen B, Ingwersen P. Renewable energy research 1995–2009: a case study of wind power research in EU, Spain, Germany and Denmark. Scientometrics 2013;95(1):197–224.

[7] EurObserv'ER. Photovoltaic barometer – a study carried out by EurObserv'ER. SYSTÈMES SOLAIRES le journal du photovoltaïque 2010;3:128–60. Available at: http://www.eurobserv-er.org/pdf/baro196.pdf.

[8] Garg KC, Sharma P. Solar power research: a scientometric study of world literature. Scientometrics 1991;21(2):147–57.

[9] Tijssen RJW. A quantitative assessment of interdisciplinary structure in science and technology: co-classification analysis of energy research. Res Policy 1992;21(1):27–44.

[10] Celiktas MS, Sevgili T, Kocar G. A snapshot of renewable energy research in Turkey. Renew Energy 2009;34(6):1479–86.

[11] Goel M, Maurya V, Desai PN. R&D indicators and mapping of solar energy research output in India. J Sci Res 2013;2(1):52–8.

[12] Dutt B, Nikam K. Solar cell research in India: a scientometric profile. Ann Lib Inf Stu 2013;60(2):115–27.

[13] Dong B, Xu G, Luo X, Cai Y, Gao W. A bibliometric analysis of solar power research from 1991 to 2010. Scientometrics 2012;93:1101–17.

[14] Romo-Fernández LM, López-Pujalte C, Guerrero Bote VP, Moya-Anegón F. Analysis of Europe's scientific production on renewable energies. Renew Energy 2011;36:2529–37.

[15] Romo-Fernández LM, Guerrero Bote VP, Moya-Anegón F. Análisis de la producción científica española en energías renovables, sostenibilidad y medio ambiente (Scopus, 2003–2009) en el contexto mundial. Investig Bibliotecol 2013;27(60):125–51.

[16] Web of Science. Available at: http://thomsonreuters.com/products_services/science/science_products/a-z/web_of_science/ [accessed Nov 2012].

[17] Ward JH. Hierarchical grouping to optimize an objective function. J Am Stat Assoc 1963;(301):236–44.

[18] International Energy Agency (IEA). World Energy Outlook 2010. Paris: International Energy Agency (IEA); 2010.

[19] European Wind Energy Association. Green growth. The impact of wind energy on jobs and the economy. European Wind Energy Association; 2012.

[20] Tsay MA. Bibliometric analysis of hydrogen energy literature, 1965–2005. Scientometrics 2008;75(3):421–38.

[21] Sakata I, Sasaki H, Inoue T. Structure of international research collaboration in wind and solar energy. In: Industrial Engineering and Engineering Management (IEEM), 2011 IEEE International Conference, Singapore; 2011 (6–9 Dec.

[22] Liping D. Analysis of the relationship between international cooperation and scientific publications in energy R&D in China. Appl Energy 2011;88:4229–38.

[23] Larsen K. Knowledge network hubs and measures of research impact, science structure, and publication output in nanostructured solar cell research. Scientometrics 2008;74(1):123–42.