# Bibliometric Analysis of Leading Countries in Energy Research

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## Abstract

Given our growing dependence on energy, it is relevant to examine how to define, measure, and assess energy research and development. This study discusses the use of bibliometric methods for examining the evolution of energy research at the world level and in leading countries. The originality of the proposed method lies in the use of a several-pronged approach to delineating the field: seeding a keyword set with the output of research organisations in the field, augmenting this dataset with specialized journals, papers selected on the grounds of number of references made to a basic dataset and papers selected on the basis of citations received from papers in that basic dataset. This strategy results in both high recall and high precision. Results show that scientific output in energy research has doubled since 1996. Among leading countries, China has demonstrated a stupendous growth rate, specialization in the field, and immense scientific output. In contrast, many English-speaking countries (with the exception of Canada, which performs above the world average) are not performing as strongly, and some of the traditionally well established countries in energy R&D (e.g., the US and Japan) are progressively losing ground.

## Introduction

Energy is fundamental to life. Human society is increasingly dependent on energy, as it is simultaneously an enabling factor of economic growth and technological change and the most important factor limiting such growth. Energy use is also a key determinant in quality of life, due not only to its capacity to increase wellbeing but also to create discord resulting from pollution as well as geopolitical tensions over ownership and the capacity to secure key resources. Therefore, performing scientific research on energy is a potent instrument to sustain and increase the economic prowess of nations and their citizens' quality of life in addition. Energy research can also be instrumental to alleviating international conflicts by lowering competition for fossil fuels through the development of alternative forms of energy and of means to increase energy-efficiency.

In this context, it is relevant to examine how to define, measure, and assess energy research and development (R&D). Due to the extensive nature of the field and the crucial importance of energy systems innovation to wide-ranging issues such as the environment, economic prosperity, and national security, energy as a domain of research cannot be easily depicted or summarized (Changlin, 2007). In fact, researchers attempting to create a universal definition, capture meaningful measures, or assess the outputs of energy R&D have come up against several formidable challenges. For one, energy-relevant research may be carried out under the umbrella of numerous other fields, making it difficult to determine whether this research may be categorized strictly as energy research and, subsequently, to provide an accurate picture of R&D activity in the sector (Sagar & Holdren, 2002).

Investigators such as Kostoff (1993), Sagar and Holdren (2002), Kostoff and Geisler (2007), and Changlin et al. (2007), and Kajikawa (2008) have observed that basic research, applied basic research, applied research, technological development, and commercialization phases are part of a highly intertwined and involved chain of energy production and utilization technologies, and this complex chain cannot easily be broken down into discrete parts. Perhaps this is because, in comparison with other sectors, the development of energy

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technologies involves long periods of innovation and high levels of investment before reaching market deployment, so energy research literature is heavily weighted towards the development and demonstration of these advanced and emerging technologies.

Another factor complicating such analyses is that energy related R&D is multidisciplinary and is carried out by a wide array of players: government laboratories, firms (large conglomerates, large and small manufacturers, specialized/niche players, and start-ups), universities, research consortia, independent think-tanks, and non-governmental and non-profit organizations. These activities are also performed by these stakeholders for diverse purposes and with distinct goals—different actors have vastly different interests. Furthermore, not all of these players are active in all parts of the energy R&D chain, and their respective roles have not been adequately researched or distinguished (Sagar & Holdren; United Nations Department of Economic and Social Affairs, 2008).

*Defining Energy R&D*

A universally accepted definition of energy R&D has not appeared in the literature, and in fact, very few scholars in the field have attempted to forward a definition that can be put to collective use, probably due to some of the complicating factors previously discussed. Despite these factors, researchers have noted that this lack of an explicit definition of what constitutes energy R&D greatly complicates the task of collecting relevant data (Byrne, Toly, and Wang, 2006; Dooley, Runci, & Luiten, 1998; Sagar & Holdren, 2002). One of the most prolific authors in the area of energy research evaluation, J. J. Dooley (2000), along with the Global Climate Change Group at the Pacific Northwest National Laboratory in the US, has provided a comprehensive, though conventional, definition of energy R&D. According to this definition, energy R&D is:

> The linked process by which an energy supply, energy end use, or carbon management technology moves from its conception in theory to its feasibility testing and small scale deployment. [...] 'Energy R&D' encompasses activities such as basic and applied research as well as technology development and demonstration in all aspects of production (e.g., mining, drilling, refining, exploration), power generation (i.e., nuclear fission and fusion, fossil, and renewable energy), transmission, distribution and energy storage and energy efficiency technologies (p. 4).

*Measuring and Assessing Energy R&D*

As evidenced by the current literature, the most commonly used proxy measure for energy R&D is represented by data on expenditures and investments (inputs) in R&D carried out in energy-related areas. This measure is most often meant to signify the energy research intensity of specific countries, as well as public versus private sector engagement in energy innovation. In most cases, country-level statistics can be easily obtained through federal budgetary and energy ministry reports, as well as in aggregate form through reports generated by international organizations. Private sector data, on the other hand, are not systematically collected among firms and can be more difficult to access due to limits on proprietary information. Despite their widespread usage, researchers have questioned the utility of expenditure data, primarily because they can be extremely difficult to interpret, but also because they are misrepresented as an indicator of output rather than of input (Dooley, 2000). Furthermore, significant gaps exist in the data.

However, in terms of utilization of outputs and indicators of innovation capabilities, few other feasible measures have been proposed, though a small number have used bibliometric methods or have studied patent records (though mostly for specific areas of energy R&D) (Kajikawa et al., 2008; Margolis & Kammen, 1999). Sagar and Holdren (2002) assert that energy innovation capabilities can potentially be measured by a variety of indicators (such as those measuring allocation of the input, input-output relationships, and utilization of the output) but that these are often overlooked; in addition, energy research literature will often present arguments as being “applicable to the whole system while being based on data and analysis relating to only a part of it” and this presents an “incomplete understanding of the global energy innovation system” (p. 467). As a result, there is currently little in the way of meaningful output measures for R&D in the field.

*Objectives and structure of this paper*

The present study discusses the use of bibliometric methods for examining the evolution of energy research at the world level and in leading countries. The paper comprises two main sections. The following sections present the methods used to delineate the field of energy research, an examination of energy research at the world and the country levels, and a discussion of the results.

## Methods

This section presents the methods used to construct the dataset that will be used to benchmark the output of laboratories and countries in the field of energy research. The method used in this paper is relatively original. Although all the parts have been used elsewhere, the paper proposes a new combination of methods which promises to combine high recall with high precision. This paper presents this approach which is still in its infancy and there is clearly a need for greater characterization of the results as well as a need to study how to tune the different parts of the method in particular in other fields of R&D.

*Dataset Delimitation*

Considering the problems associated with incorporating a definition such as that proposed by Dooley (2000) into a query that would extract relevant papers from a bibliographic database (such as Thomson's Web of Science or Elsevier's Scopus), it was decided to use the output of a government energy R&D laboratory to provide a ‘seeding’ set of relevant keywords. These keywords would subsequently be searched for in titles, abstracts and authors’ keywords of papers indexed in Scopus (only papers considered as original contribution to knowledge, that is, the types of documents comprising references and being cited frequently).

The first step in this study involved the extraction of papers that were written by researchers who develop and demonstrate energy-efficient, alternative, and renewable energy technologies and processes. This seeding effort concentrated on examining the scientific output of researchers at the CANMET Energy Technology Centre (CETC), which is one of Canada’s leading federal government S&T organization in energy research (and part of Natural Resources Canada). Papers published by the CETC between 1996 and 2007, inclusively, and indexed in the Scopus database were retrieved and their titles and abstracts examined to single out energy research-specific keywords. This initial work provided a seeding list of about 100 keywords, allowing for the retrieval of 87% of the CETC’s output (i.e. this keyword set retrieves 408 out of 469 papers by CETC in Scopus).

This score (87%) represents a very high level of *recall*, which is the proportion of records relevant to a field that a search query retrieves from all papers comprised in a database. Another important goal in the development of the method was to obtain a high level of *precision*, which is the capacity to capture only relevant records or, conversely, the capacity to not extract false records. Building a dataset on a field of activities is a balancing act between maximizing recall and precision. As one seeks to increase recall, errors necessarily creep in and precision declines. In fact, it is commonly recognized in the field of information retrieval that an inverse relationship often exists between precision and recall, wherein it is possible to increase one, but only at the cost of reducing the other. In a field such as energy research, which is fairly broad in scope and has not generated a large vocabulary of specialized terms that are unique to the field, this balancing act rapidly becomes an important challenge. As finding the right balance between recall and precision is not easy, it was necessary to use a multi-pronged approach in order to increase recall without compromising precision. The approach used for this project is complex, which explains why this methodological section is relatively lengthy.

The initial set of keywords that was developed based on the CETC's scientific output was used to build an initial dataset from which a number of government laboratories would be identified and whose research would be examined to enlarge the initial keyword set. Although the goal of this undertaking was eventually to compare the output of the CETC to comparable laboratories, it is noteworthy that selecting government research institutes to identify keywords is a potent approach, as these laboratories tend to have a fairly wide scope. Care was taken to select laboratories, such as the CETC, that took broad approaches to energy research. The list of laboratories that was initially considered comprised the following: Forschungszentrum Jülich, Institute of Energy Research (Germany); National Energy Technology Laboratory, Morgantown facility (United States); *Institut français du pétrole*, Lyon facility (France); Chinese Academy of Science, Guangzhou Institute of Energy Conversion (China); Central Research Institute of Electric Power Industry, Energy Engineering Research Laboratory, Yokosuka area facility (Japan).

Once this selection of comparables was finalized, a similar process to that conducted for the CETC was performed again. The papers from each of the retained laboratories were analyzed and keywords relating to energy studies were compiled. This provided a preliminary general keyword query, which was then analysed to remove biases that could have been induced by seeding the initial dataset with papers from the CETC. For instance, keywords relating to refrigeration, chilling, and drying were removed because although they represented aspects that were linked with energy, they were too specific to the CETC's activities and could not be readily found in the activities of the comparable laboratories. Moreover including these terms would likely have lowered the precision of the dataset as these subjects were not deemed sufficiently linked with energy R&D.

Following the development of the initial keyword set, an analysis was conducted to determine whether it was precise enough to retrieve only papers relating to energy studies. This was accomplished by computing statistics on the percentage of occurrence of keywords in the various fields of science. This process showed that some keywords were no doubt used in contexts others than energy research. For instance, "ethanol" is widely used in life science research as a solvent. Following this analysis, it was decided that papers should only be retrieved when they had at least two different keywords—with the exception of papers in biomedical research and health research, which appeared more likely to produce false positives. In this case, it was decided to retrieve a paper only if it contained at least four different keywords. Also, in specific fields, some keywords were not considered altogether, such as ethane or ethanol, which are not retrieved from journals classified in biology, biomedical research, or clinical medicine.

The resulting keyword set was then used to identify journals in which relevant papers were published. The resulting list of journals was carefully screened, and specialist journals on energy were identified. This journal set was thence used to retrieve papers on energy that were added to the set of papers obtained with the keyword search (we will refer to this set of papers comprising both those obtained from keywords and from journals as "Dataset 1").

In order to extend this dataset to articles that might be published in journals outside of the core set of energy journals, as well as papers that used keywords less frequently than the number of times stipulated in the keyword search (two or more, except for journals in clinical medicine and biomedical research, which required four different keywords), further tests were conducted to examine how expanding the dataset using data from the references and citations would contribute to increasing recall. Thus, a strategy was devised to select papers that used at least one keyword and had at least two references or received two citations from papers in Dataset 1. This was used to create an expanded dataset ("Dataset 2"). Another test was also conducted to see how precise were 1) papers that had at least two references to Dataset 2 and amounted to more than 50% of the references in these papers as well as 2) papers that received at least two citations and where the number of citations received were present in at least 50% of the cases from papers in Dataset 2. Sampling showed that this method added worthwhile results by increasing recall without compromising precision. The strategy of adding papers based on citations and references was retained and contributed to creating the "Final Dataset".

After sampling the results and examining papers from the comparable research institutions that were missed by this approach, it was decided that for certain specific keywords (e.g., solar cell), one keyword would be sufficient. Also, the threshold for the query to build Dataset 2 was increased to at least two references or two received citations and, like in the original query, one keyword had to be present in a paper. The following schema presents the search strategy used (Figure 1).

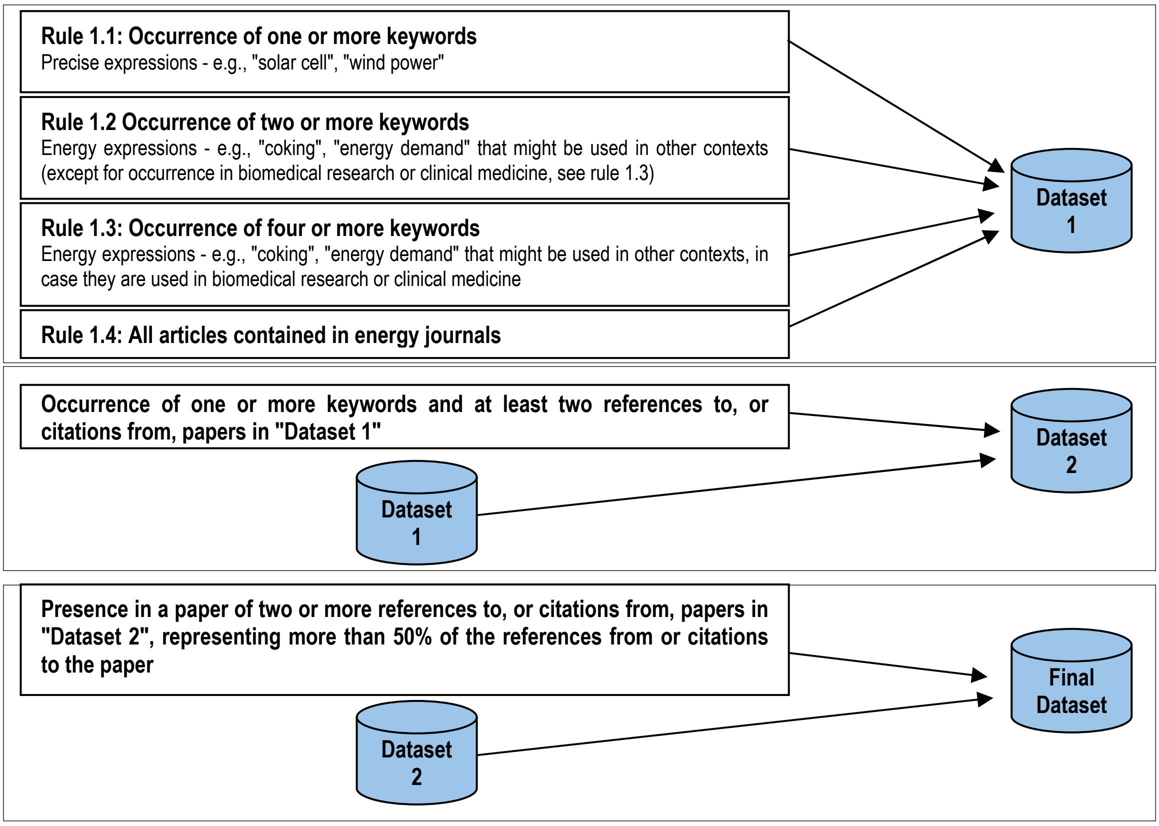


**Figure 1. Final search strategy used to construct the dataset on energy research**

*Bibliometric Indicators*

The following indicators were used to examine the scientific output in energy R&D:

**Number of papers:** Number of scientific papers written by authors located in a given country.

**Papers per capita:** The number of papers at the country level is weighted per capita using population statistics produced by the US Census Bureau.

**Growth:** Growth is measured by dividing the papers published between 2002 and 2007 by those published between 1996 and 2001. A growth Index is obtained by dividing the growth calculated at the country level by the growth observed at the world level.

**Specialization index (SI):** The SI is an indicator of *research intensity* in a given country relative to the world. An index value above 1 means that a given entity is specialized relative to the world, whereas an index value below 1 means the reverse.

**Average of relative citations (ARC):** The ARC is an indicator of the *scientific impact of papers* produced by a given country, which takes into account interfield variations in citedness.

**Average relative impact factor (ARIF)**: This indicator is a proxy for the quality of the journals in which an entity publishes. For each journal, an impact factor (IF) is calculated based on the number of citations it received relative to the number of papers it published. The IF is calculated in a symmetrical manner, meaning that the types of papers counted at the numerator are also counted at the denominator.

**Positional analysis:** To more easily interpret the strengths and weaknesses of a country through the use of several separate indicators, we use a graphical representation called a positional analysis. This graphical representation logically combines three of the previously mentioned indicators (number of papers, SI, and ARC).

**Energy Research at the World and Country Levels**

The field of energy research has doubled in terms of scientific output since 1996. Importantly though, it is always important to examine this type of growth pattern in light of the growth of the coverage of the database used to evaluate scientific output. In this case, one can see that over the last 12 years, energy-related papers grew by about one percentage point, from 2.3% of the Scopus database in 1996 to 3.3% in 2007 (Figure 2.). Examined in this manner, the presence of energy-related papers has increased about 42% more than the overall rate of growth of science, compared to a doubling of the number of energy papers when measured in absolute terms. Thus, despite the decreasing investments in research noted by several authors, the field's output is growing quite steadily.

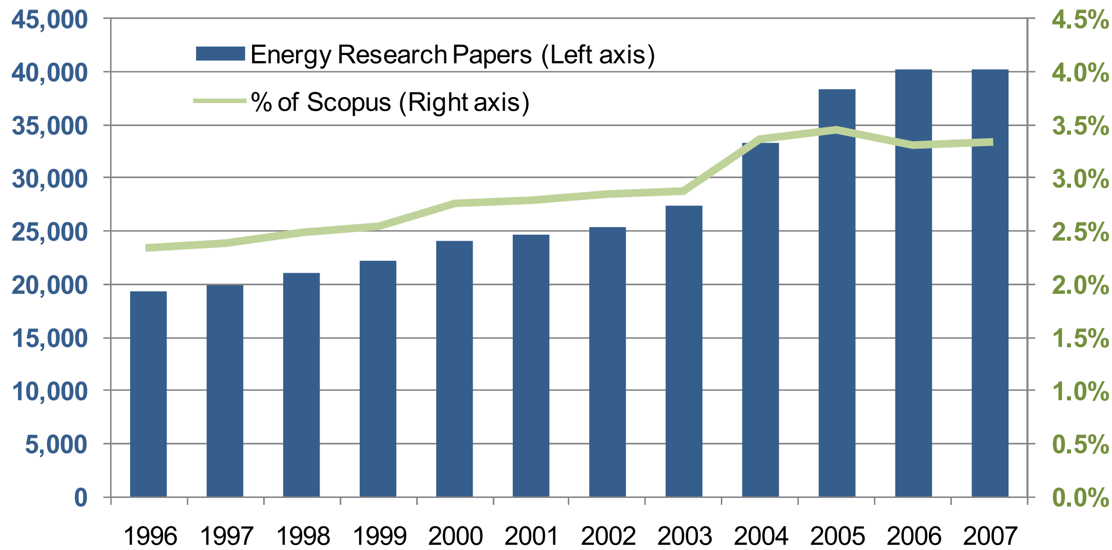


**Figure 2. Number of papers in energy research in Scopus, 1996-2007**

It is worth noting that among the leading countries, energy is one of the rare major scientific fields in which the US is not the dominant force—as is clear in Figure , China overtook the US in 2004, which is hardly surprising given the decreasing US investments in energy R&D during the eighties and nineties (Nemet & Kammen, 2007). Among other G7 countries, Japan maintains a clear leadership (Figure 4. ). Germany, ranking third in scientific output, overtook the UK in 2000, but these two countries are running a tightly contested race. Likewise, France (5th in output) and Canada (ranking 6th) also appear to be running in the same corridor, despite the considerably smaller size of Canada. Italy ranks last among G7 countries.

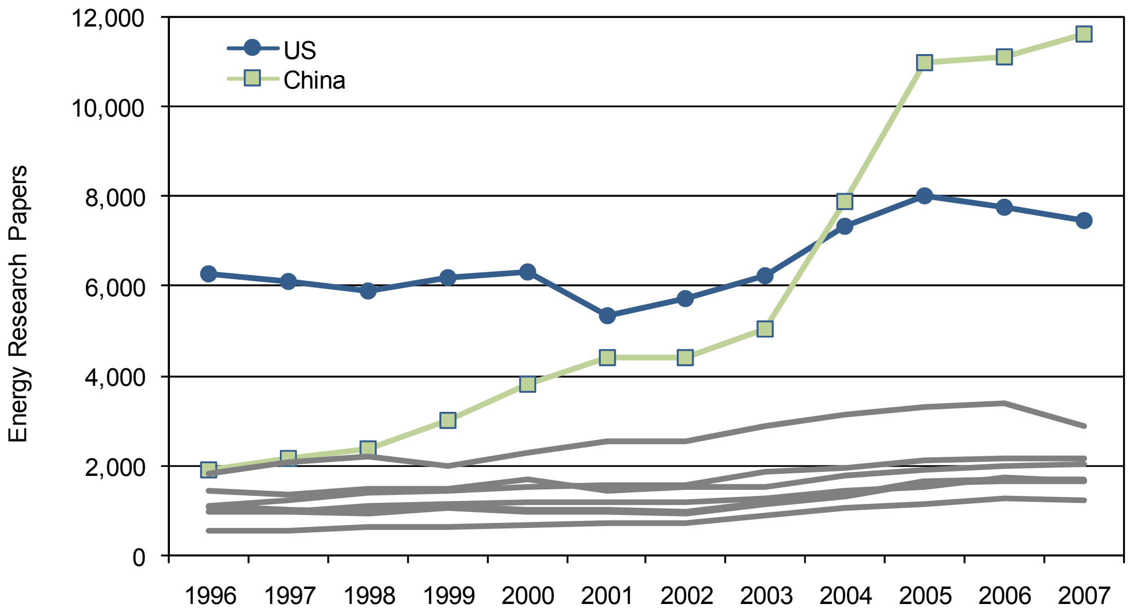


**Figure 3. Papers in energy research produced by the US and China, 1996-2007**

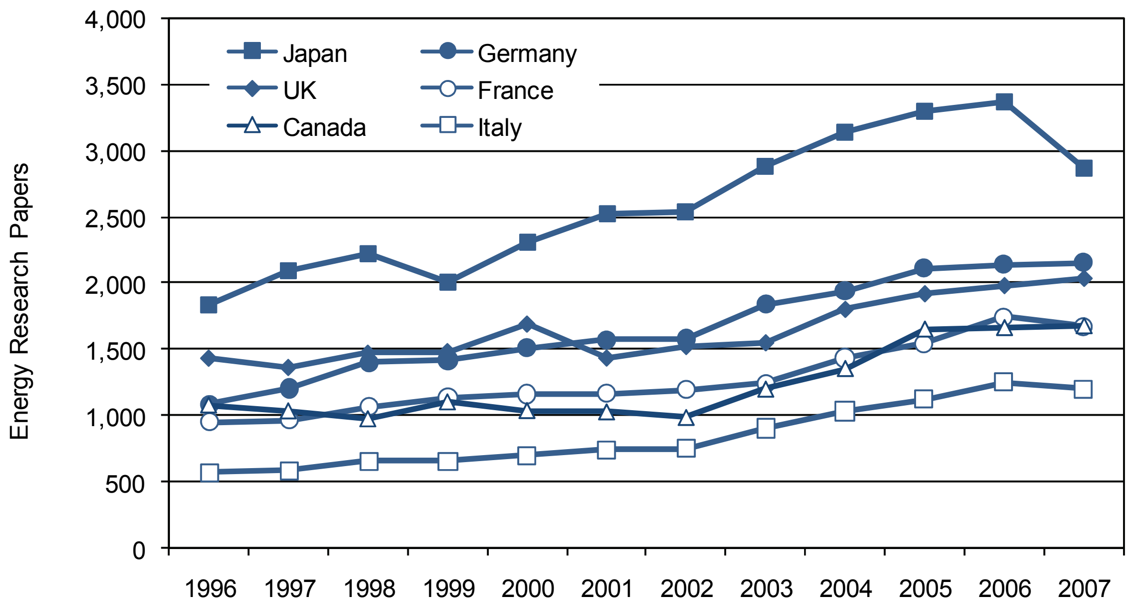


**Figure 4. Papers in energy research produced by G7 countries (excluding the US), 1996-2007**

The view that Canada performs well relative to its size is confirmed when examining papers per capita—Canada has a greater output than all other G7 countries (Figure ). In fact, when examining the 20 countries with the largest scientific paper output per capita in energy research, only Norway, Switzerland, and Sweden exceed Canada's performance. It is noteworthy that although China has the largest overall output, its output per capita is among the lowest of the leading countries, which means that it still has an enormous capacity to increase its output. This is likely to happen as a larger proportion of the population is becoming mobilized to undertake R&D-related activities.

Data on growth in output in the most productive countries show that China, the Republic of Korea, Turkey, Brazil, and Spain are the countries that have expanded their scientific capabilities in energy research the most during the period under review (Figure ). Conversely, the output of well established countries in the field, such as the US and Japan, is not growing nearly as quickly as the world average, and therefore, these countries are progressively losing ground in energy R&D. In fact, the output of all of the G8 countries is growing at a slower rate than the world average, except for that of Italy, which is growing at the average world rate.

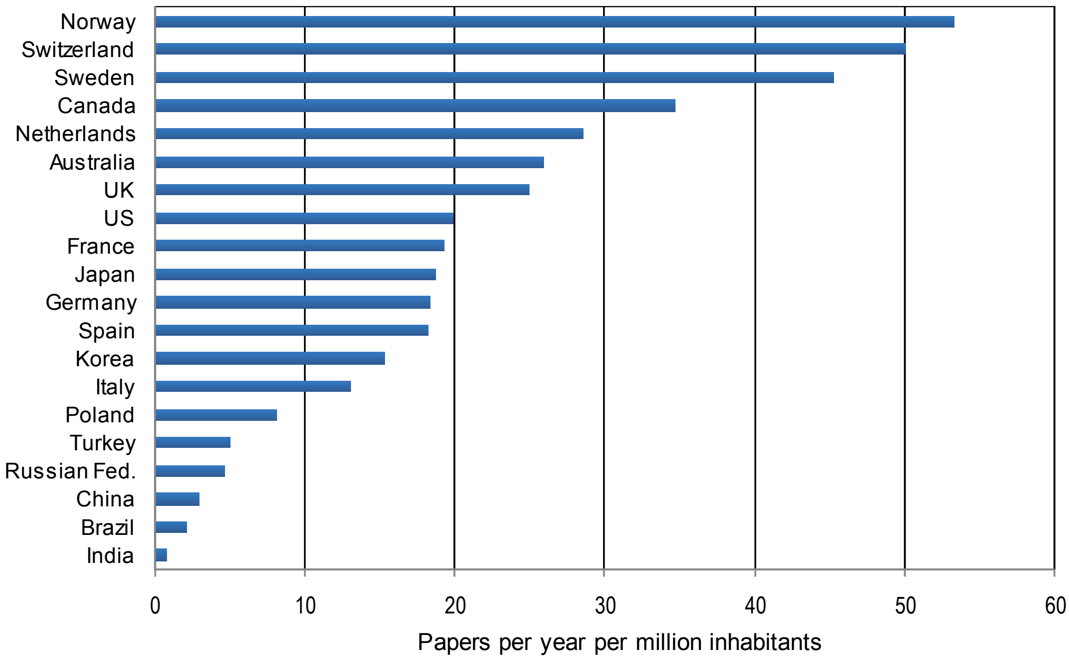


**Figure 5. Papers in energy research per capita (20 most active countries), 1996-2007**

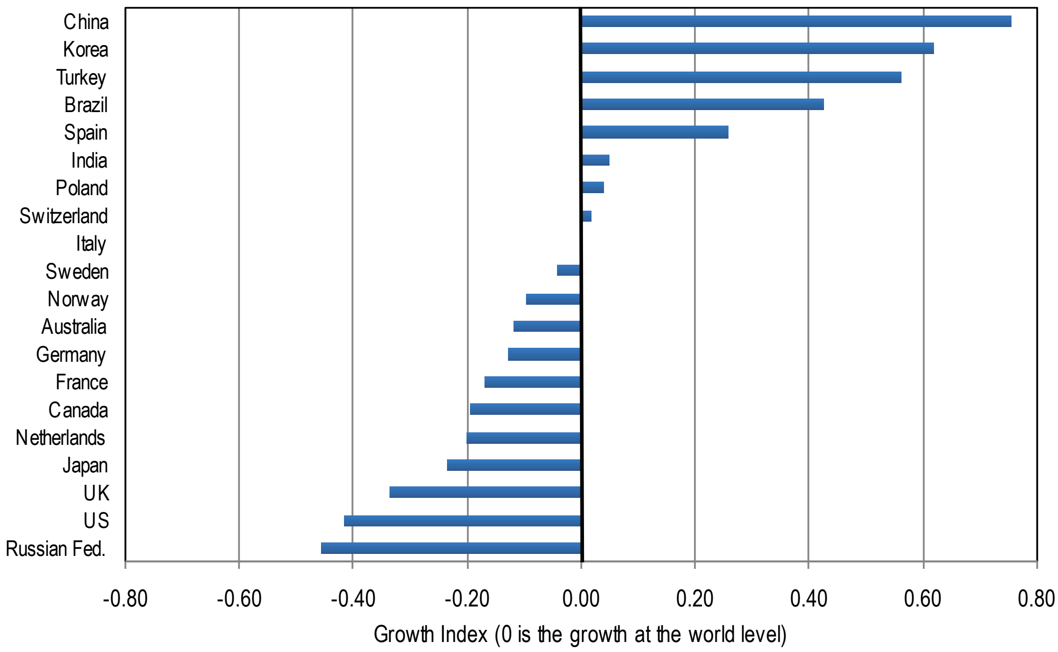


**Figure 6. Growth Index in energy research (20 most active countries), 1996-2007**

Examining research intensity shows that energy R&D is a clear priority in Asia as China, South Korea and India are among the countries with the greatest research intensity in this field. In fact, China and South Korea are clearly the countries to watch, as a great proportion of their output is in this field and, as noted before, they have the greatest growth rate of the top 20 countries in the field. The countries with the greatest energy-related scientific output intensity are either countries that are known for their important investments in fossil fuels (e.g. Norway, Russia, and Canada) or countries with extraordinary growth, such as China, South Korea, and India. Thus, both supply and demand factors seem to play a role in increasing the intensity of scientific research in energy-related areas. It is noteworthy that although the US is a very important producer of scientific output in the field, its percentage of publication in the field is lower than the world average; also, along with all G7 countries (except Canada), it is among the least specialized leading countries in the field.

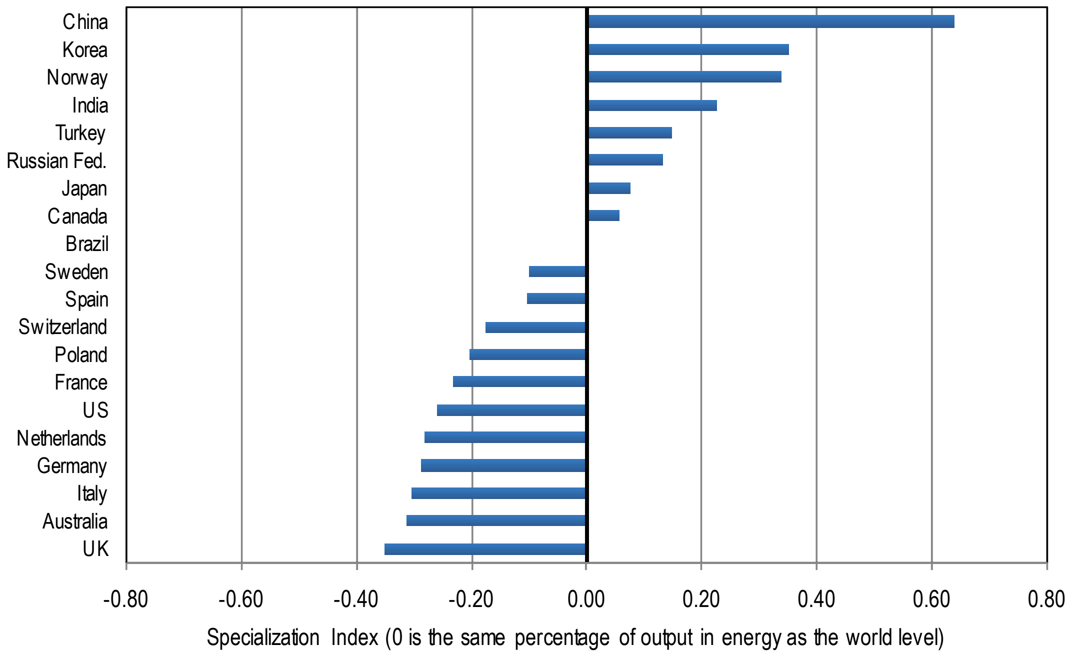


**Figure 7. SI of energy research (20 most active countries), 1996-2007**

An examination of the scientific impact of energy research leads to some unsurprising findings: the top-ranking countries are Switzerland, the Netherlands, the US, and Sweden. These countries are frequently recognized for their scientific excellence in a wide variety of fields. Although they are leaders in output, Russia, China, and India lag behind in scientific impact. Together with Norway, Canada is the only country that combines a percentage of output in energy research and a scientific impact above the world average (Figure ). However, one must not lose sight of the fact that the scientific output of the US and China dwarf the production of Canada and Norway in the field. Moreover, there are many countries with substantially greater relative citation scores, such as Switzerland, the Netherlands, the US, and Sweden.

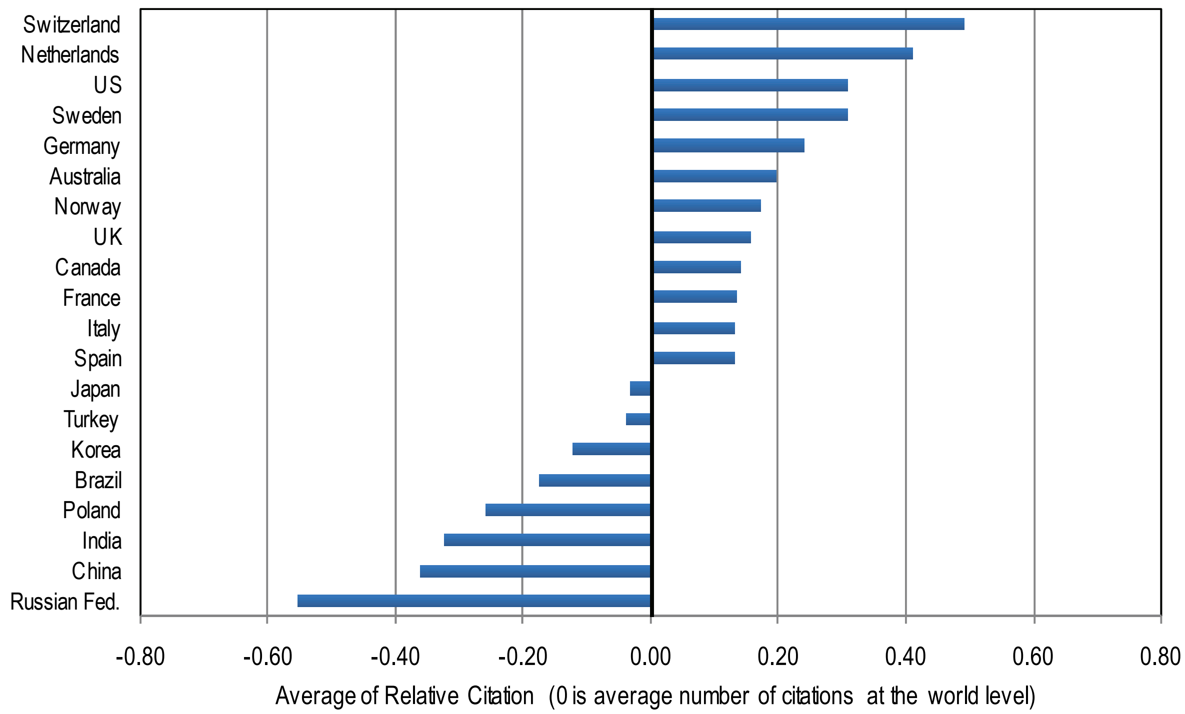


**Figure 8. ARC in energy research (20 most active countries), 1996-2007**

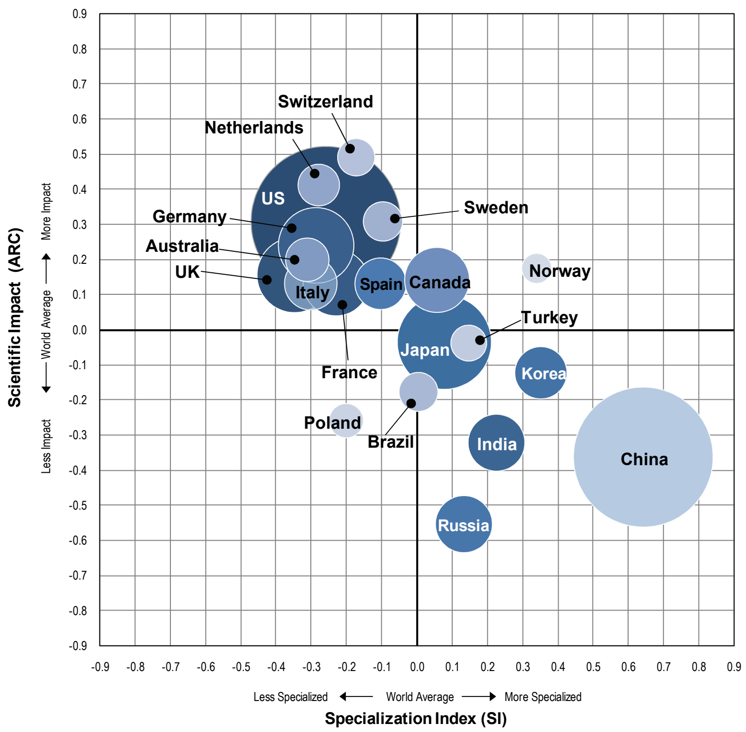


**Figure 9. Global scientific positioning of the 20 most active countries, 1996-2007**

## Discussion and Conclusion

Scientific research in the field of energy is key to unlocking the door to economic growth, but it can also play a crucial role in curtailing the adverse effects associated with energy exploitation and use. Energy research has always been important and is currently as relevant as ever. In the future, it will continue to grow in importance, as easily accessible non-renewable energy resources dwindle rapidly (IEA, 2008). Modern economies will have no choice but to perform more research in order to develop new sources of energy and to palliate the adverse effects associated with our seemingly insatiable thirst for energy, including using existing sources of energy more wisely.

This paper has presented an innovative strategy to retrieve a dataset that combines high recall and high precision in a complex field of research. This method involves the combined use of keywords, specialized journals, references, and citations. Although more research is needed to accurately estimate recall and precision as well as how to fine tune the various parameters used, the study's sampling shows that the resulting keyword set is highly precise. As for recall, the main problem in estimating a value is that there are no clear boundaries that determine at which point energy research stops and where fundamental research begins. It is easier to establish whether a paper is relevant than to identify the reasons why a paper that is only loosely linked with energy should or should not be included.

This paper shows that if there is one country to watch in energy research, it is China, due to its stupendous growth rate, specialization in the field, and immense scientific output. It falls behind only in measures of citedness, but there are several mitigating factors to explain China's low impact. Firstly, the measurement instrument used for this study is not ideal for measuring the scientific impact of China. Indeed, Scopus indexes a high number of scientific journals and papers compared to Thomson's Web of Science, but in most cases where references from Chinese articles are not provided in English, data goes unentered. Although one can hardly blame Elsevier for this decision, it probably has a significant adverse effect on the measured impact of Chinese output. Additionally, it is well known that non-English papers are not as widely cited, if only because English is the *lingua franca* of science.

In contrast, English-speaking and G7 countries, perhaps with the exception of Canada, are not performing very well, especially when one considers relative measures such as the specialization index and the number of papers per capita. This is particularly alarming, given that they consume a significant share of the world's energy. The countries that present the most balanced scorecard are in fact the Nordic countries such as (in no particular order) Norway, Sweden, the Netherlands and Switzerland. Importantly, it is clear that this paper is only a beginning and that more efforts are needed to characterize the many sub-fields of energy research with bibliometric methods.

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