INNOVATION IN FUEL CELLS: A BIBLIOMETRIC ANALYSIS

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FOREWORD

As part of an effort to compare the structure and operation of national innovation systems at the sectoral level, the OECD Working Party on Innovation and Technology Policy launched a series of case studies in 2002 to examine innovation in energy technology, pharmaceutical biotechnology and knowledge-intensive service activities.

This report contributes to the case study on innovation in energy technology by providing a quantitative analysis of scientific publications and patents related to fuel cell technology. It develops and presents a number of indicators of patenting and publication in fuel cell technology across OECD countries, distinguishing where possible among publications and patents resulting from industry, universities and government laboratories. It complements more in-depth country reviews of innovation in energy technology that were prepared by researchers in nine participating countries (from Canada, France, Germany, Italy, Japan, Korea, Norway, United Kingdom and United States).

This report was prepared by the OECD Secretariat, in consultation with the researchers engaged in preparing the country studies. The analysis was performed by Emmanuel Hassan, under the supervision of Jerry Sheehan. Statistical support was provided by Sandrine Kergroach, Cristina Serra-Vallejo and Corrine Doenges. It benefited from the comments and suggestions of participants in the International Conference on Innovation in Energy Technology that was organised in Washington, DC in September 2003.

An electronic version of this document, as well as the individual country studies, is available on the OECD Web site:

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EXECUTIVE SUMMARY

1. Recent years have seen significant growth in innovative activity related to fuel cells. Fuel cells are electro-chemical devices that use hydrogen (or hydrogen-rich fuel) and oxygen to create electricity. They constitute an important enabling technology for the hydrogen economy, offering potentially cleaner, more-efficient alternatives to the combustion of gasoline and other fossil fuels. They can be powered by domestically available sources of energy (including fossil fuels, renewable, and nuclear power), making them attractive to countries that rely on imports for large portions of their energy needs. The market for fuel cells and related products is expected to be large in the medium-term, and many industrialized countries are investing heavily in fuel cell technology as part of larger efforts to shift toward a hydrogen economy. Realizing the economic potential and environmental benefits of fuel cells will, however, depend heavily on continued scientific and technological advances. In order to be able to effectively examine and monitor scientific and technological activities in the field of fuel cells, it is important to be able to provide reliable statistics of its knowledge base at the level of countries, institutional sectors, and most active institutions.

2. This report investigates innovation in fuel cell technology via the development and analysis of set of internationally comparable indicators of scientific and technological activity. Data on patents and publications in the scientific and technical literature are used to create indicators that measure scientific and technological outputs and provide insight into the knowledge structure of the fuel cell innovation system in the 1990s. The report focuses on seven major types of fuel cells that account for the bulk of innovative activity: 1) alkaline fuel cells (AFCs); 2) direct methanol fuel cells (DMFCs); 3) molten carbonate fuel cells (MCFCs); 4) phosphoric acid fuel cells (PAFCs); 5) proton exchange membrane fuel cells (PEMFCs); 6) solid oxide fuel cells (SOFCs); and 7) regenerative fuel cells (RFCs). These types of fuel cell support a range of applications, from stationary residential and industrial power supplies, to automotive propulsion, to portable power supplies for electronic equipment. As such, they face a diverse set of challenges in their development and commercialization and innovation patterns have been affected by a variety of government policies and initiatives.

3. The analysis shows:

- *Scientific and technological activity related to fuel cells increased significantly during the 1990s*. Growth in scientific publications was sharp, rising by a factor of five between 1990 and 2000. EU countries saw the fastest increases and accounted for 40% of scientific publications fuel cells in 2000, roughly twice the share of Japan and the US. The number of fuel cell patents filed at the European Patent Office (EPO) more than doubled during this time period, with the EU, Japan and US accounting for roughly equal shares of EPO patents in 1999. Perhaps reflecting growth in scientific publications, the rate of growth in patenting during the 1990s was fastest among EU countries.

- *Substantial differences exist in the levels of scientific and technical activity for different types of fuel cells.* SOFCs, MCFCs, and PEMFCs accounted for approximately three-quarters of all scientific publications in fuel cells between 1990 and 2000. PEMFCs, SOFCs, and RFCs account for the vast majority of EPO patent applications, with PEMFC accounting for almost half the total. Of the three types of fuel cells, however, only PEMFCs grew as a share of total patents, as did DMFCs, which represented just 5% of all fuel cell patents, on average, between 1990 and 2000. Despite accounting for a growing share of scientific publications, SOFCs declined as a share of patents.

- *Links between science and technology are strengthening*. The varied patterns of scientific publications and patent applications across and within the main types of fuel cells do not imply an absence of effective linkages between the scientific and technological activity in fuel cells. On the contrary, by some measures the cognitive links strengthened over the past decade, notably for SOFCs, MCFCs, RFCs, PEMFCs, and DMFCs. Furthermore, there were substantial cognitive interrelations among the scientific and technological bases of these latter sub-fields.

- *Fewer countries are active in technological exploitation than scientific development related to fuel cells*. It appears as though scientific competencies are more widely distributed among the OECD countries than are technological capabilities. Most of the countries that account for the largest shares of scientific publications also accounted for the largest shares of patents the share of publications. Nevertheless, inventors from only 12 countries applied for EPO patents, whereas researchers from 27 countries published in the field. Inventors from the EU, Japan and US accounted for approximately 95% of all EPO patent applications in 1999, they accounted for less than 80% of all scientific publications. Canada and Korea are also active in publishing and patenting.

- *Countries exhibit considerable variation in their specializations in different types of fuel cells.* Some degree of similarity exists in the distribution of publications and patents among different types of fuel cells in the major OECD countries. In larger countries, such as France, Germany, Japan, the UK and the US, for example, approximately 75% to 85% of publications between 1990 and 2000 related to SOFCs, MFCs and PEMFCs. Nevertheless, Japan places less emphasis on PEMFCs and relatively more on SOFCs, which account for more half of its fuel cell publications. In smaller economies, fuel cell efforts are often more concentrated. In Canada, more than 60% of fuel cell publications and more than 80% of fuel cell patents relate to PEMFC. In Norway, more than 80% of publications related to SOFC; the balance are in MCFCs.

- *International co-operation in fuel-cell science is limited.* International scientific co-operation, as measured by internationally co-authored publications, seemed to have played a minor role in the generation and diffusion of scientific knowledge related to field of fuel cells in the 1990s. The share of international co-publications was relatively low in the 1990s compared with the situation of other specific technical fields. For only two types of fuel cells, AFCs and DMFCs, did international co-publications represent more than 10% of all publications. As a rule, countries with large numbers of publications had a lower propensity to collaborate at the international level. Three of them were nevertheless central in the global network of international co-publications: the United States, the United Kingdom, and Germany.

- *Most scientific work takes place in the public sector, but business also contributes to the science base*. Public sector organizations account for most scientific publications in fuel cells, but among countries with the largest number of scientific publications, business tends to account for between 10% and 20% of the total. The most notable exception to this rule is Japan, in which business and other private non-profit organizations accounted for more than 40% of scientific publications between 1990 and 2000. Business tends to play an even larger role in publications related to MCFCs and PEMFCs than in SOFCs, which are the fields that generate the largest numbers of publications. Within this same set of countries, the contributions of public sector organizations (universities and government laboratories) also varies considerably, with the share of publications emanating from universities (as opposed to government labs), ranging from 30% in Germany to almost 80% in France.

- *Patenting reflects broad business interests*. As expected, the business sector accounts for the vast majority of fuel cell patents in most countries. In Japan, Canada, and the US, for example, businesses applied for more than 90% of EPO patents. The industries in which patenting firms operate are highly diverse and reflect national differences. In Japan, for example, the top 5 patenting firms in fuel cells are Matsushita Battery Industrial Co., NKG Insulators Ltd., Honda Motor Company, Hitachi, and Toyota Motor Corp, reflecting the interests of the electrical, automotive and electronics sectors. Similarly, in the United States, the top patent holders are Westinghouse Electric Corp, General Motors, International Fuel Cells Corp., Gas Technology Institute, and Siemens.

- *Public research organizations also patent*. In Germany, Denmark and France, public sector institutions account for 20% to 35% of fuel cell patents. German government labs have been most active in patenting SOFC inventions, whereas French labs have been more active in PEMFC. In the US, universities accounted for 11% of PEMFC patents, but have played a much smaller role in patenting other fuel cell technologies.

CHAPTER 1. INTRODUCTION

Towards hydrogen-based energy systems

4. Global demand for energy is growing rapidly. Currently this demand is met, in large part, by reserves of fossil fuel, but such fuels have several drawbacks. First, they are known to emit greenhouse gasses and other pollutants. Second, as reserves of fossil fuels are depleted, they are expected to become increasingly expensive in the long-term. Moreover, fossil fuel, particularly crude oil, is confined to a few areas of the globe, and the stability of supply is governed by political, economic, and ecological factors. These factors conspire to force volatile, often high fuel prices, while at the same time, environmental policy strongly recommends a reduction in greenhouse gasses and toxic emissions. Energy systems based on hydrogen could resolve growing concerns about industrialized countries' energy supply, security, air pollution, and greenhouse gas emissions.

5. Over the past 30 years, interest has thus been increasing in the potential use of hydrogen as an energy source. Hydrogen offers the long-term potential for an energy system that produces near-zero emissions and is based on domestically available resources, including fossil fuels, renewable, and nuclear power (EC, 2003*a*; US DoE, 2002). For these reasons, many industrialized countries have invested in the development of hydrogen production, distribution, and storage technologies, especially over the past 10 years when enabling technology such as fuel cells, began to show real promise.

Realizing the potential of fuel cells

6. Fuel cells[1] are efficient electrochemical converters, in which the chemical energy of an energy carrier is converted directly into electric energy. They offer electric efficiency rates up to 70%, far in excess of conventional power production technologies. Even though real efficiency rates remain below this theoretical limit, fuel cells offer other significant benefits compared to conventional energy systems since they are characterized by potentially substantially lower negative externalities (Figure 1.1.). Fuel cells are also a very flexible, with a broad range of potential applications that can be classified into three primary categories: 1) transportation applications such as passenger cars and buses, 2) stationary applications for powering homes or commercial buildings, and 3) portable applications such as cell phones or laptops (IPTS, 2003; Alleau, 2003).

7. The market for fuel cells and related products is expected to be large in the medium-term. Global demand is projected to reach USD 29.3 billion by 2011 and could exceed USD 1.7 trillion by 2021 (Fuel Cells Canada and PricewaterhouseCoopers, 2002), but significant scientific and technological hurdles remain. Moreover, fuel cells have to compete with existing technologies such as internal combustion engines (ICE), gas turbines, micro turbines; photovoltaic, wind turbines, and other energy sources. (Mina and Criqui, 2003).

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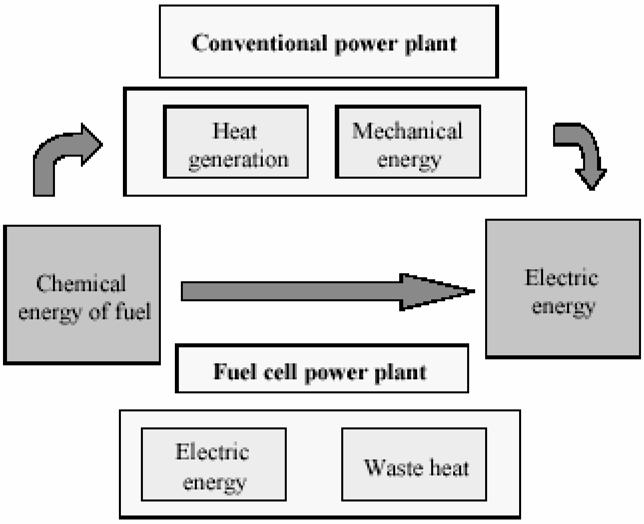
1 . Fuel cells principle is not new. The fuel cell was first developed by William Grove, a Welsh judge with strong scientific inquisitiveness. In 1839, Grove was experimenting on electrolysis when he observed that combining the same elements could also produce an electric current. Other scientists paid sporadic attention to fuel cells throughout the 19th century. From the 1930s through 1950s Francis Thomas Bacon, a British scientist, worked on developing alkaline fuel cells. He demonstrated a working stack in 1958. This technology was licensed to Pratt and Whitney where it was utilized for the Apollo spacecraft fuel cells.

Figure 1.1. Working of a fuel cell in comparison with conventional power production



Source: IPTS (2003).

8. Government and industry funding on fuel cell research and development (R&D) have both grown sharply over the past recent years. For instance, the US government proposes spending USD 1.7 billion over the next five years on hydrogen and fuel cell R&D and advanced automotive technologies. In Japan, where the government provided over USD 175 million in support of fuel cell R&D and commercialization in 2002, annual government spending is expected USD 242 million per year starting in 2003. The European Community recently announced plans to spend USD 2.1 billion from 2003 to 2006 on renewable energy, mostly on hydrogen and fuel cells (Industry Canada *et al.*, 2003).

9. Realizing the economic potential and environmental benefits of fuel cells will heavily depend on continued scientific and technological advances. Many technical barriers related to, for example, the fuel cell drive itself for mobile applications, the properties of materials, the miniaturization of components, the stability of fuel cells systems for stationary applications, or the reliability of the whole fuel cell system for portable applications still hamper progress in this field, and competitive cost structures for production have yet to be accomplished (IPTS, *op. cit.*).

A bibliometric approach

10. Recognizing the critical role played by science and technology in the development of fuel cells, this report examines the way actors (*i.e.* countries, institutional sectors, and institutions) interact in the production and diffusion of scientific and technological knowledge at the national and international levels. Such insight can help policy makers determine how best to strengthen and support innovation processes for fuel cells. In that respect, the report adopts a quantitative methodology that enables the in-depth analysis of the scientific and technological knowledge bases of the field of fuel cells in the 1990s.

11. This report uses a systematic method for quantifying information on fuel cells research and development activity over the past decade, details of which are provided in Annex A. Data on patents and publications in the scientific and technical literature (bibliometric information) are used to create internationally comparable indicators that measure and characterize:

- scientific and technological outputs of the various actors (*i.e.* countries, institutional sectors, and institutions) engaged in the generation of knowledge within the field;

- linkages between these actors in terms of knowledge flows and scientific collaborations.

- evolution of the cognitive structure of the field;

Advantages of bibliometric analysis

12. Publications and patents are among the main outputs of scientific and technological activity, respectively, and thus can be used to quantify its results. Moreover, when authors or inventors publish in journals (or other supports) or apply for patents, they reveal not only what they are doing but also with whom they did it, and when and where it was done. These indicators have become common tools to analyze the organization of research activity and its performance from a quantitative point of view (OECD, 1994, 1997; Callon *et al*., 1993; NSB, 2002; EC, 2003*b*). The main benefit of such indicators is the unique empirical characterization they provide of the way actors interact as a collective system of knowledge production and diffusion (OECD, 1996).

Limitations

13. Indicators based on publications and patent data are subject to several general limitations that influence their interpretation. Publications, for example, cover information that consists of exchanges that have been formalized and codified; informal communication and embodied knowledge are not captured. The limits of publication data are even more restrictive with regard to industrial or defense-related research. Articles published by industrial laboratories often give a limited view of the aims of research, which are generally to create products or processes subject to commercial competition (OECD, 1997). The same goes for defense-related research, the results of which are often kept secret for national security reason. Patents are also limited in their ability to measure technological activity, as patents are not the only means to protect technological knowledge. Firms use several other means such as lead-time and trade secrets to protect their competitive advantage (Levin *et al.*, 1987). Moreover, when using indicators based on patents, especially patent counts, to measure the technological output of an actor, it is necessary to assume that the propensity to patent does not vary from one actor to the next and that the value of all patents (as well as publications) is equal. Finally, patents from single patent offices such as the US Patent & Trademark Office (USPTO), European Patent Office (EPO), or Japan Patent Office (JPO) are subject to "home bias"; national residents are likely to be over-represented in the statistics of their own patent office because they usually file for a patent in their home country before filing in foreign offices. Often they file with their home institution alone, at least until they expect to exploit an invention in foreign markets.

14. Two specific considerations apply to the indicators developed in this report. First, the publication data reflect publications in high-quality, peer-reviewed scientific and technical literature only (as outlined in Annex A). They do not include numerous other publications such as book chapters, technical reports, and conference proceedings, but instead focus on those types of publications most likely to reflect a contribution to advancing scientific state-of-the-art. Secondly, the patenting indicators are based on patents applications and grants at the European Patent Office. They will therefore tend to under-represent patenting activity by non-European inventors, including those in Japan and the US. This limitation is especially true of fuel cells as the technology has not been widely commercialized and is not exploited globally by many inventors. In fact, the OECD Patents Database indicates that relatively few fuel cell inventions have been patented in the EPO, JPO and USPTO.

15. For this analysis, a list of seven sub-fields was defined to delineate the field of fuel cells either on the science or technology side. These seven sub-fields, which correspond to the most common types of fuel

cells in accordance with the employed electrolytes, are the following (see Box 1 for a description of each type of fuel cell and main application areas):

- alkaline fuel cells (AFCs);
- direct methanol fuel cells (DMFCs);
- molten carbonate fuel cells (MCFCs);
- phosphoric acid fuel cells (PAFCs);
- proton exchange membrane fuel cells (PEMFCs);
- solid oxide fuel cells (SOFCs);
- and regenerative fuel cells (RFCs).

16. This approach has the main consequence that not all publications and patents dealing with fuel cells or even related hydrogen-based technologies are considered in the analysis. It nevertheless has the advantage of allowing the identification of the main features of the process of scientific and technological knowledge production and diffusion related to the different types of fuel cells in further analyses.

Box 1. Types of fuel cells and their applications

The differences among fuel cell types include on their operating temperature and pressure, the types of fuels employed and the electrolytes used to catalyze the electro-chemical reaction. Such factors influence the applications for which different types of fuel cells are best suited, as well as their cost. The names most commonly used for designated at the international level tend to be based on the electrolayte used. The most common are: Proton Exchange Membrane (or Polymer Electrolyte), Phosphoric Acid, Direct Methanol, Alkaline, Molten Carbonate, Solid Oxide, and Regenerative (Reversible). Each is described below:

Proton Exchange Membrane: Proton exchange membrane (PEMFC) fuel cells—also called polymer electrolyte fuel cells—deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEMFC fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. They are typically fueled with pure hydrogen supplied from storage tanks or onboard reformers. Polymer electrolyte membrane fuel cells operate at relatively low temperatures, around 80°C (176°F). Low temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components, resulting in better durability. However, it requires that a noble-metal catalyst (typically platinum) be used to separate the hydrogen's electrons and protons, adding to system cost. The platinum catalyst is also extremely sensitive to CO poisoning, making it necessary to employ an additional reactor to reduce CO in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This also adds cost. Developers are currently exploring platinum/ruthenium catalysts that are more resistant to CO. PEMFC fuel cells are used primarily for transportation applications and some stationary applications. Due to their fast startup time, low sensitivity to orientation, and favorable power-to-weight ratio, PEM fuel cells are particularly suitable for use in passenger vehicles, such as cars and buses. A significant barrier to using these fuel cells in vehicles is hydrogen storage. Most fuel cell vehicles (FCVs) powered by pure hydrogen must store the hydrogen onboard as a compressed gas in pressurized tanks. Due to the low energy density of hydrogen, it is difficult to store enough hydrogen onboard to allow vehicles to travel the same distance as gasoline-powered vehicles before refueling, typically 300-400 miles. Higher-density liquid fuels such as methanol, ethanol, natural gas, liquefied petroleum gas, and gasoline can be used for fuel, but the vehicles must have an onboard fuel processor to reform the methanol to hydrogen. This increases costs and maintenance requirements. The reformer also releases carbon dioxide (a greenhouse gas), though less than that emitted from current gasoline-powered engines.

Phosphoric Acid: Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst. The phosphoric acid fuel cell (PAFC) is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially, with over 200 units currently in use. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses. PAFCs are more tolerant of impurities in the reformate than PEM cells, which are easily "poisoned" by carbon monoxide—carbon monoxide binds to the platinum catalyst at the anode, decreasing the fuel cell's efficiency. They are 85 percent efficient when used for the co-generation of electricity and heat, but less efficient at generating electricity alone (37 to 42 percent). This is only slightly more efficient than combustion-based power plants, which typically operate at 33 to 35 percent efficiency. PAFCs are also less powerful than other fuel cells, given the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. Like PEM fuel cells, PAFCs require an expensive platinum catalyst, which raises the cost of the fuel cell. A typical phosphoric acid fuel cell costs between $4,000 and $4,500 per kilowatt to operate.

Alkaline: Alkaline fuel cells (AFC) were one of the first fuel cell technologies developed, and they were the first type widely used in the US space program to produce electrical energy and water on-board spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. High-temperature AFCs operate at temperatures between 100ºC and 250ºC (212ºF and 482ºF); however, more-recent AFC designs operate at lower temperatures of roughly 23ºC to 70ºC (74ºF to 158ºF). AFCs are high-performance fuel cells due to the rate at which chemical reactions take place in the cell. They are also very efficient, reaching efficiencies of 60 percent in space applications. The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO2): even the small amount of CO2 in the air can affect the cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell, which adds to their cost. Cost is less of a factor for remote locations such as space or under the sea, but to compete in most mainstream commercial markets, these fuel cells will have to become more cost effective. Susceptibility to poisoning also affects the cell's lifetime, further adding to cost. AFCs have been shown to maintain sufficiently stable operation for more than 8,000 operating hours. To be economically viable in large-scale utility applications, these fuel cells need to reach operating lifetimes exceeding 40,000 hours. This is possibly the most significant obstacle in commercializing this fuel cell technology.

Molten Carbonate: Molten carbonate fuel cells (MCFC) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide (LiAlO2) matrix. Since they operate at extremely high temperatures of 650ºC (roughly 1,200ºF) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs. Molten carbonate fuel cells can reach efficiencies approaching 60 percent, considerably higher than the 37-42 percent efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85 percent. Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which they operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost. Molten carbonate fuel cells are not prone to carbon monoxide or carbon dioxide poisoning—they can even use carbon oxides as fuel—making them more attractive for fueling with gases made from coal. Although they are more resistant to impurities than other fuel cell types, scientists are looking for ways to make MCFCs resistant enough to impurities from coal, such as sulfur and particulates. The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

Solid Oxide: Solid oxide fuel cells (SOFC) use a hard, non-porous ceramic compound as the electrolyte. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. SOFCs are expected to be around 50-60 percent efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies could top 80-85 percent. Solid oxide fuel cells operate at very high temperatures—around 1,000ºC (1,830ºF). High temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more sulfur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This allows SOFCs to use gases made from coal. High-temperature operation has disadvantages. It results in a slow startup and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for transportation and small portable applications. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology. Scientists are currently exploring the potential for developing lower-temperature SOFCs operating at or below 800ºC that have fewer durability problems and cost less. Lower-temperature SOFCs produce less electrical power, however, and stack materials that will function in this lower temperature range have not been identified.

Regenerative (Reversible): Regenerative fuel cells (RFC) produce electricity from hydrogen and oxygen and generate heat and water as by-products, just like other fuel cells. However, regenerative fuel cell systems can also use electricity from solar power or some other source to divide the excess water into oxygen and hydrogen fuel—this process is called "electrolysis." This is a comparatively young fuel cell technology being developed by NASA and others.

Source: www.eere.energy.gov/hydrogenandfuelcells/technologies.html

Structure of this report

17. This report is structured as follows: Chapter 2 reviews the analytical approach used in the analysis and identifies the sources of information used for scientific publications and patents. Chapter 3 examines global trends in publishing and patenting for fuel cells, highlighting differences by type of fuel cell and the linkages between the scientific and technological knowledge bases. Chapter 4 assesses publishing and patenting trends at the national level. It explores the degree of national specialization in particular types of fuel cell and examines the degree of international co-operation in fuel cell science. Chapter 5 analyses the role of public and private sector organizations in scientific and technological work related to fuel cells, underscoring trends in intra-sectoral co-operation. The Annexes, provide additional information on the methodology used for the study and the construction of specific indicators, including specialization indexes.

CHAPTER 2. DEVELOPMENT OF FUEL CELL SCIENCE AND TECHNOLOGY

Introduction

18. Although the fuel cells are expected to have a huge economic impact, many fuel cell technologies are still under development. Intensive research and development efforts are therefore needed so that fuel cells can compete with other existing technologies and enter the market place. One must however realize that the field of fuel cells is not homogeneous but heterogeneous and complex. It covers diverse sub-fields that are marked by idiosyncratic characteristics (*e.g.* actors, applications, knowledge and learning process, inputs, regulation) and different historical developments. Mounting evidences suggest that these factors have contributed to influence the pace and direction of the process of scientific and technological knowledge production in these various sub-fields, as well as the intensity of linkages between the realms of science and of technology. The existence of these specific characteristics nevertheless does not deny the presence of competition among the various types of fuel cells technologies (*e.g.* low temperature cells versus high temperature cells) nor does it imply an absence of complementarities their knowledge bases.

19. This chapter examines the complexity of fuel cells from the evolution of its scientific and technological bases over the past decade. In a first section, it quantifies the growth of the scientific and technological knowledge of fuel cells throughout the past decade and highlights the specific trends in the generation of scientific and technological knowledge at the level of sub-fields. In a second section, the chapter deals with the spatial dimension of the field of fuel cells during the same period, characterizing the interrelations among the scientific and technological knowledge bases of its main sub-fields.

Growth of fuel cell science and technology

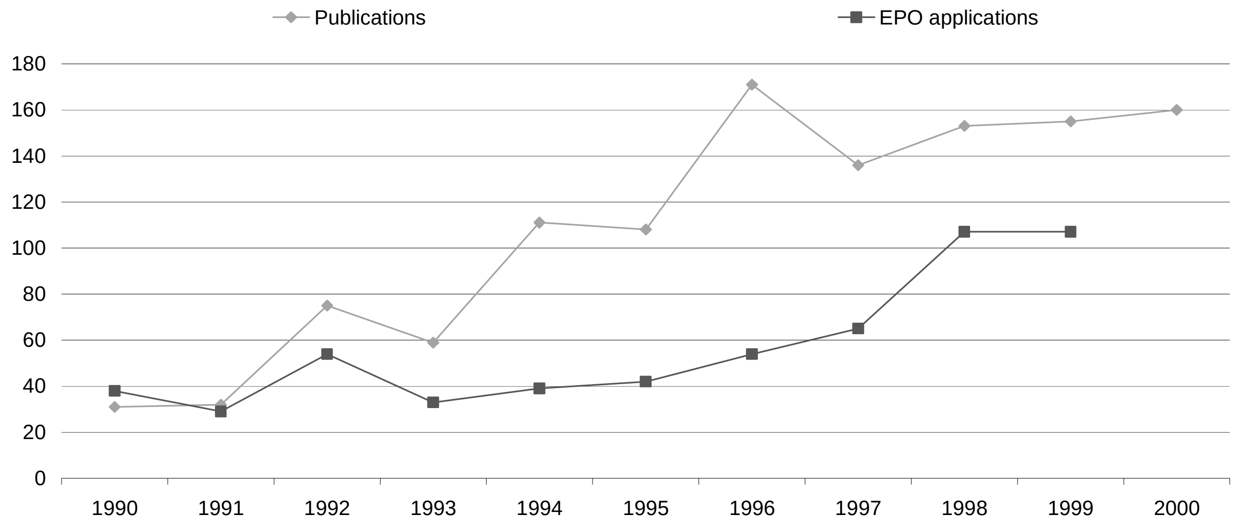
Worldwide trends in global scientific publications and EPO applications

20. Figure 2.1 shows the development of publications and EPO applications in fuel cells worldwide from the beginning of the 1990s up to 2000. The time slope of publications as indicator of scientific development shows small numbers in the early 1990s and a surge after 1993. The number of relevant scientific articles in this field, about 30 in 1990, increased to more than 160 in 2000. The evolution of the number of EPO applications as measure of technological progress throughout 1990-1995 appears to be slow compared with the growth of scientific publications during the same the period, but then sharply increased until 1999.

21. Several factors are likely to explain the different trends in scientific publications and EPO applications in the field of fuel cells as a whole at the worldwide level. First, advances in research infrastructures and changes in national science policies, including restricted finance for public R&D and the growing importance of evaluation of research, over the past decade have contributed to fuel the general increase of scientific publications (Tijssen and Leeuwen, 2003). Second, fuel cells has become a priority in public budgets devoted to energy R&D in many industrialized countries during the 1990s such as the United States (Avadikyan and Larrue, 2003), Canada (Amesse *et al*., 2003), Japan (Avadikyan and Harayama, 2003) and within the framework of international programs (Markantonatos, 2003). Increasing public

resources dedicated to fuel cells R&D in these countries have certainly stimulated the growth in scientific publications[2] and to a lesser extent EPO patent applications in the field over the past recent years.

Figure 2.1. Publications and EPO patent applications, 1990-1999/2000, worldwide



1. Publications in SCI Expanded. Publication years: 1990-2000.

2. EPO applications are classified according to the priority date. Priority years: 1990-1999.

Source: ETDE, ISI, EPO, OECD (treatments).

Scientific publishing and patenting by sub-field

22. Although both scientific publications and EPO applications were on the rise throughout the 1990s in the field of fuel cells, a further examination of the dynamics of scientific and technological knowledge production at the level of its main sub-fields reveals different patterns. Dissimilar growth rates in both scientific publications and EPO applications across and within the main sub-fields of fuel cells characterized this period.

Scientific publishing and patenting across sub-fields

23. Figure 2.2. shows that scientific publications increased sharply in PEMFCs, DMFCs, and to a lesser extent in SOFCs throughout the 1990s while it declined in the four other sub-fields: AFCs, RFCs, PAFCs and MCFCs. SOFCs, MCFCs and PEMFCs, nevertheless accounted for the largest shares of scientific publications, on average, in the field of fuel cells during that period, significantly ahead of PAFCs, DMFCs, AFCs and RFCs.

24. On the technology side, only PEMFCs and DMFCs experienced an increasing share of EPO applications throughout these years. Significant declines in patenting marked MCFCs, AFCs, and SOFCs over the past decade (Figure 2.3.).[3] On average, PEMFCs, followed by SOFCs and RFCs, remained the principal types of fuel cells for which patents were applied at EPO during 1990-1999.

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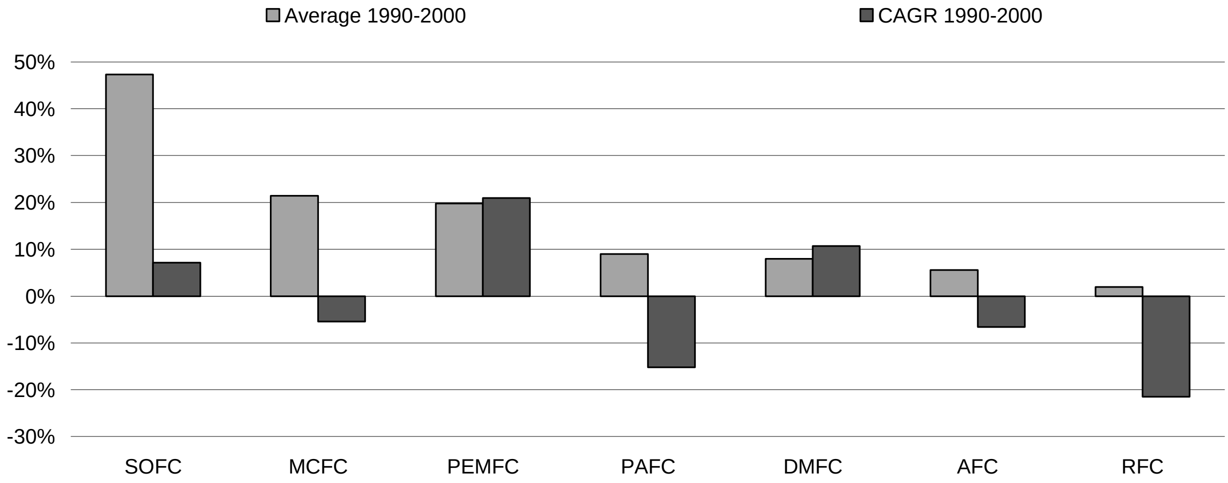
2 . See www.esi-topics.com/fuelcells/.

3 . The compound annual growth rate (CAGR) is a year over year growth rate applied to a variable over a multiple-year period. The formula for calculating CAGR is (Current Value/Base Value)^(1/# of years) -1.

Figure 2.2. Average shares and growth of shares of publications by sub-field, 1990-2000

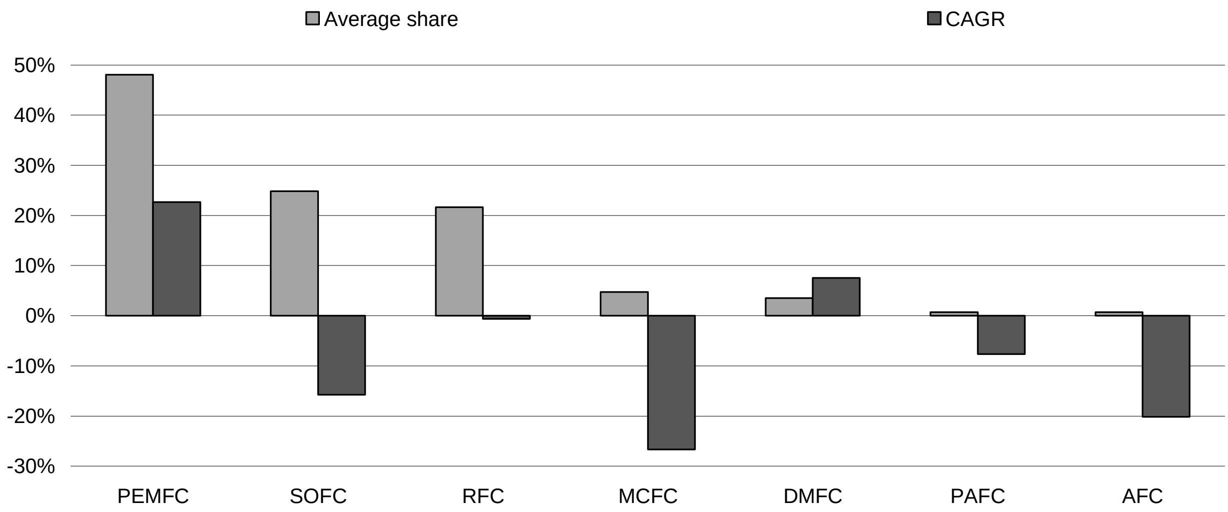


1. CAGR = Compound annual growth rate.

2. Since there are some overlaps between the sub-fields in terms of publications, the sum of the average shares for the period 1990-2000 is higher than 100%.

Source: ETDE, ISI, OECD (treatments).

Figure 2.3. Average shares and growth of shares of EPO applications by sub-field, 1990-1999



1. CAGR = Compound annual growth rate.

2. Since there are some overlaps between the sub-fields in terms of EPO applications, the sum of the average shares for the period 1990-1999 is higher than 100%.

3. EPO applications are classified according to the earliest priority date.

Source: EPO, OECD (treatments).

Scientific publishing and patenting within sub-fields

25. The comparison of the compound annual growth rates of the relative scientific publications and EPO applications in each sub-field of fuel cells also reveals different patterns in the dynamics of scientific and technological knowledge production during the past decade. From Figures 2.2 and 2.3, one can see that PEMFCs and DMFCs were characterized by positive compound annual growth rates of their relative scientific publications and EPO applications. Conversely, RFCs, MCFCs, PAFCs, and AFCs were marked by declining shares in total publications and EPO applications. Finally, SOFCs showed a positive compound annual growth rate in terms of relative scientific output but a negative one in terms of relative EPO applications.

26. To understand these disparate trends in scientific publications and EPO applications, one must take into consideration that the field fuel cells is subjected to a great diversity of its main sub-fields (Bourgeois and Mima, 2003). Almost all the main sub-fields of fuel cells can be described as particular sub-systems of innovation. The latter differentiate from one to another based on the following core elements[4]: products; institutions and mechanisms of interactions between them; knowledge bases and learning processes; basic technologies, inputs, demand, and the related links and complementarities (IPTS, *op. cit.*, Alleau and Barbier, 2001). Moreover, the different types of fuel cells under consideration have not been explored at the same time and thus are not at the same development stages (Schaeffer, 1998) although there is a certain competition among the latter (Mima and Criqui, *op. cit.*). Some of them effectively are relatively mature systems such as AFCs and PAFCs, while others, including PEMFCs, SOFCs, DMFCs, and MCFCs, have attracted mounting attention over these past few years and are still at an early stage (*e.g.* RFCs).

Linkages between scientific and technological knowledge

27. The above analysis provides insight into the expansion of the scientific and technological knowledge bases in fuel cell technology and its main sub-fields throughout the 1990s, but they do not give any information on the interrelations that may exist between them. The production of knowledge is a source of positive externalities (David, 1993; David and Foray, 1995) and is cumulative (Scotchmer, 1991), implying that the expansion of knowledge bases in many fields or sectors can be stimulated by advances in other fields. Furthermore, scientific and technological advances are frequently mutually dependant. Several economic studies (Griliches, 1995; Mansfield, 1995), bibliometric studies (Narin and Noma, 1985; Narin *et al*., 1997), and case studies (Trajtenberg, 1990) stress the positive impact of the production of scientific knowledge to technological developments in various fields and sectors. Reciprocally, technological developments may also influence the production of scientific knowledge by providing it with new questions. In fact, technological developments are still slow and costly in many fields and sectors because scientific knowledge has not yet provided the right answers relative to these issues (Rosenberg, 1991). Examining these various interrelations in the process of knowledge production from a cognitive point of view[5] is thus essential insofar as the former can lead to the reinforcements of the knowledge bases in addition to endogenous cumulative effects (Price, 1963; Scotchmer, *op. cit.*) or even to the creation of new avenues (Kodama, 1992).

4 . See Malerba (2002) for a general description of these elements.

5 . Here, we use the term “cognitive” to stress that these interrelations are only “potential” ones because they may not be effective. Indeed, despite the fact that knowledge is a public good, it does not mean that it is available to all at no cost since the value of positive externalities may be limited by its tacit character (David and Foray, 1995) and by the costs required for its access and transmission (Callon, 1999).

Cognitive interrelations between science and technology

28. Table 2.1. provides insight into the intensity of cognitive linkages between science and technology in the field of fuel cells over two periods: 1990-1994 and 1995-1999. Information contained in this table are based on the results of a lexical analysis performed on the scientific publications and EPO applications' titles and abstracts associated with each main sub-field of fuel cells.[6]

Table 2.1. Cluster membership of the S&T bases of main sub-fields of fuel cells, 1990-1999

	cluster 1	cluster 2	cluster 3	cluster 4	cluster 5	cluster 6	cluster 7
1990-1994	AFCs (T)	DMFCs (S)	RFCs (S)	AFCs (S)	MCFCs (S) MCFCs (T)	DMFCs (T) PEMFCs (T)	PAFCs (S) PAFCs (T) PEMFCs (S) RFCs (T) SOFCs (S) SOFCs (T)
1995-1999	AFCs (T)	PAFCs (T)	AFCs (S)	MCFCs (S) MCFCs (T)	PAFCs (S)	DMFCs (S) DMFCs (T)	PEMFCs (S) PEMFCs (T) RFCs (S) RFCs (T) SOFCs (S) SOFCs (T)

1. T = Technology; S = Science.

2. The distance and aggregation criteria used in this ascendant hierarchical clustering are the Euclidian distance and the Ward criteria.

3. The interpretation of the table is relatively straightforward. If two knowledge bases belong to a same cluster, then it implies that their sets of keywords are rather similar and sub-consequently that they maintain close cognitive relations.

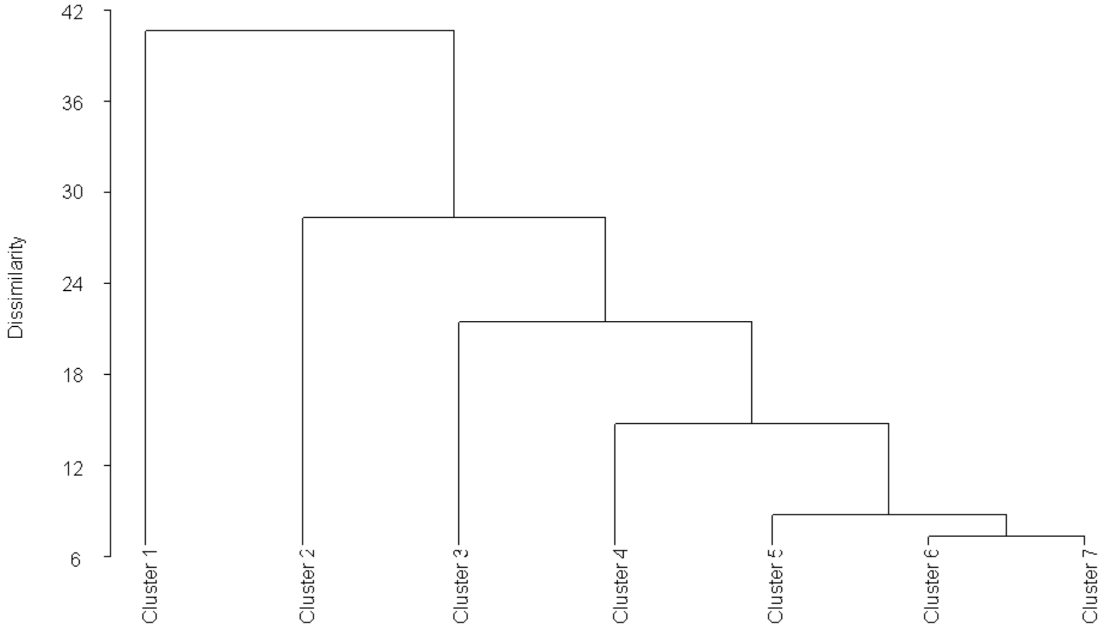
Source: ETDE, ISI, EPO, OECD (treatments).

29. The table shows an increasing interconnection between science and technology from a cognitive point of view. Relatively strong cognitive relations between science and technology characterized several main sub-fields – especially, SOFCs and MCFCs – over the two periods under consideration since same clusters grouped their scientific and technology knowledge bases. These cognitive linkages between science and

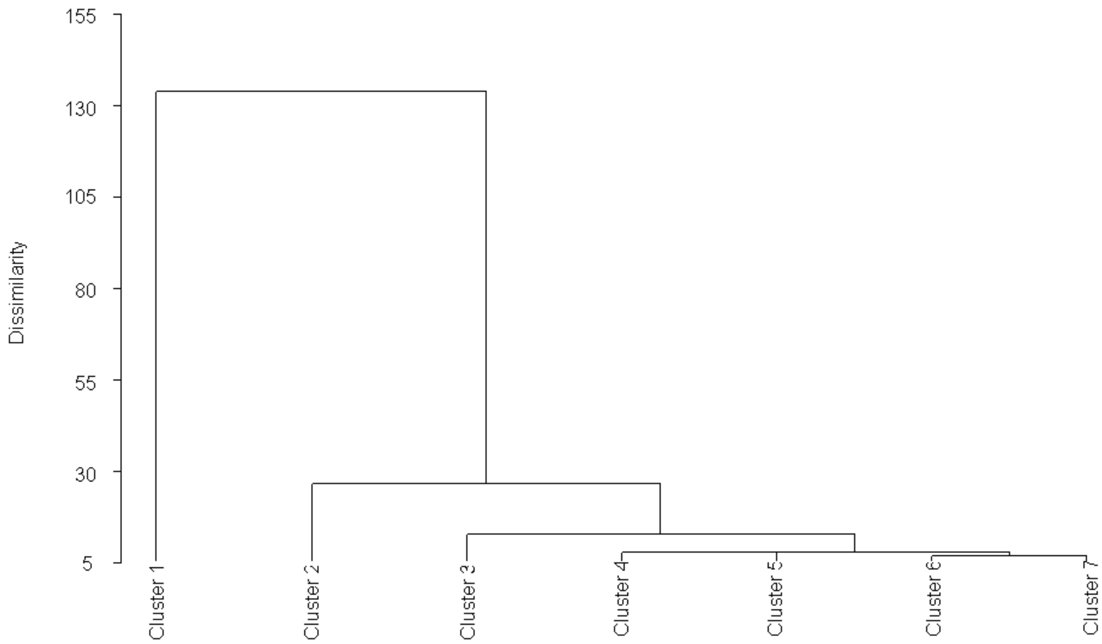
[6] The main steps of the analysis, extensively described in Annex A, are the following. First, each sub-field was split into two dimensions: one for the science side (related scientific publications) and one for the technology side (related EPO applications). Secondly, the titles and abstracts of the publications and EPO applications corresponding to both dimensions of each sub-field were scanned by means of lexical software. This step enabled the definition of a set of relevant keywords for each dimension of the seven main sub-fields of fuel cells and thus the approximate delineation of their scientific and technological knowledge bases. An ascendant hierarchical clustering[6] was performed after a correspondence analysis in order to examine the similarities/dissimilarities among these scientific and technological bases. For each period, the latter were assigned to seven clusters in accordance to a specific criterion of "affinity".

Figure 2.4. Hierarchical clustering of the S&T bases of main sub-fields of fuel cells, 1990-1999

a. Dendrogram, 1990-1994



b. Dendrogram, 1995-1999



1. The distance and aggregation criteria used in this ascendant hierarchical clustering are the Euclidian distance and the Ward criteria.

2. The content of clusters is given in Table 2.1.

Source: ETDE, ISI, EPO, OECD (treatments).

technology in the field of fuel cells also changed throughout the 1990s. In particular, they tended to increase during that period. While these relations were substantial for PAFCs (cluster 7) during 1990-1994 and decreased afterwards, three sub-fields, namely – DMFCs (cluster 6), RFCs (cluster 7), and PEMFCs (cluster 7) – were subjected to opposite trends. It should be noted that these increasing cognitive relations between science and technology might be explained by the fact that researchers and inventors tended to solve increasingly similar problems throughout the 1990s in almost all the main sub-fields of fuel cells. This does not necessarily mean that methods of investigation became roughly similar on the science and technology sides. In fact, weak cognitive linkages between scientific and technological knowledge bases marked only AFCs during the past decade.

Cognitive interrelations among different knowledge bases

30. Significant cognitive interrelations also existing among the knowledge bases of the various sub-fields of fuel cells during the 1990s. From Table 2.1, one can see that knowledge bases associated with different sub-fields of fuel cells are grouped together in same clusters. During the period 1990-1994, the technological base of DMFCs appeared to be close to scientific knowledge of PEMFCs from a cognitive point of view insofar that they are linked with cluster 6. The same goes for the scientific and technological bases of PAFCs and SOFCs. The latter are grouped in cluster 7. This cluster also associates the scientific base of PEMFCs and the technological base of RFCs. Furthermore, it seems that the cognitive relations among the scientific and technological knowledge bases of the main sub-fields of fuel cells slightly changed during the second half of the past decade. As shown in Table 2.1., both the scientific and technological knowledge bases of PEMFCs, RFCs, and SOFCs are linked with a same cluster, namely cluster 7, while those of PAFCs are separated into two single-clusters, cluster 2 and cluster 5.

31. The grouping of the various scientific and technological bases of the main sub-fields of fuel cells in different clusters for the two periods under consideration does not imply that the latter were very dissimilar from a cognitive point of view. The technique used for this analysis does not produce a single set of clusters, but rather a multi-level hierarchy, where clusters at one level are joined together as larger clusters at the next higher level of agglomeration. For that purpose, Figure 2.4a presents the structure of the agglomeration resulting from the hierarchical clustering performed for the period 1990-1994. From this figure, on can see that clusters 5, 6, and 7 agglomerate at an early stage while cluster 1, merges with all other clusters at the latest stage of the hierarchy. Consequently, one can assume that clusters 5, 6, and 7 were subjected to substantial cognitive interrelations during that period. The same goes for clusters 4, 5, 6, and 7 over the years 1995-1999 (Figure 2.4.b.). Finally, the comparison of the composition of the clusters from one period to another emphasizes the strengthening of the cognitive relations among DMFCs, PEMFCs, RFCs, and SOFCs at either the science or the technology side throughout the past decade while the scientific and technological knowledge bases of AFCs remained isolated.

CHAPTER 3. COUNTRY COMPARISONS OF SCIENTIFIC AND TECHNOLOGICAL ACTIVITY IN FUEL CELLS

Introduction

32. This chapter presents a general overview of the scientific and technological activities of the main regions and countries in the OECD the field of fuel cells, providing first insights on the attributes of its institutional structure. In a first section, it assesses the performance of these major regions and countries by measuring their global scientific publications and EPO applications as well as their strengths and weaknesses in the field during the 1990s. It then focuses on the examination of their scientific and technological specialization profiles. The chapter ends with an analysis of the intensity and scope of international scientific co-operation – as measured by internationally co-authored publications – in fuel cells and its main sub-fields.

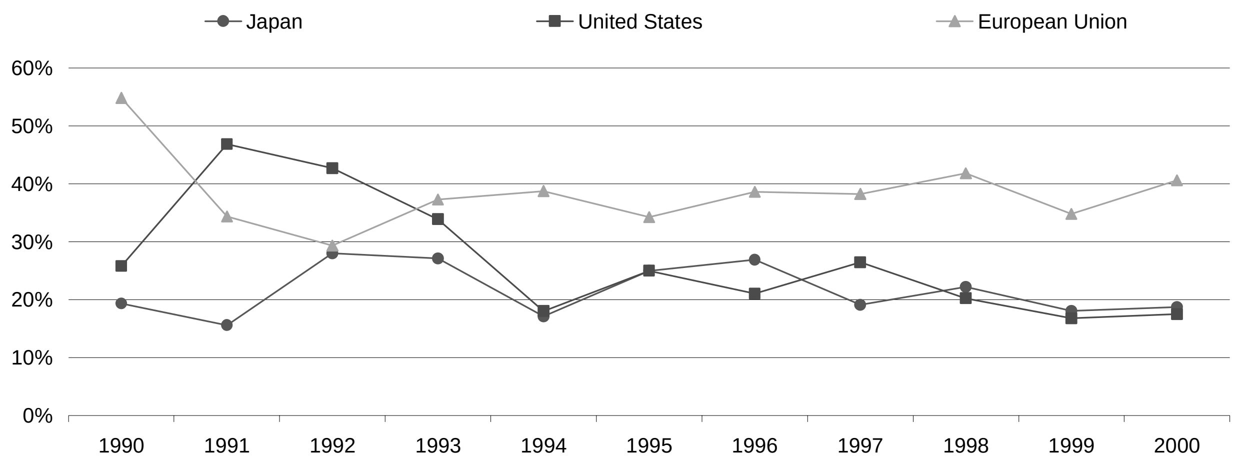
Global scientific and technological output

Comparing scientific publications

33. Despite an overall increase of the number of scientific publications in the field of fuel cells over the past decade, significant regional differences exist within the OECD (Figure 3.1.). In particular, the rate of growth in publications in the European Union (EU-15) outpaced that of the United States and Japan after 1993. As a result, the share of publications produced by EU authors increased to approximately 40% of global output in 2000. The share of the United States declined sharply since the early 1990s, from around 50% in 1991 to less than 20% in 2000.

Figure 3.1. Shares of the United States, the European Union, and Japan in publications, 1990-2000

In percentage

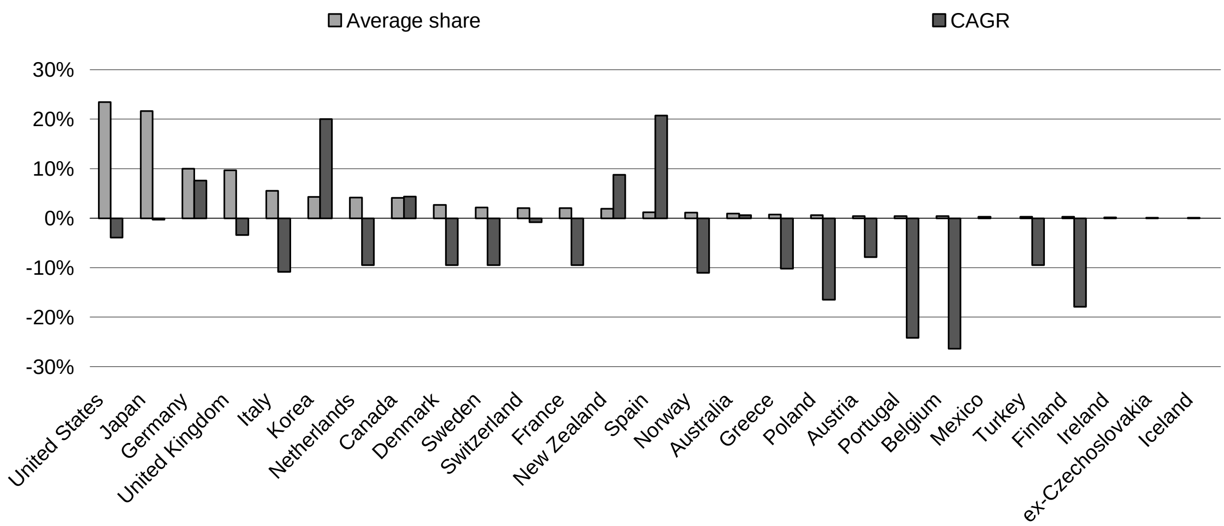


Source: ETDE, ISI, OECD (treatments).

34. Figure 3.2 shows OECD countries according to their average share in total publications over the period 1990-2000. Only eight countries had a share of 4% or more. The dominant country was the United States. Even though its share was declining over that period, the United States produced more than 20% of scientific world's output. The other largest publishing countries included Japan, which average share was comparable to the US, as well as Germany, the United Kingdom, Italy, Korea, the Netherlands, and Canada. Among these countries, Germany and Korea, especially, experienced an increasing share of the world total throughout the past decade while significant decreases marked Italy and the Netherlands. Below these leading countries, seven countries each produced between 1% and 4% of the world scientific output as measured by publications. These medium-size publishing countries were Denmark, Sweden, France, Switzerland, New Zealand, Spain, and Norway. Most the latter, with the exceptions of Spain and New Zealand, saw decreasing shares in total publications in the field over the 1990s.

Figure 3.2. Average shares and growth of shares of OECD countries in publications, 1990-2000

In percentage of total publications



1. CAGR = Compound annual growth rate.

2. Only active OECD countries are shown in the figure.

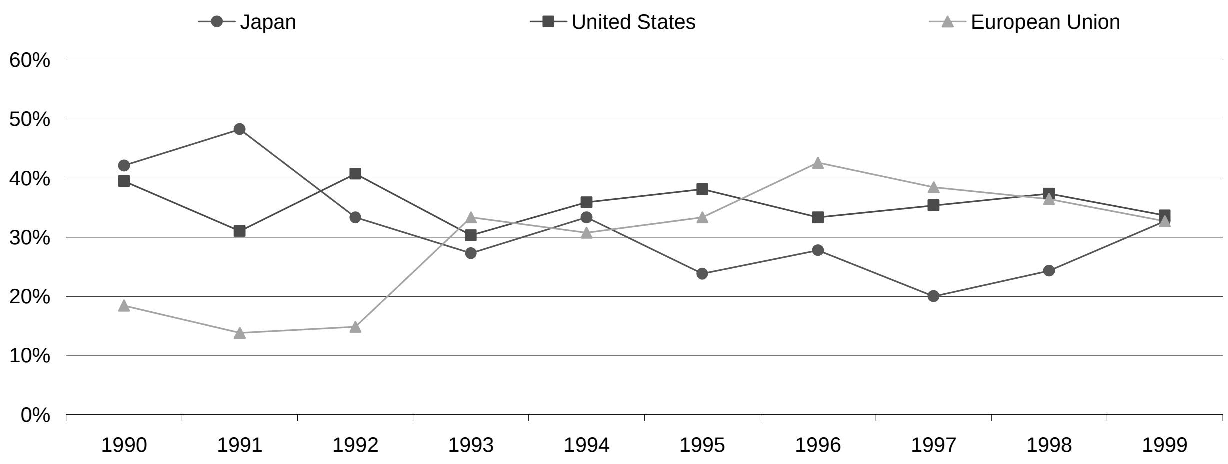
Source: ETDE, ISI, OECD (treatments).

Comparing global EPO applications

35. The mounting share of EU countries as a whole in scientific publications within the field of fuel cells also appears when comparing regional trends in the EPO applications (Figure 3.3.). The EU share in total EPO applications grew at 6% average compound growth rate throughout the past decade while the United States and Japan saw a slow decline in their relative shares of EPO applications during that period. This decline was essentially the consequence of a very low share of the European Union in total EPO applications at the beginning of the 1990s and its sustained increase after 1992. In 1999, the relative EPO applications out of the three main regions of the Triad were roughly similar, each climbing up to around 33%.

Figure 3.3. Shares of the United States, the European Union, and Japan in EPO applications, 1990-1999

In percentage



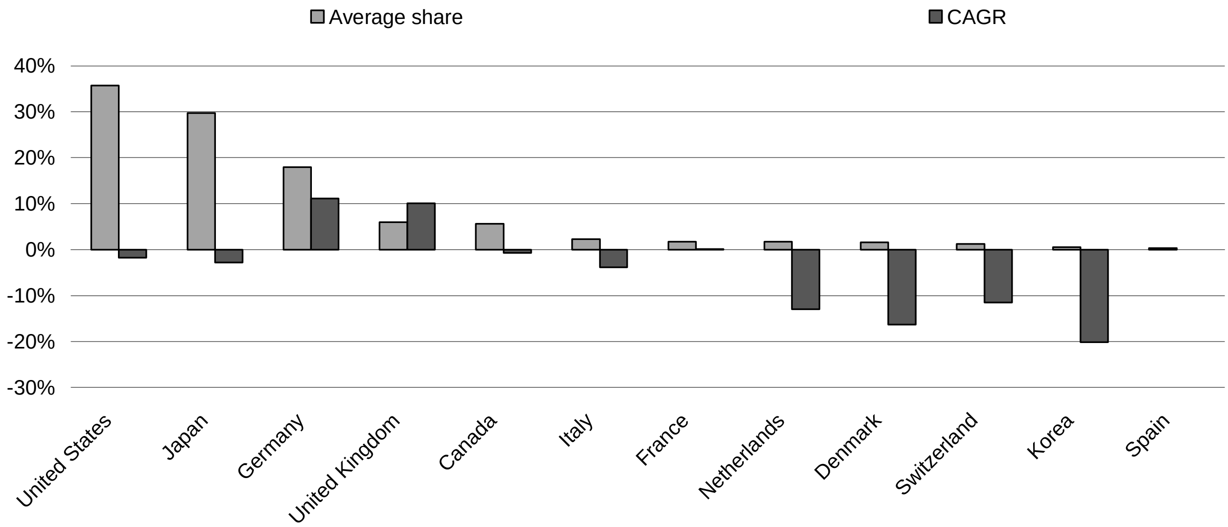
1. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

Source: EPO, OECD (treatments).

36. From Figure 3.4., one can see that the technological capabilities appeared to be rather concentrated in the OECD area since only twelve countries applied for EPO applications from 1990 to 1999. Most the leading OECD countries in terms of scientific publications during the past decade were also strongly involved in EPO applications. This is particularly true of the United States, Japan, Germany, the United Kingdom, and Canada whose average shares in total EPO applications were higher than 4% in the 1990s. This result tends to corroborate the fact that sustained national scientific efforts are required to turn research into technological innovations in this field of fuel cells in many OECD countries even more since science and technology are strongly linked from a cognitive point of view. Under this threshold, average shares higher than 1% characterized five medium-size patenting countries, namely Italy, France, the Netherlands, Denmark, and Switzerland. Finally, Korea and Spain were marked by average shares in total EPO applications lower than 1%.

Figure 3.4. Average shares and growth of shares of OECD countries in EPO applications, 1990-1999

In percentage of total EPO applications



1. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

2. CAGR = Compound annual growth rate.

3. Only active OECD countries are shown in the figure.

Source: EPO, OECD (treatments).

Publications and patent applications by sub-field: strengths and weaknesses

37. In order to assess the strengths and weaknesses of the main regions and countries in the OECD zone, it is helpful to examine their relative scientific publications and EPO applications in the seven sub-fields of fuel cells.

Regional and national scientific strengths and weaknesses

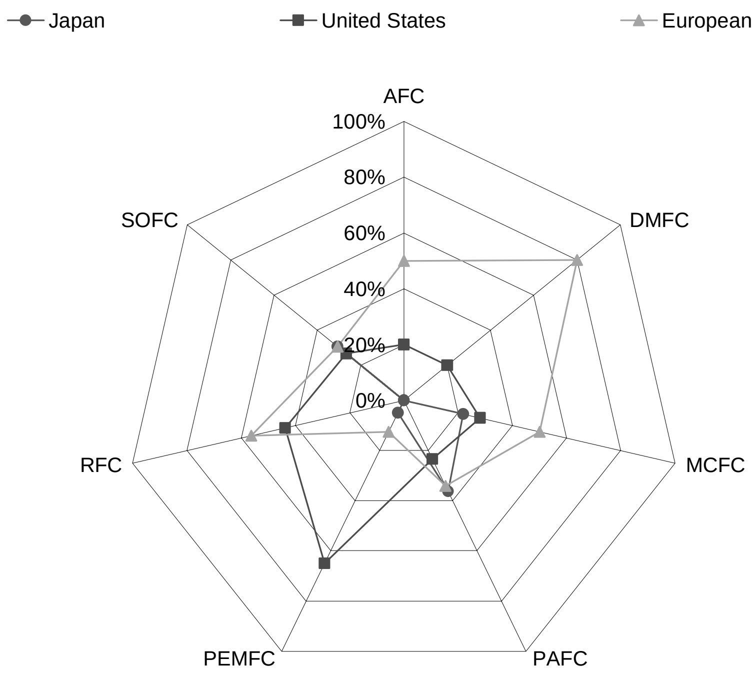
38. Figure 3.5.a. shows the average shares of the United States, Japan, and the United States in total scientific publications of each main sub-field of fuel cells over 1990-1994 and 1995-1999. From this figure, one can see that the European Union had the largest share of publications in AFCs, RFCs, DMFCs, and MCFCs during 1990-1994, accounting for 50% or more of all publications in these fields. Its share declined sharply in RFCs in 1995-1999, but this decline was offset by growing shares of publications in both PEMFCs and SOFCs, which constituted large and fast growing sub-fields on the science side. The EU also maintained the largest share of publications in two small sub-fields, AFCs and DMFCs, and in MCFCs, which was one of the largest sub-fields, despite a declining share of publications in the 1990s.

39. The United States and Japan positions complementary to the EU's. The United States held the largest share of scientific publications in PEMFCs in 1990-1994 (approximately two-thirds of total PEMFC publications), but its share dropped to approximately 30% – below that of the EU – during 1995-2000. In RFCs, the US share of publications surged ahead of the EU's, accounting for almost 60% of all RFC publications in 1995-2000. In total, however, RFCs account for a relatively small share of total fuel cell publications, a share that declined during the decade. Japan, for its part, held the largest shares of publications PAFCs and SOFCs (with the European Union) in the first half of the 1990s. In 1995-2000, Japan apparently broadened its scientific competencies and began publishing in the fields of RFCs and

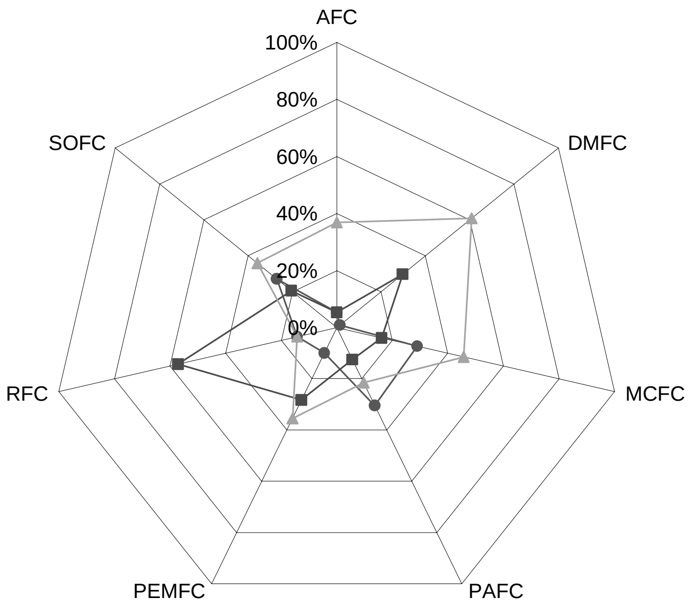
PEMFCs (Figure 3.5.b.). Japanese publications kept a leading position in PAFCs, with more than 30% of all publications in 1995-2000, but its share declined somewhat in SOFCs between the first and second halves of the decade.

40. Figure 3.5. Average shares of the United States, the European Union, and Japan in publications by sub-field, 1990-2000

a. 1990-1994



b. 1995-2000

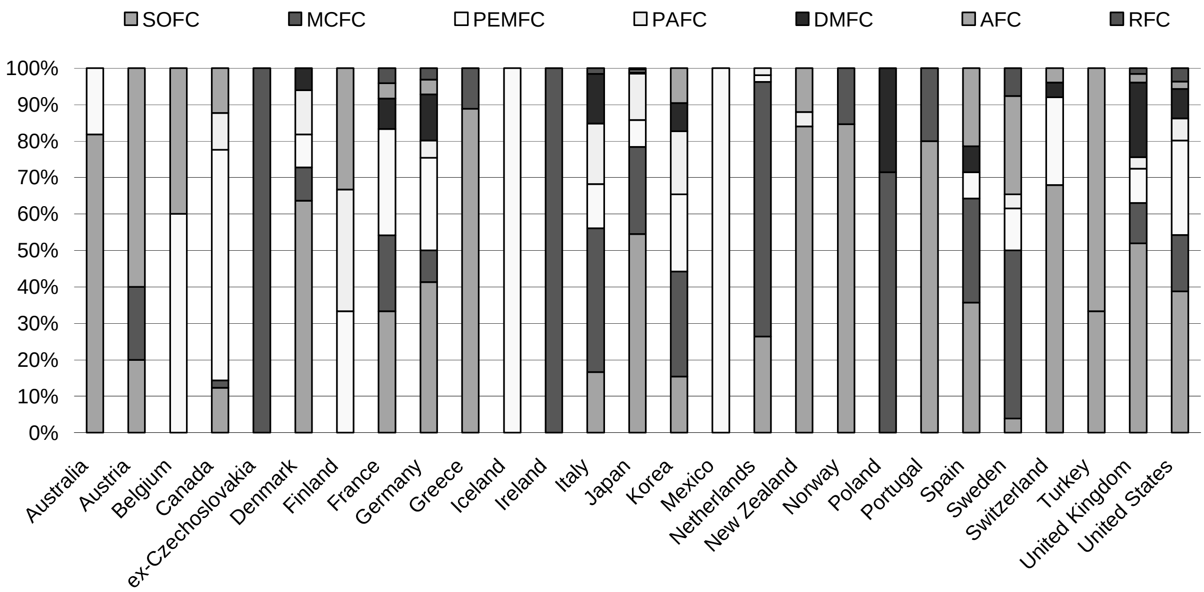


Source: ETDE, ISI, OECD (treatments).

41. Figure 3.6 presents the breakdown of the scientific publications of each OECD country by main sub-field of fuel cells in 1990-2000. A cursory examination of the distribution of scientific publications indicates that countries with a relatively low numbers of fuel cell publications, such as Belgium, Greece, Ireland, and Turkey, tend to concentrate their efforts within a limited number of sub-fields. Countries with average levels of scientific output, such as Denmark, France, New Zealand, Norway, Spain, Sweden and Switzerland present dissimilar publication profiles: while Denmark, France, Spain and Sweden published in several sub-fields during the past decade, New Zealand, Norway and Switzerland had much more focused efforts, more similar to those of the less active countries. Finally, more diversified publication profiles tended to mark the largest publishing countries but the Netherlands.

Figure 3.6. Breakdown of scientific publications by sub-field, 1990-2000

Publications by sub-field as a percentage of the sum of publications in all sub-fields



1. Countries are sorted by alphabetic order.

2. Only active OECD countries are shown in the figure.

3. Here, the total number of publications by country was measured by the sum of its publications in each sub-field.

Source: ETDE, ISI, OECD (treatments).

42. Countries with the largest shares of fuel cell publications tended to exhibit a degree of similarity in their publication profiles. The US, Japan, Germany and the UK not only had publications in almost all sub-fields of fuel cell technology, but SOFCs, MCFCs and PEMFCs accounted for between 72% and 85% of their publications. The balance among these three types of fuel cells varied from country to country, however. Germany and the United States showed higher shares of publications in PEMFCs than did Japan or the UK, which, in turn, showed higher shares of publications in SOFCs. By comparison with the other countries, Germany and the United States also exhibited high shares in DMFCs and RFCs. Korea, another country with a high share of total fuel cell publications had a high concentration of publications in MCFCs and PEMFCs, but relatively smaller shares in SOFCs and RFCs compared with the other countries.

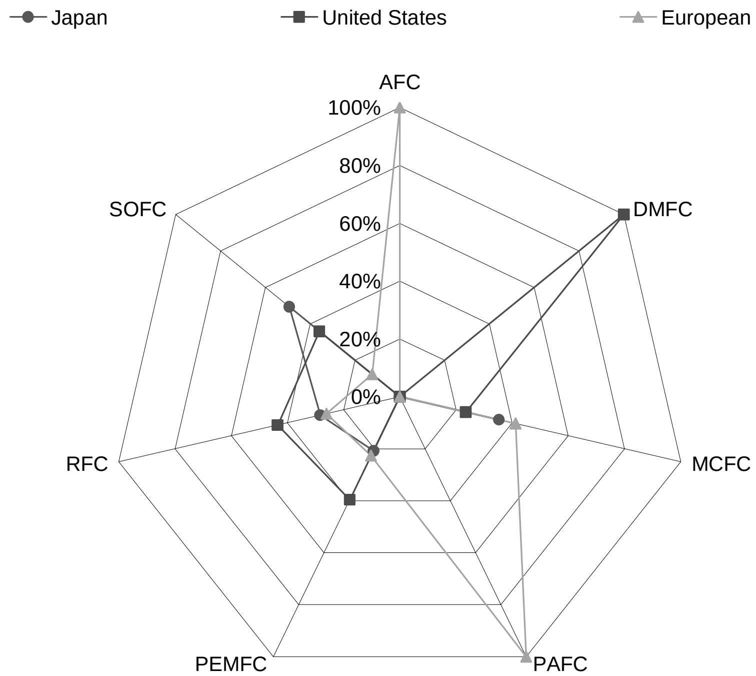
43. Regional and national technological strengths and weaknesses

44. On the patenting side, the average shares of the main regions of the OECD in total EPO applications in each sub-field of fuel cells in 1990-1994 and 1995-1999 are shown in Figure 3.7. Because the absolute number of EPO applications in some sub-fields of fuel cells (AFCs, DMFCs, MCFCs, and PAFCs) was so low in the 1990s, the discussion concentrates on EPO applications in just three subfields: PEMFCs, SOFCs, and RFCs.

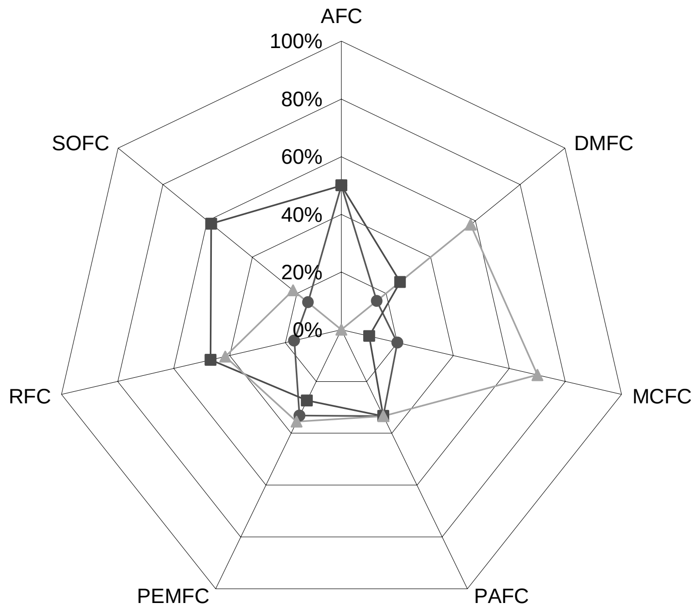
45. The European Union experienced a growing share of EPO applications in PEMFCs throughout the 1990s. During 1995-1999, it took the lead in EPO patenting in this sub-field of fuel cells. The EU also increased its share of patents in two other large sub-fields of fuel cells, namely RFCs and SOFCs, in which it accounted for just above and just below 40% of all EPO patent applications between 1995 and 1999. From Figure 3.7.a., one can also see the United States held the largest share of EPO applications in PEMFCs and RFCs in the first half of the 1990s. In 1995-1999, its share of EPO applications in PEMFC declined from approximately 40% to below 30%, while its share of RFC patent applications increased from to approximately 50% and its share of SOFC applications jumpted from less than 40% to almost 60%. These two latter sub-fields were nevertheless marked by decreasing shares of EPO applications. Japan, for its part, experienced a decreasing share of EPO applications in RFCs and SOFCs throughout the 1990s but was marked by a growing shares of applications in PEMFCs (Figure 3.7.b.).

Figure 3.7. Average shares of the United States, the European Union, and Japan in EPO applications by sub-field

a. 1990-1994



b. 1995-1999



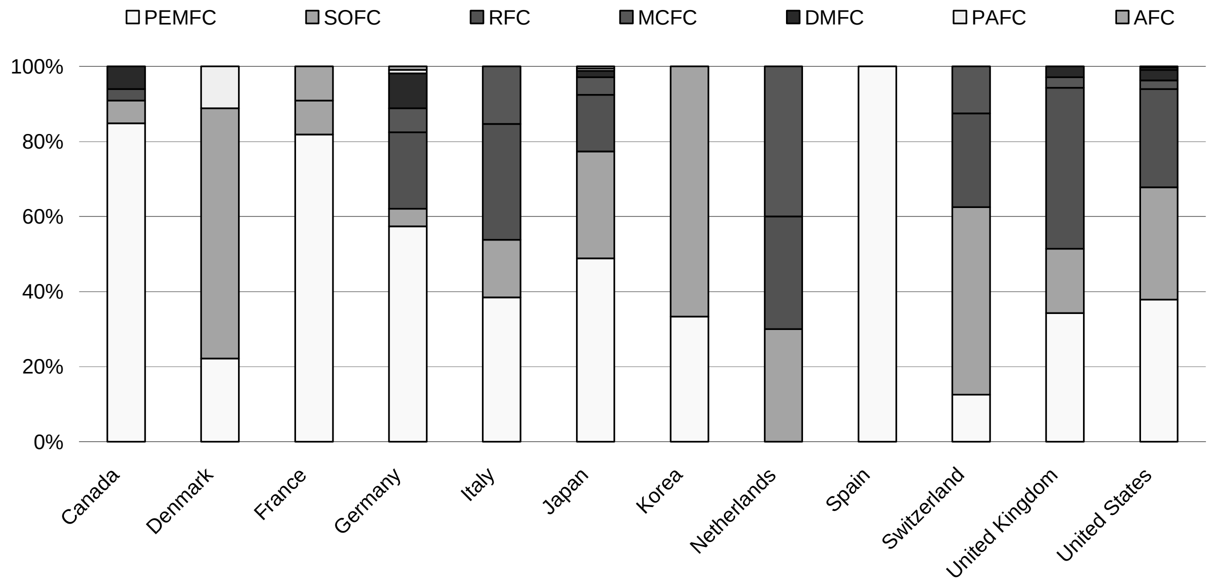
1. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

Source: EPO, OECD (treatments).

46. Figure 3.8. shows the breakdown of the EPO applications of each OECD country by main sub-field as a share of its total EPO applications in all main sub-fields between 1990 and 1999. From this figure, one can see that the EPO applications of the twelve patenting countries were principally concentrated in three main sub-fields of fuel cells – PEMFCs, SOFCs, and RFCs – except for the Netherlands, which patented intensively in MCFCs. These countries nevertheless exhibited certain preferences. Within the group of the largest patenting countries, Canada, Germany, and Japan strongly patented in PEMFCs. Shares higher than the average characterized the United Kingdom and the United States in RFCs. The same goes for Japan and the United States in SOFCs.

Figure 3.8. Breakdown of EPO applications by sub-field, 1990-1999

EPO applications by sub-field as a percentage of the sum of EPO applications in all sub-fields



1. Countries are sorted by alphabetic order.

2. Only active OECD countries are shown in the figure.

3. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

4. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

Source: EPO, OECD (treatments).

47. It is interesting to note that some OECD countries showed dissimilarities in their patterns of scientific and technological activity over the past decade. This concerns all the largest patenting countries but Canada, which intensively published and patented in PEMFCs. For example, although Germany was quite active in PEMFCs on both the science and technology sides during the past decade, it revealed dissimilar publishing and patenting profiles. It patented heavily in RFCs but did not publish much in this sub-field. Conversely, it has a large share of its publications in SOFCs and to a lesser extent in DMFCs, in addition to PEMFCs. Nonetheless, the share of its EPO applications in SOFCs and DMFCs appears low. Japan strongly published in SOFCs, MCFCs, and to a lesser extent in DMFCs but patented mainly in PEMFCs and SOFCs. The United Kingdom published intensively in SOFCs and DMFCs while it principally patented in RFCs, PEMFCs, and SOFCs. Finally, the United States published strongly in SOFCs, PEMFCs, and MCFCs; nevertheless, it patented almost exclusively in RFCs, SOFCs and PEMFCs. A review of the lists of publishing and patenting organizations in Appendices B and C reinforce these differences. Leading publishing organizations are not necessarily leading patenting organizations, reflecting differences in both organizational strategy (especially for firms) and capabilities.

S&T specialization

48. The above analysis underscores certain degrees of scientific and technological specialization among the OECD countries in their fuel cell activity. This analysis does not, however, take into account the relative sizes of the sub-fields. In that respect, it is not surprising to find that several countries appeared to be very active in SOFCs, MCFCs, and PEMFCs on the science side and in PEMFCs, SOFCs, and RFCs on the technology side.

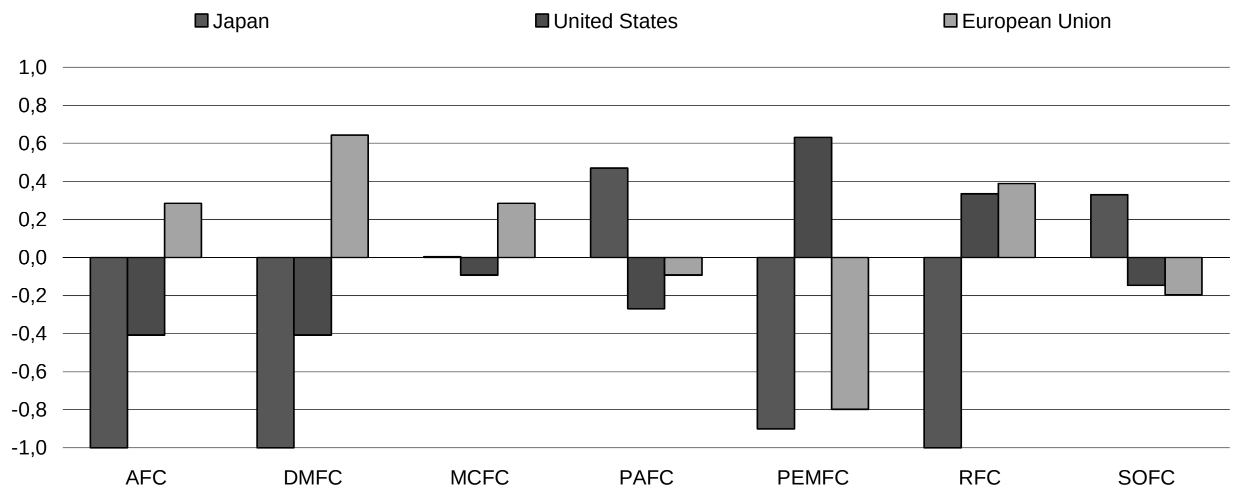
49. In order to better highlight significant scientific and technological specialization profiles, it is necessary to normalize the size of the main sub-fields of fuel cells. This can be done using a specific “specialization index” that is defined as the share of a particular country in a given sub-field of fuel cells relative to its global share in the field. Taking the logarithm of this ratio leads to symmetry around the neutral value 0. Measuring the hyperbolic tangent of the logarithm enables us to keep the value of the index within the range of – 1 and + 1. Its interpretation is relatively straightforward. An index higher (respectively lower) than 0 in a certain sub-field for a given region/country means a relative scientific specialization (respectively under-specialization) of the latter in that sub-field.

Comparing scientific specialization profiles

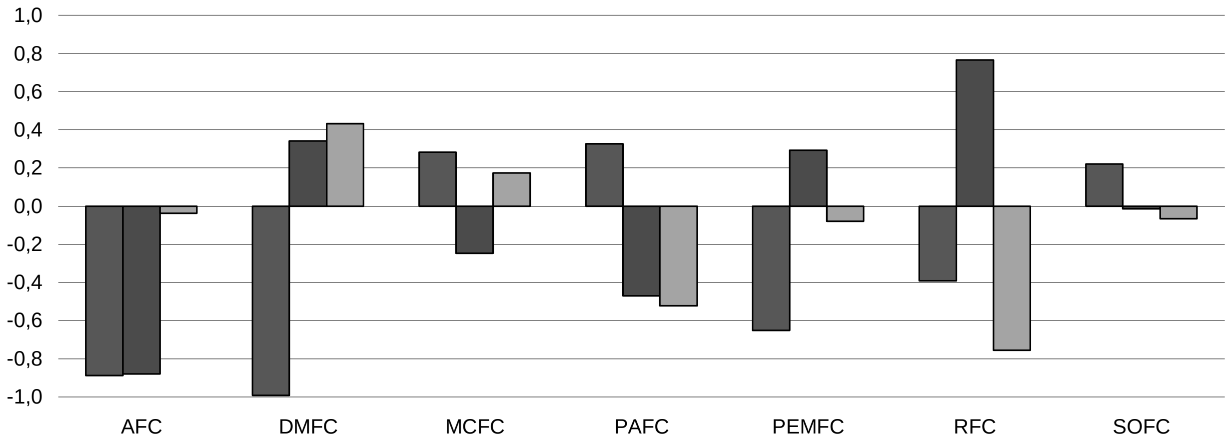
50. Figure 3.9 compares the relative scientific specialization profiles of the United States, the European Union, and Japan in the field of fuel cells over two periods: 1990-1994 and 1995-2000. From Figure 3.9.a., one can see that the United States was relatively strongly specialized in PEMFCs and to a lesser extent in RFCs during the first half of the past decade but under-specialized in the other main sub-fields of fuel cells. During 1995-2000, the scientific specialization profile of the United States changed slightly. It reinforced its relative specialization in RFCs while the value of its index in PEMFC decreased. The United States also fostered its efforts in scientific efforts in DMFCs compared to the European Union and Japan over that period. Its relative scientific specialization index in this sub-field indeed climbed to around 0.3. It nevertheless still showed an under-specialization in the other sub-fields of fuel cells.

Figure 3.9. Relative scientific specialization profiles of the United States, the European Union, and Japan

a. 1990-1994



b. 1995-2000



1. Scientific specialization index as measured by scientific publications.

2. An index higher (respectively lower) than 0 in a certain sub-field for a given region/country means a relative scientific specialization (respectively under-specialization) of the latter in that sub-field.

3. Even though some regions/countries might not show high rates of scientific specialization in certain sub-fields of fuel cells, they can still be quite active in those sub-fields, and their scientific base may be good or even excellent quality. Especially in the case of the smaller region/country and fields, the specialization profiles should be interpreted with caution.

Source: ETDE, ISI, OECD (treatments).

Concerning the European Union, it showed relative scientific specialization in four sub-fields of fuel cells over 1990-1994, namely AFCs, DMFCs, RFCs, and MCFCs. This diversified specialization profile during that period significantly changed afterwards. In the second half of the past decade, it was characterized by relative scientific specialization in only DMFCs and MCFCs. Japan, for its part, showed relative scientific specialization in PAFCs, SOFCs, and to a lesser extent in MCFCs, during 1990-1994. Throughout these years, it was also marked by an absence of scientific activity in AFCs, DMFCs, and RFCs. Finally, Japan was relatively under-specialized compared to the United States and the European Union in PEMFCs. Its relative scientific specialization profile did not experience substantial modifications in the second half of the 1990s. It still showed relative high scores in PAFCs, SOFCs, and MCFCs as well as an absence of scientific activity in DMFCs. In the other main sub-fields of fuel cells (*i.e.* AFCs, PEMFCs, and RFCs), Japan presented relative under-specialization from a scientific point of view.

Table 3.1. Relative scientific specialization profile of the OECD countries, 1990-2000

	AFC	DMFC	MCFC	PAFC	PEMFC	RFC	SOFC
Australia	-1,0	-1,0	-1,0	-1,0	0,0	-1,0	0,6
Austria	1,0	-1,0	0,0	-1,0	-1,0	-1,0	-0,7
Belgium	1,0	-1,0	-1,0	-1,0	0,8	-1,0	-1,0
Canada	0,7	-1,0	-1,0	0,2	0,8	-1,0	-0,9
ex-Czechoslovakia	-1,0	-1,0	0,9	-1,0	-1,0	-1,0	-1,0
Denmark	-1,0	-0,1	-0,6	0,4	-0,6	-1,0	0,4
Finland	1,0	-1,0	-1,0	0,9	0,5	-1,0	-1,0
France	-0,2	0,2	0,0	-1,0	0,4	0,6	-0,3
Germany	-0,1	0,6	-0,6	-0,5	0,4	0,5	0,0
Greece	-1,0	-1,0	-0,5	-1,0	-1,0	-1,0	0,6
Iceland	-1,0	-1,0	-1,0	-1,0	0,9	-1,0	-1,0
Ireland	-1,0	-1,0	0,9	-1,0	-1,0	-1,0	-1,0
Italy	-1,0	0,6	0,6	0,6	-0,4	-0,2	-0,7
Japan	-1,0	-1,0	0,2	0,4	-0,7	-0,9	0,2
Korea	0,6	0,1	0,4	0,6	0,1	-1,0	-0,8
Mexico	-1,0	-1,0	-1,0	-1,0	0,9	-1,0	-1,0
Netherlands	-1,0	-1,0	0,9	-0,9	-1,0	-1,0	-0,4
New Zealand	0,8	-1,0	-1,0	-0,6	-1,0	-1,0	0,6
Norway	-1,0	-1,0	-0,3	-1,0	-1,0	-1,0	0,6
Poland	-1,0	0,9	0,9	-1,0	-1,0	-1,0	-1,0
Portugal	-1,0	-1,0	0,0	-1,0	-1,0	-1,0	0,5
Spain	0,9	0,0	0,3	-1,0	-0,7	-1,0	-0,2
Sweden	0,9	-1,0	0,7	-0,7	-0,4	0,9	-1,0
Switzerland	-0,2	-0,5	-1,0	-1,0	0,3	-1,0	0,4
Turkey	1,0	-1,0	-1,0	-1,0	-1,0	-1,0	-0,3
United Kingdom	-0,6	0,8	-0,5	-0,7	-0,5	-0,1	0,3
United States	-0,7	0,2	-0,2	-0,3	0,4	0,6	-0,1

1. Scientific specialization index as measured by scientific publications.

2. An index higher (respectively lower) than 0 in a certain sub-field for a given region/country means a relative scientific specialization (respectively under-specialization) of the latter in that sub-field.

3. Even though some regions/countries might not show high rates of scientific specialization in certain sub-fields of fuel cells, they can still be quite active in those sub-fields, and their scientific base may be good or even excellent quality. Especially in the case of the smaller region/country and fields, the specialization profiles should be interpreted with caution.

4. Only active OECD countries are shown in the table.

Source: ETDE, ISI, OECD (treatments).

51. From Table 3.1., one can see that slightly different relative scientific specialization profiles characterised OECD countries in the 1990s. For instance, France, the United States, and Germany showed relatively high scientific specialization in DMFCs, PEMFCs, and RFCs. Canada and Finland were characterized by almost equivalent scientific specialization patterns in AFCs, PAFCs, and PEMFCs. The same goes for Portugal, Norway, and Greece, which revealed a strong relative scientific specialization in SOFCs, and a certain under-specialization in the other main sub-fields of fuel cells. Italy presented relative strong scientific specialization in DMFCs, MCFCs, and PAFCs, while Korea had a high relative specialization in AFCs, MCFCs, and PAFCs, and to a lesser extent in DMFCs and PEMFCs. The United Kingdom showed positive values in only DMFCs and SOFCs. Australia and Switzerland specialized mostly in SOFCs and PEMFCs. Austria and Spain mainly concentrated on AFCs and MCFCs from a scientific point of view. Finally, Denmark revealed a relative scientific specialization profile roughly

similar to the Japanese one with positive values in PAFCs and SOFCs and negative ones in AFCs, DMFCs, PEMFCs and RFCs.

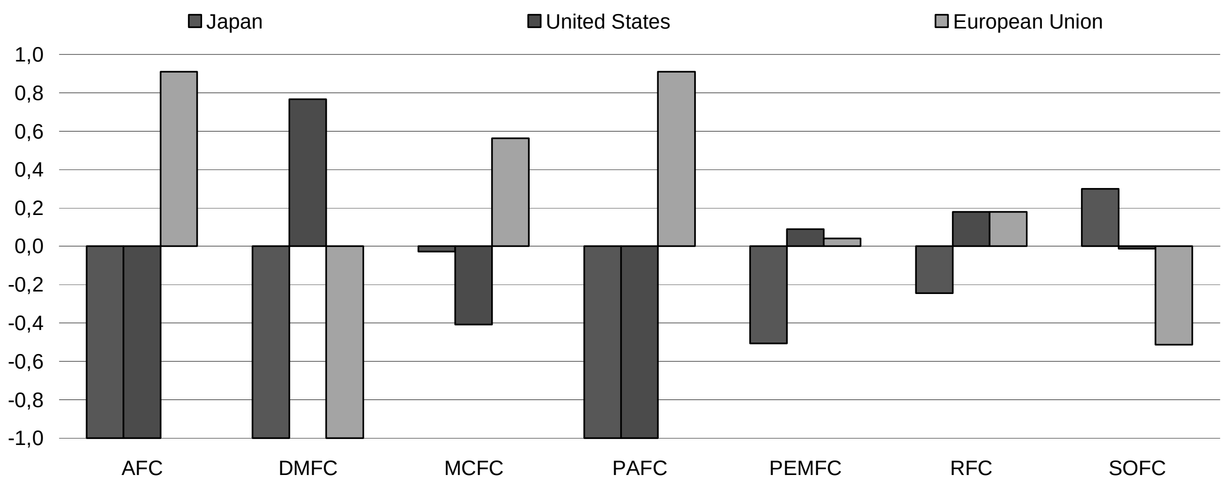
Comparing technological specialization profiles

52. Because the absolute number of EPO applications in some sub-fields of fuel cells (AFCs, DMFCs, MCFCs, and PAFCs) was very low in the 1990s, it is preferable to concentrate the analysis of the relative technological specialization profiles of the regions/countries of the OECD zone on PEMFCs, SOFCs, and RFCs.

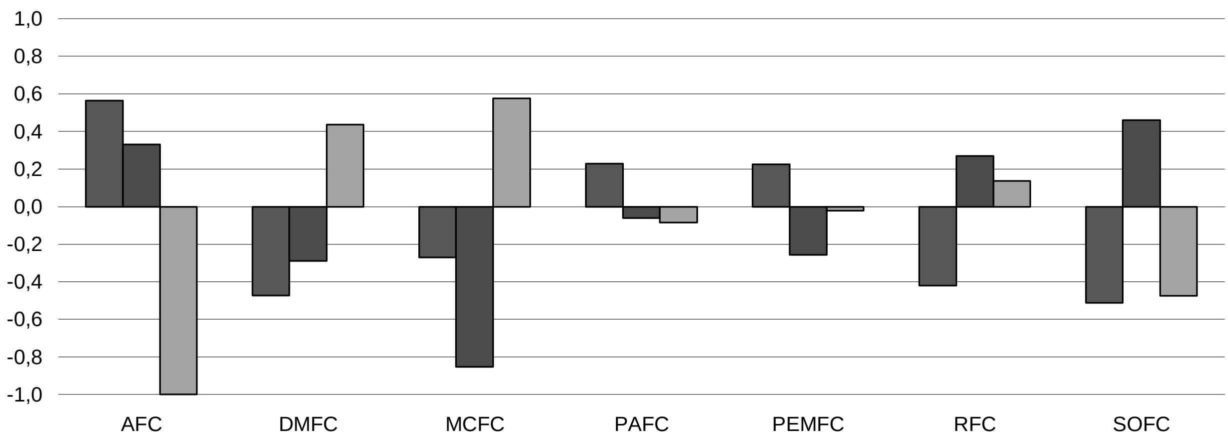
53. The United States specialized in RFCs, and to a lesser extent in PEMFCs during the first half of the past decade (Figure 3.10.a). It showed an under-specialisation in SOFCs. Throughout the period 1995-1999, its relative technological specialization profile changed substantially. The United States showed a relative technological specialization in RFCs and SOFCs but an under-specialization in PEMFCs (4.10.b.). The European Union, for its part, was also specialized in RFCs and PEMFCs and revealed an under-specialization in SOFCs at the beginning of the past decade. It also revealed an absence of technological activity in DMFCs. Nevertheless, the European Union presented a different relative technological specialization profile afterwards. Its relative technological index was above 0 in RFCs and below 0 in PEMFCs and SOFCs. During the years 1990-1994, Japan specialized in SOFCs and revealed and under-specialisation in PEMFCs and RFCs. Its patterns of relative technological specialization largely changed in the second half of the past decade. It henceforth specialized in PEMFCs and revealed an under-specialization in SOFCs and RFCs during these years.

Figure 3.10. Relative technological specialization profiles of the United States, the European Union, and Japan

a. 1990-1994



b. 1995-1999



1. Technological specialization index as measured by EPO applications. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

2. An index higher (respectively lower) than 0 in a certain sub-field for a given region/country means a relative technological specialization (respectively under-specialization) of the latter in that sub-field.

3. Even though some regions/countries might not show high rates of technological specialization in certain sub-fields of fuel cells, they can still be quite active in those sub-fields, and their technological base may be good or even excellent quality. Especially in the case of the smaller region/country and fields, the specialization profiles should be interpreted with caution.

Source: EPO, OECD (treatments).

54. From Table 3.2., one can see that the Netherlands and Switzerland had similar relative technological specialization profiles to that of the United States during the past decade, with a focus on RFCs and SOFCs. Korea and Denmark like Japan revealed relative technological specialization in SOFCs over that period while Canada, France, Germany, and Spain mainly showed positive values in PEMFCs. The United Kingdom and Italy, for their parts, specialized in RFCs.

Table 3.2. Relative technological specialization profile of the OECD countries, 1990-1999

	AFC	DMFC	MCFC	PAFC	PEMFC	RFC	SOFC
Canada	-1,0	0,5	-1,0	-1,0	0,5	-1,0	-0,9
Denmark	-1,0	-1,0	-1,0	1,0	-0,6	-1,0	0,8
France	1,0	-1,0	-1,0	-1,0	0,6	-1,0	-0,7
Germany	0,3	0,8	0,4	0,3	0,2	0,0	-0,9
Italy	-1,0	-1,0	0,8	-1,0	-0,2	0,3	-0,4
Japan	-0,2	-0,6	0,0	-0,2	0,0	-0,3	0,2
Korea	-1,0	-1,0	-1,0	-1,0	-0,4	-1,0	0,8
Netherlands	-1,0	-1,0	1,0	-1,0	-1,0	0,3	0,2
Spain	-1,0	-1,0	-1,0	-1,0	0,6	-1,0	-1,0
Switzerland	-1,0	-1,0	0,8	-1,0	-0,8	0,3	0,7
United Kingdom	-1,0	-0,2	-0,4	-1,0	-0,3	0,6	-0,3
United States	-0,3	-0,2	-0,6	-0,3	-0,2	0,2	0,2

1. Technological specialization index as measured by EPO applications. EPO applications are classified according to the earliest priority date and the countries of residence of inventors.

2. An index higher (respectively lower) than 0 in a certain sub-field for a given region/country means a relative technological specialization (respectively under-specialization) of the latter in that sub-field.

3. Even though some regions/countries might not show high rates of technological specialization in certain sub-fields of fuel cells, they can still be quite active in those sub-fields, and their technological base may be good or even excellent quality. Especially in the case of the smaller region/country and fields, the specialization profiles should be interpreted with caution.

4. Only active OECD countries are shown in the table.

Source: EPO, OECD (treatments).

Patterns of international scientific cooperation

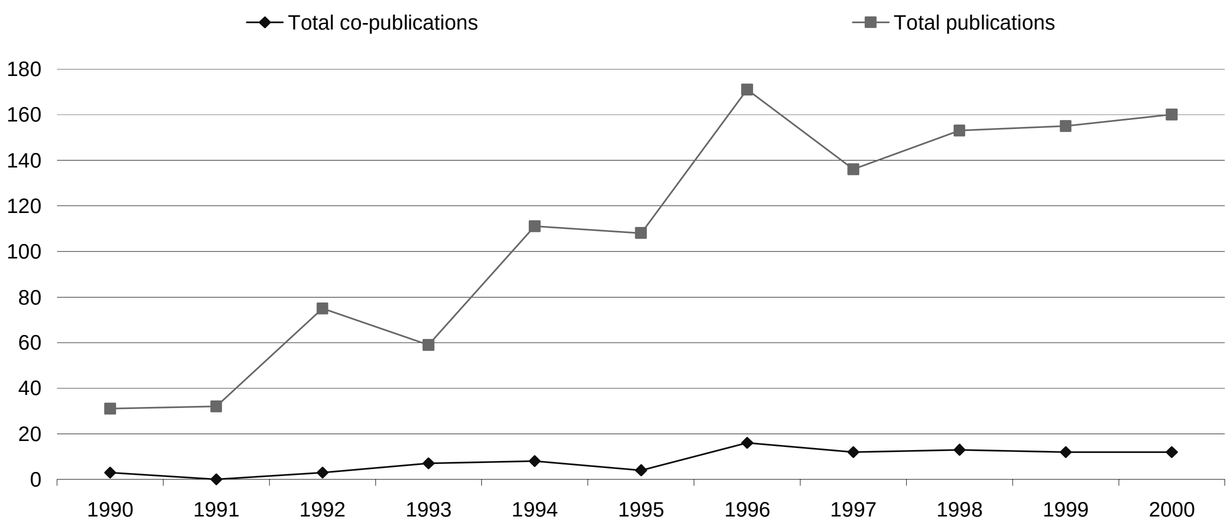
Trends in internationally co-authored publications

55. In the past two decades, scientific co-operation and subsequently co-authored publications (hence, co-publications) have followed an upward trend in almost all scientific fields. Many scientists and engineers are now actively involved in both domestic and international cooperation. For instance, the share of publications produced by co-authors in different countries (*i.e.* internationally co-authored publications) rose from 14% in 1986 to 31% in 1999. Nearly all OECD countries experienced high growth in international scientific co-publications (OECD, 2002*b*). The following sections examine the trends in internationally co-authored publications within the field of fuel cells and its main sub-fields.

Global trends in internationally co-authored publications

56. International scientific cooperation as measured by international co-publications in the field of fuel cells nevertheless followed a different trend. As shown by Figure 3.11, the share of total internationally co-authored publications in total publications in the field over the period was relatively stable throughout the 1990s with annual values lower than 10%. Therefore, one can assume that the globalization of scientific research in the field is still very weak as well as the international dissemination of scientific knowledge.

Figure 3.11. Publications and international co-publications, 1990-2000, worldwide

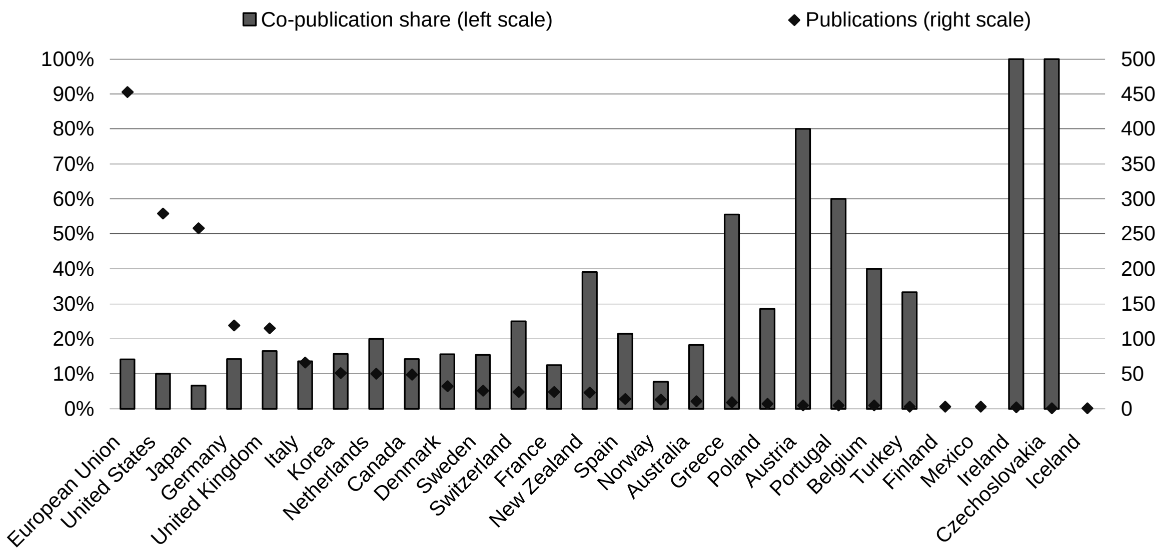


Source: ETDE, ISI, OECD (treatments).

57. Figure 3.12 shows the total number of publications and the ratio of international co-publications to total publications by country/region for the period 1990-2000. The smallest contributors in total scientific publications in fuel cells tended to exhibit the highest shares of internationally co-authored articles, which

accounted for more than 30% of publications in Greece, Austria, Portugal, Belgium, Turkey, Ireland, and in the former Czechoslovakia. On the contrary, the leading countries/regions in terms of scientific contributions revealed the lowest level of international co-authorship publications. This includes the United States, Japan, Germany, the United Kingdom, Italy, Korea, the Netherlands, and the European Union. Although a negative correlation between the number of total publications and the propensity to cooperate at the international level is seen in Figure 3.12, it is important to stress that the differences in the propensity to cooperate of the OECD countries can also be due to disparities in S&T policy, geographic situation, country's size, and culture.

Figure 3.12. Publications and international co-publication shares of OECD countries/regions, 1990-2000



1. Co-publications are measured at the worldwide level. This means that co-publications between OECD countries and non-OECD countries are considered.

2. The EU ratio excludes intra-EU co-publications.

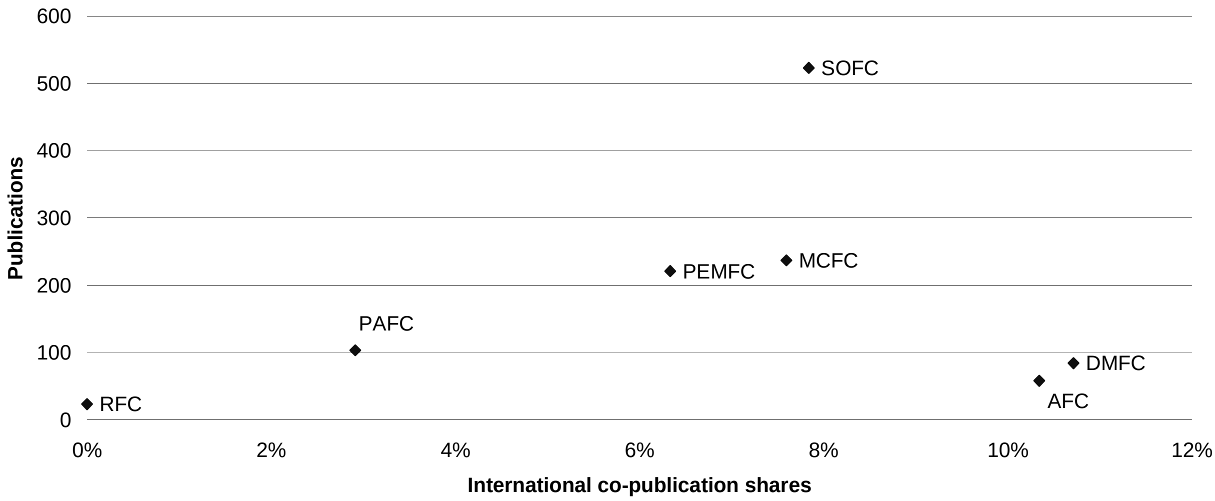
3. Only active OECD countries are shown in the figure.

Source: ETDE, ISI, OECD (treatments).

Internationally co-authored publications by sub-field

58. Figure 3.13 presents the publications and international co-publication shares by sub-field in the 1990s. From this figure, one can see that the share of internationally co-authored fluctuated considerably from one sub-field to the next. For instance, the share of international co-publications in AFCs and DMFCs was higher than 10% while it remained below 3% in PAFCs. Moreover, an absence of international co-publications characterized RFCs in 1990s. Finally, the shares of internationally co-authored publications varied from 6% to 8% in PEMFCs, MCFCs, and SOFCs. These results tended to demonstrate the propensity to cooperate at the international level did not only depend on the level of the scientific publications in each sub-field. Rather, certain sub-fields such as AFCs and DMFCs seemed more incline to favor international scientific collaborations than others.

Figure 3.13. Publications and international co-publication shares by sub-field, 1990-2000

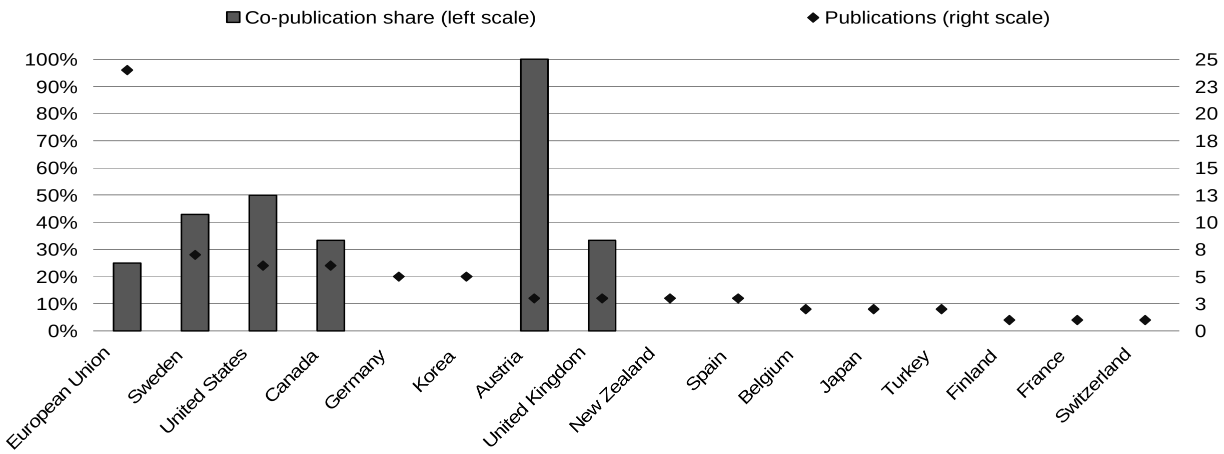


Source: ETDE, ISI, OECD (treatments).

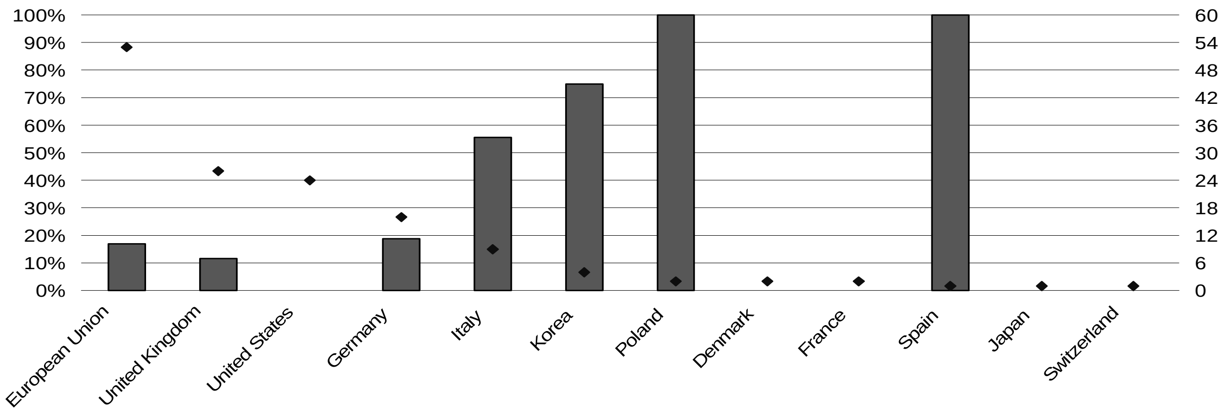
59. Not only did the shares of internationally co-authored publications vary across the sub-fields, but the propensities to cooperate at the international level also differed greatly across the large and medium-sized publishing countries/regions over the 1990s (Figure 3.14.). In AFCs, one can see that the ratio of international co-publications exceeded 40% in Sweden and the United States, while Germany and Korea recorded no co-publications. Co-publications amounted to around 30% and 25% of publications in the Canada and the European Union, respectively (Figure 3.14.a.). In DMFCs, the share of internationally co-authored publications climbed up to more than 50% in Italy and Korea while it was 0% in the United States. The EU countries as a whole revealed a ratio near 20% (Figure 3.14.b).

Figure 3.14. Publications and international co-publication shares of OECD countries/regions, 1990-2000

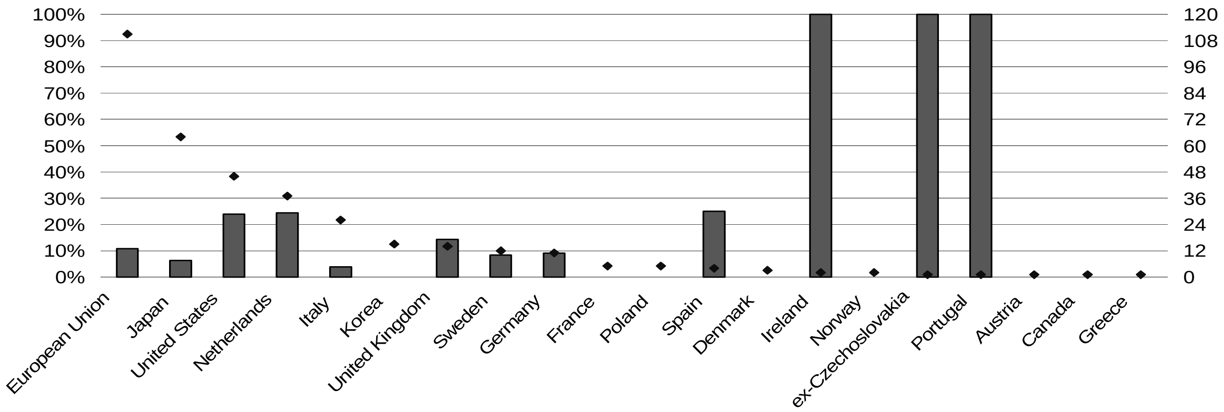
a. AFC



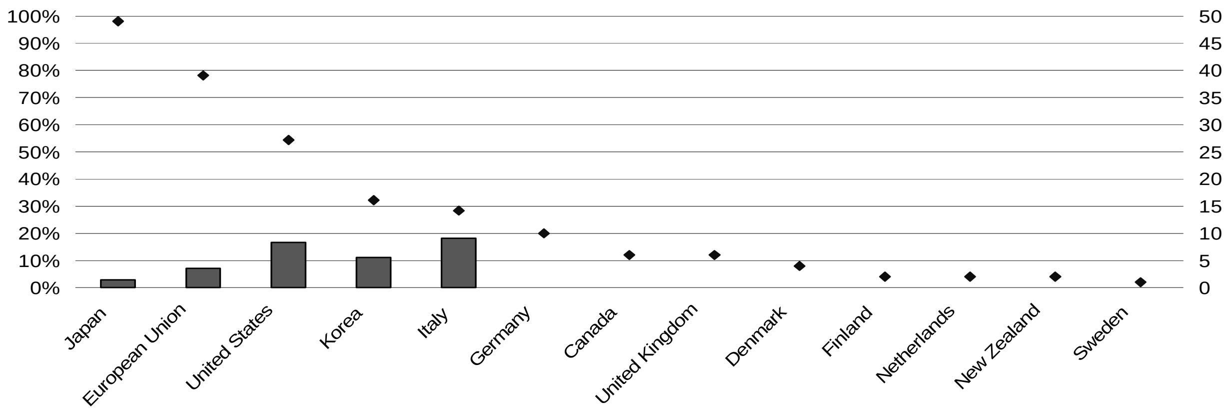
b. DMFC



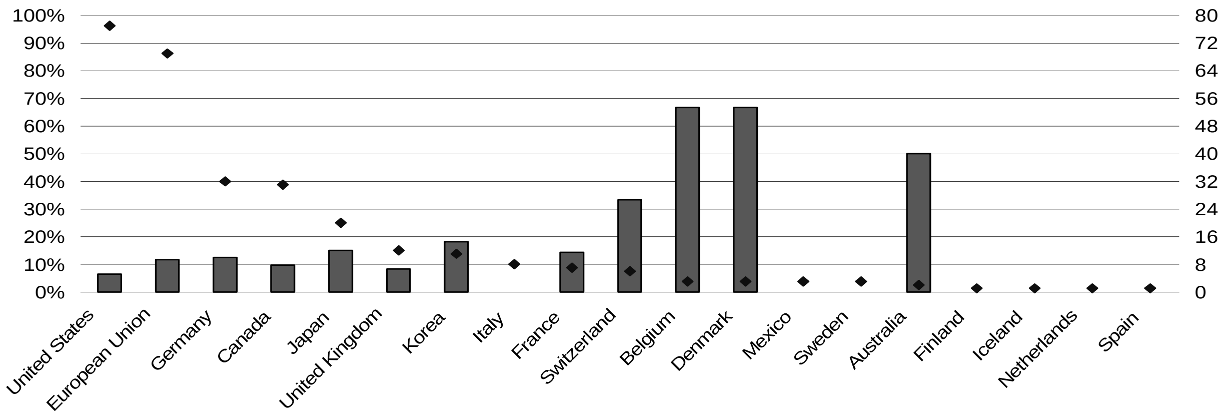
c. MCFC



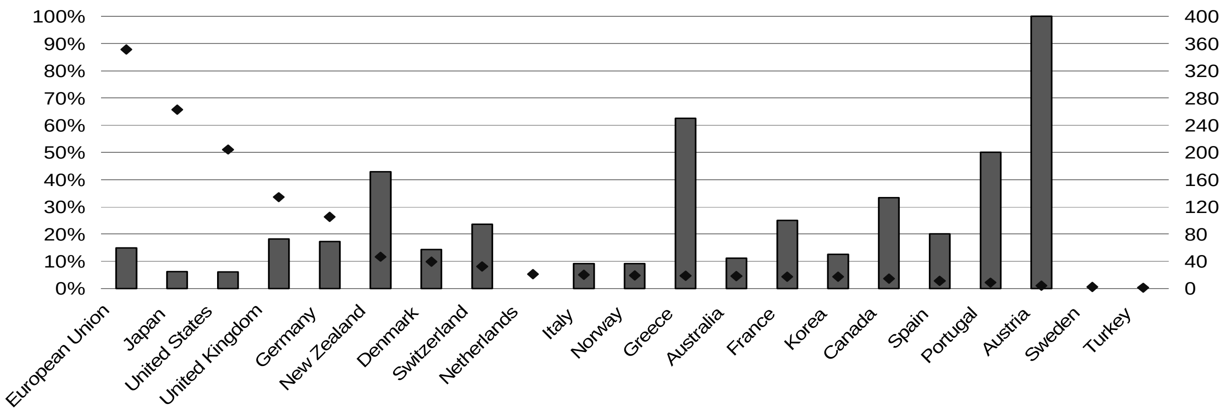
d. PAFC



e. PEMFC



f. SOFC



1. Co-publications are measured at the worldwide level. This means that co-publications between OECD countries and non-OECD countries are considered.

2. The EU ratio excludes intra-EU co-publications.

3. Only active OECD countries are shown in the figure.

Source: ETDE, ISI, OECD (treatments).

60. In MCFCs, the share of international co-publications was higher than 20% in the United States and the Netherlands while it was lower 10% in Italy and Japan (Figure 3.14.c). A ratio above 10% characterized the European Union in that sub-field.

61. Among the leading publishing countries/regions in PAFCs, only Italy, the United States, and Korea enjoyed high shares of international co-publications while the European Union, Japan, Germany had shares below 10% (Figure 3.14.d.).

62. In PEMFCs, most the leading publishing countries/regions but the United States and Japan were marked by ratios around 10%. A ratio higher than 15% characterized Japan while the United States revealed a very weak propensity to cooperate at the world level (Figure 3.14.e).

63. Significant differences nevertheless appeared in SOFCs in the 1990s. While the European Union, the United Kingdom, and Germany were strongly involved in internationally co-authored publications in

relative terms with ratios higher than 15%, Japan and the United States showed a weak propensity to cooperate at the international level (Figure 3.14.f).

64. Lastly, RFCs were marked by an absence of internationally co-authored publications during the past decade.

The structure of the networks of internationally co-authored publications

The structure of the global network of internationally co-authored publications

65. Data in Table 3.3 indicates the share of internationally co-authored publications by country in the field of fuel cells as a whole over the period 1990-2000. The table gives a matrix of internationally co-authored publications by the OECD countries. Reading along the rows allows one to see the proportion of the total co-publications undertaken by that country in cooperation with the OECD countries.

66. From Table 3.3, it is apparent that the United States (US), the United Kingdom (UK), and Germany (D) were locally central in the international research network of fuel cells in the 1990s. The United States (US) was strongly involved in co-operation with Japan (JP) and to a lesser extent with Korea (KR), the Netherlands (NL), Austria (A), Canada (CA), and Italy (I). The United States had few linkages with Denmark (DK), France (F), Germany (D), Spain (E), Switzerland (CH), and Turkey (TR). The United Kingdom (UK) was relatively strongly involved in co-operation with the New Zealand (NZ), and to a lesser extent with Japan (JP), Greece (EL), Germany (D), and Canada (CA). It had a small number of linkages with Denmark (DK), Korea (KR), Portugal (P), and Switzerland (CH). Germany (D) was mainly engaged in cooperation with Denmark (DK), Greece (EL), and the United Kingdom (UK). It had limited linkages with ex-Czechoslovakia (CZ), France (F), Japan (JP), the Netherlands (NL), Spain (E), and the United States (US).

67. Conversely, some countries seemed to play a peripheral role in this network during the past decade. This notably concerns Ireland, Australia, Turkey, Belgium, and the former Czechoslovakia, but also Poland, Austria, Sweden, Portugal, New Zealand, and Greece. These results are to be expected since these countries had relative low scientific outputs in the 1990s. However, this is also the case of some leading countries in terms of their contribution to the total scientific output in the field, namely Japan, the Netherlands, Canada, and Korea.

68. The density[7] of the global network of internationally co-authored publications, measured by the involvement of OECD countries in co-publications, was relatively weak over the period 1990-2000. It amounted to 0.1 and 0.02 with a threshold of 1 and 2 co-publications, respectively. This implies that the circulation of scientific knowledge among the OECD countries by means of cooperative research was rather limited.

7 . Density is a measure of the level of connectivity within the network. It reflects the actual number of links as a proportion of total possible links. In a non-directed binary graph, it can be calculated using the equation: $l/(n(n-1)/2)$, where l is the total number of lines and n is the total number of nodes.

Table 3.3. Matrix of international co-publications by OECD countries, 1990-2000

In percentage of row totals

	AU	A	B	CA	CZ	DK	FIN	F	D	EL	HU	IS	IRL	I	JP	KR	L	MX	NL	NZ	NO	P	E	S	CH	TR	UK	US
AU	..	..	..	..	..	..	..	..	..	..	..	..	..	..	100	..	..	..	..	..	..	..	..	..	..	..	..	..
A	..	..	..	40	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	60
B	..	..	..	100	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
CA	..	22	22	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	22	33
CZ	..	..	..	..	..	..	..	..	100	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
DK	..	..	..	..	..	..	..	..	60	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	20	20
FIN	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
F	..	..	..	..	..	..	..	..	33	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	33	..	..	33
D	..	..	..	..	7	21	..	7	..	21	..	..	..	..	7	..	..	..	7	..	..	..	7	..	..	..	14	7
EL	..	..	..	..	..	..	..	..	60	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	40	..
HU	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
IS	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
IRL	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	100	..	..	..	..	..	..	..	..	..
I	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	50	..	..	..	..	..	..	..	..	13	..	..	38
JP	6	..	..	..	..	..	..	..	6	..	..	..	..	..	..	..	..	..	..	31	..	..	..	..	..	..	13	44
KR	..	..	..	..	..	..	..	..	..	..	..	..	..	44	..	..	..	..	..	..	..	..	..	..	..	..	11	44
L	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
MX	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
NL	..	..	..	..	..	..	..	..	10	..	..	..	20	..	..	..	..	..	..	..	..	..	..	10	..	..	20	40
NZ	..	..	..	..	..	..	..	..	..	..	..	..	..	..	56	..	..	..	..	..	..	..	..	..	..	..	44	..
NO	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
PL	..	..	..	..	..	..	..	..	..	..	..	..	..	50	..	50	..	..	..	..	..	..	..	..	..	..	..	..
P	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	50	..	..	..	50	..
E	..	..	..	..	..	..	..	..	33	..	..	..	..	..	..	..	..	..	..	..	..	33	..	..	..	..	..	33
S	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	50	..	..	..	..	..	..	..	50	..
CH	..	..	..	..	..	..	..	33	..	..	..	..	..	33	..	..	..	..	..	..	..	..	..	..	..	..	..	33
TR	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	100
UK	..	..	..	11	..	6	..	..	11	11	..	..	..	..	11	6	..	..	11	22	..	6	..	6	..	..	..	..
US	..	10	..	10	..	3	..	3	3	..	..	..	..	10	23	13	..	..	13	..	..	..	3	..	3	3	..	..

1. In a matrix of co-publications, the number of publications mentioned is not an indicator of the number of publications being co-authored, but rather how often a country is involved in co-publications.

2. AU=Australia, A=Austria, B=Belgium, CA=Canada, CZ=Czechoslovakia, DK=Denmark, FIN=Finland, F=France, D=Germany, EL=Greece, HU=Hungary, IS=Iceland, IRL=Ireland, I=Italy, JP=Japan, KR=Korea, L=Luxembourg, MX=Mexico, NL=Netherlands, NZ=New Zealand, NO=Norway, P=Portugal, E=Spain, CH=Switzerland, TR=Turkey, UK=United Kingdom, US=United States.

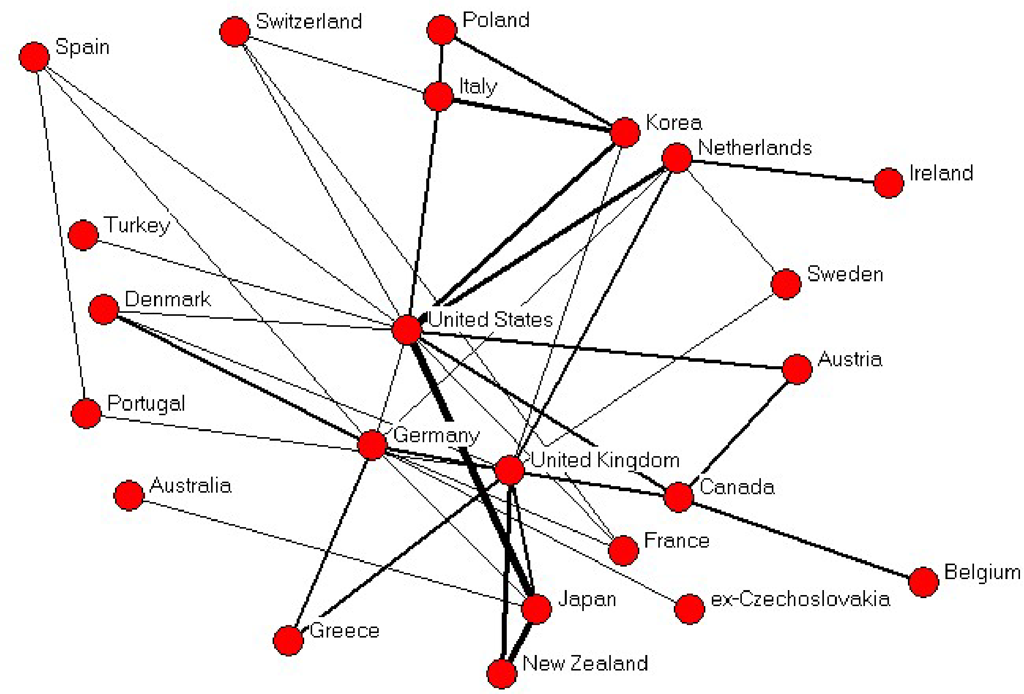
Source: ETDE, ISI, OECD (treatments).

69. A deeper look at the structure of network (Figure 3.15) reveals the existence of 16 cliques[8] of with at least 3 partners with at least 1 co-publication. The composition of these cliques was as follows: {Denmark Germany United States}, {France Germany United States}, {Germany Japan United States}, {Germany Netherlands United States}, {Germany Spain United States}, {Austria Canada United States}, {Italy Korea United States}, {Italy Switzerland United States}, {France Switzerland United States}, {Germany Greece United Kingdom}, {Japan New Zealand United Kingdom}, {Italy Korea Poland}, {Netherlands Sweden United Kingdom}, {Germany Netherlands United Kingdom}, {Denmark Germany United Kingdom}, and {Germany Japan United Kingdom}. However, with a threshold of two co-publications, only one clique of minimum size 3 is identifiable, namely {Italy Korea United States}.

8. A clique in a non-directed binary graph consists of the largest number of actors with ties to every other clique member.

Figure 3.15. Diagram of the global network of internationally co-authored publications, 1990-2000

Involvement of OECD countries in international co-publications



1. The size of lines is proportional to the strength of the ties.

2. Only the OECD countries involve in internationally co-authored publications are displayed in the figure.

Source: ETDE, ISI, OECD (treatments).

The structure of networks of internationally co-authored publications at the level of sub-fields

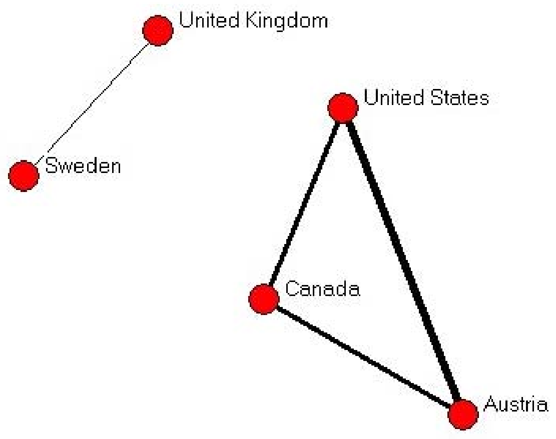
70. Figure 3.16 provides an overview of the structure of the networks of internationally co-authored publications at the level of the main sub-fields of fuel cells in the 1990s. From this figure, one can see that that the networks of international co-publications in AFCs, DMFCs, and PAFCs involved very few OECD countries compared to the other networks in MCFCs, PEMFCs, and SOFCs. However, networks of international co-authored publications also varied from one sub-field to network according their structures.

71. In AFCs, five OECD countries were engaged in co-publications linkages – namely, the United Kingdom, Sweden, the United States, Canada, and Austria (Figure 3.16.a.). These last three OECD countries formed a clique. This one was formed of both leading publishing countries (*i.e.* United States and Canada) in the sub-field and a medium-sized publishing country, namely Austria. The United Kingdom and Sweden, another leading publishing country in the sub-field, had no links with any members of this clique. They constituted a second sub-group within AFCs.

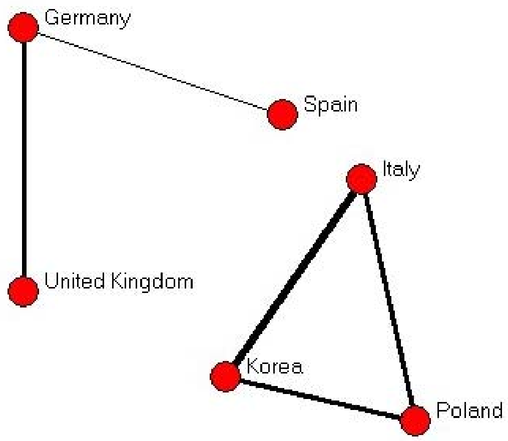
72. In DMFCs, the network of internationally co-authored publications was comprised of six OECD countries: Germany, Spain, the United Kingdom, Italy, Korea, and Poland (Figure 3.16.b.). A clique was

Figure 3.16. Diagrams of the networks of internationally co-authored publications at the levels of subfields, 1990-2000

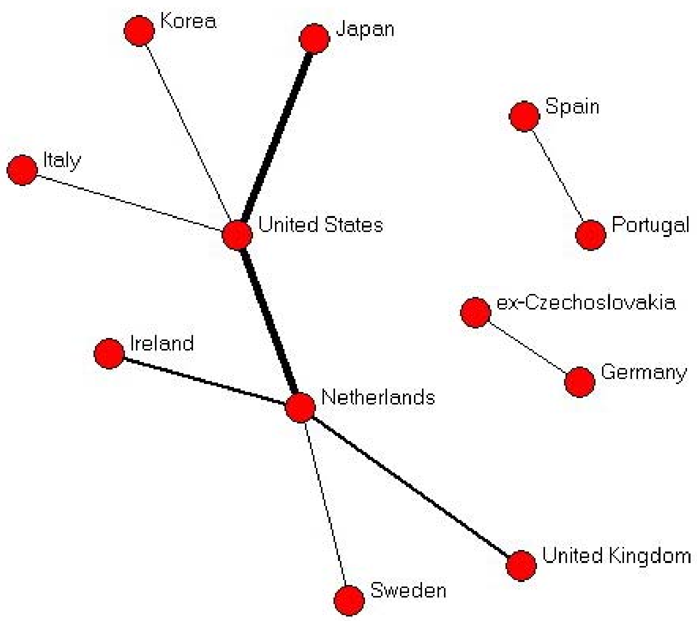
a. AFC



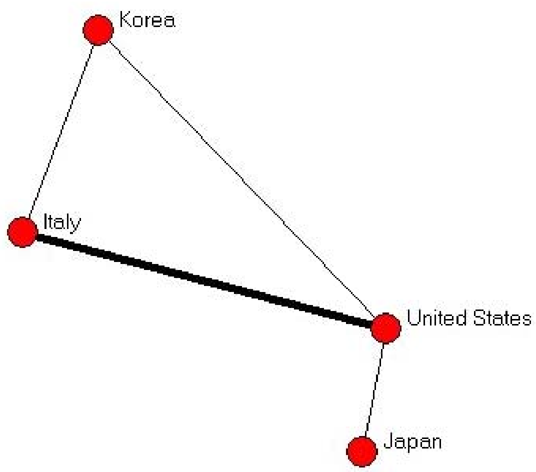
b. DMFC



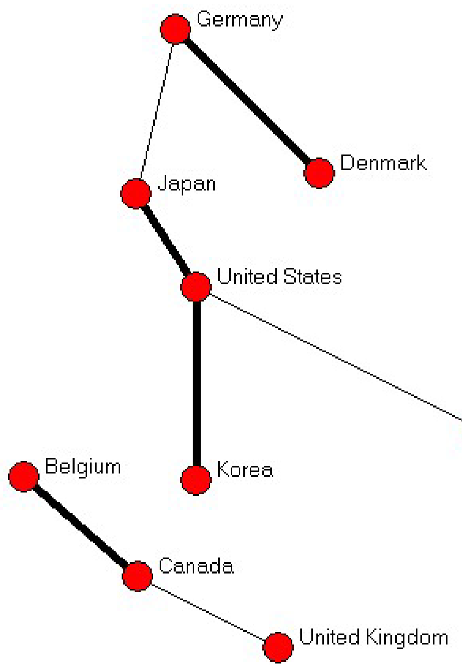
c. MCFC


Korea
Japan
Spain
Italy
United States
Portugal
ex-Czechoslovakia
Ireland
Germany
Netherlands
United Kingdom
Sweden

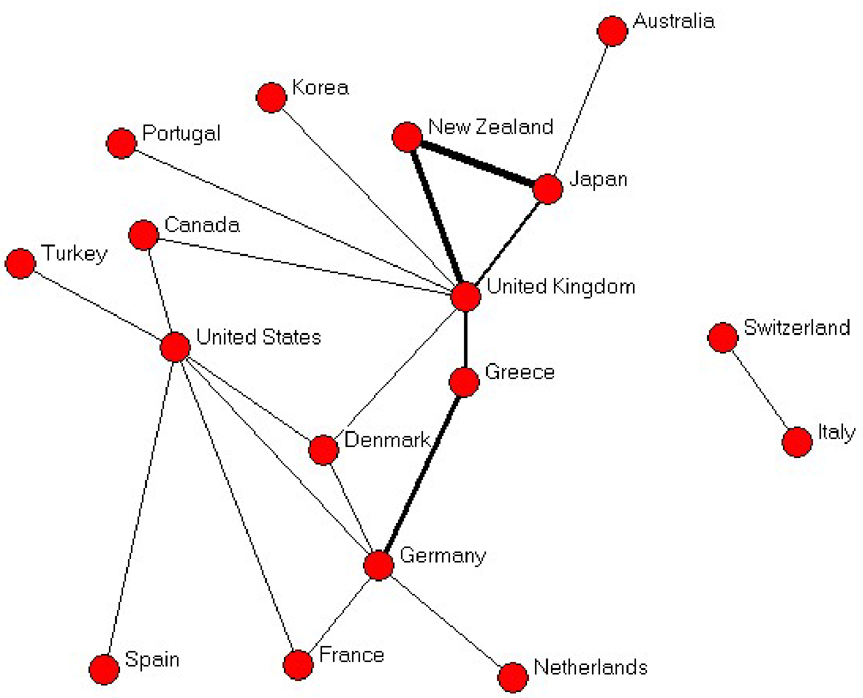
d. PAFC


Korea
Italy
United States
Japan

e. PEMFC



f. SOFC



1. The size of lines is proportional to the strength of the ties.

2. Only the OECD countries involve in internationally co-authored publications are displayed in the figure.

Source: ETDE, ISI, OECD (treatments).

formed by these three latter countries. This clique was therefore constituted of only medium to small-sized publishing countries in that sub-field. Concerning the other countries, one can see that Germany was engaged in co-publications with United Kingdom, which ranked first in DMFCs in terms of number of publication, and Spain. Nonetheless, neither Germany, nor the United Kingdom, or Spain was linked to the members of the clique. Furthermore, the United Kingdom and Spain were not associated in any international co-authored publications.

73. The network of international co-publications appeared to be much larger in MCFCs since it was made up of ten OECD countries. However, no clique could be identified in that network. In addition, the latter was constituted of three different sub-grouped (Figure 3.16.c.). In the larger one, the United States and the Netherlands were central. They were also the leading publishing countries in that sub-field. The United States was engaged in co-publications with Italy, Korea, Japan, and the Netherlands. The latter participated to co-publications with Ireland, Sweden, the United Kingdom, and the United States. The two other sub-groups involved Spain and Portugal, on one hand, and on the other hand, ex-Czechoslovakia and Germany. The existence of these sub-groups associated with an absence of clique in the network implies that the circulation of scientific knowledge among the countries was certainly rather limited in the 1990s.

74. In PAFCs, four OECD countries were involved the network of international co-publications in which the United States was central. Interesting to note is that all these countries were directly or indirectly linked (Figure 3.16.d.): Korea, Italy, and the United States formed a clique; Japan, for its part, was engaged in co-publications with the United States. Both these countries were leading producers of publications in that sub-field in the 1990s.

75. In PEMFCs, one can see that that the network of international co-authored publications was constituted of two sub-groups. The larger one associated Germany, Denmark, Japan, the United States, Korea, Switzerland, and France. The second one was made up of Belgium, Canada, and the United Kingdom (Figure 3.16.e.). Both these sub-groups therefore were made up of leading publishing countries in PEMFCs: Germany, the United States, and Japan on one hand and, on the other hand the United Kingdom and Canada. No clique could be identified in these sub-groups, which entails that the diffusion of scientific knowledge by means of scientific cooperation was probably reduced in spite of the high number of countries involved in that sub-field.

76. In SOFCs, the network of international co-publications was formed of seventeen OECD countries. All countries but Switzerland and Italy were linked directly or indirectly together. The main sub-group that excluded Switzerland and Italy was made up of three cliques: {Japan New Zealand United Kingdom}, {France Germany United States} {Denmark Germany United States}. In this sub-group, leading publishing countries such as the United States, the United Kingdom, and Germany were central while others countries such as Australia, Korea, Portugal, Turkey, Spain, and the Netherlands were peripheral.

CHAPTER 4. THE ROLE OF PUBLIC AND PRIVATE SECTOR ACTORS IN FUEL CELL SCIENCE AND TECHNOLOGY

77. This chapter examines the organization of S&T knowledge production and diffusion in the OECD countries within the field of fuel cells over the past decade. The first section analyzes the division of labor among the main institutional sectors in the generation of S&T knowledge within the OECD countries. The second section examines patterns of cooperation among and within the main institutional sectors in the production of scientific knowledge, with a special focus on public/private linkages.

The institutional division of labor in the production of S&T knowledge

78. Examining the institutional division of labor among the main institutional sectors in the generation of S&T knowledge within the field of fuel cells is essential. These main institutional sectors (business enterprise, higher education, and government) are traditionally marked by different incentive structures and objectives in the production of S&T knowledge[9] but their activities remain nevertheless highly complementary. The higher education sector generates public knowledge that constitutes a major input for private R&D in many domains (Salter and Martin, 1999)[10]. Conversely, the higher education sector also depends on the business enterprise sector insofar as the latter offers efficient methods for the application

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9 . Three generic institutional mechanisms have been imagined in order to support the production of knowledge in presence of market failures and positive externalities leading to an insufficient and inefficient allocation of resources devoted to R&D. These institutional mechanisms clearly derived from the ones identified by Pigou (1932) for the general provision of public goods and are referred by David (1993) in the framework of the economics of knowledge as the three P's, *i.e.* Patronage, Procurement and Property. The Patronage system characterizes the provision of funding by the society to institutions engaged in the process of knowledge generation. The compensation of this public support to the production of knowledge is the requirement of the full public disclosure of the knowledge created. However, this does not mean the non-existence of any reward. Indeed, the "priority rule" rewards the first producer how publishes its research and thus create incentives to the creation of knowledge through non-market mechanisms (Dasgupta and David, 1994). The Procurement system is combined with the engagement of the government into the production of knowledge through contract with mission-oriented agencies or firms. The public disclosure of knowledge is normally secured with few exceptions related to military or national security research activities. Finally, the Property system lies in the creation of markets for private knowledge through the use of intellectual property rights and commercial secrecy. In fact, these three mechanisms lead to describe the main features of the organization of knowledge production and diffusion between the main institutional sectors: the high education sector, the government sector *(e.g.* public research institutes) and the industry. These three sectors meet different objectives that are nevertheless complementary. For instance, the Patronage system has for principal objective the growth of public knowledge and the maximization of the value of positive externalities through the broad dissemination of knowledge in the economy. Conversely, the Property system has for main purpose the maximization of the economic value of the knowledge newly produced and sub-consequently the minimization of positive externalities. Lastly, the aim of the Procurement system lies on the generation of new knowledge either public or private according to the government strategic interests. From then on, the question of the public management of positive externalities is only tackled in terms of contingent externalities.

10 . Moreover, it allows the training of high-qualified scientists whose competencies prove to be very helpful to the industry (Gibbons and Johnston, 1974; Zucker and Darby, 1995).

and commercialization of the knowledge newly created according to the market needs[11]. Finally, the government sector usually meets the specific requirements of “big science” and large-scale projects for which the centralization of resources and decisions is crucial. In this perspective, it plays the role of a catalyst in the knowledge production. Maintaining a good balance between these main institutional sectors in the generation of S&T knowledge is therefore fundamental because the way in which these sectors interact as a collective system of knowledge production and diffusion largely defines its capacity to generate positive externalities and sub-consequently its performance.

79. Admittedly, the institutional division of labor in the creation of S&T knowledge tends to become blurred in some knowledge field or sectors because of close links between science and technology (Narin and Noma, 1985), increasing university patenting (OECD, 2003), and a high propensity of firms to perform scientific research and publish their results (Rosenberg, 1990; Godin, 1996). However, most empirical studies (Hicks and Katz, 1997; Godin and Gindras, 2000; OECD, 2002*b*) show that: the higher education sector is strongly specialized in the production of scientific knowledge and has a weaker role in the production of technological knowledge; firms are active in the production of technological knowledge generating private returns in the short- or mid-terms; public research institutes play a critical role in mission-oriented research. These differences between the main institutional sectors in the division of innovative labor reflect the dissimilarities of their incentive structures and objectives.

The institutional division of labor on the science side

The institutional distribution of the global scientific publications

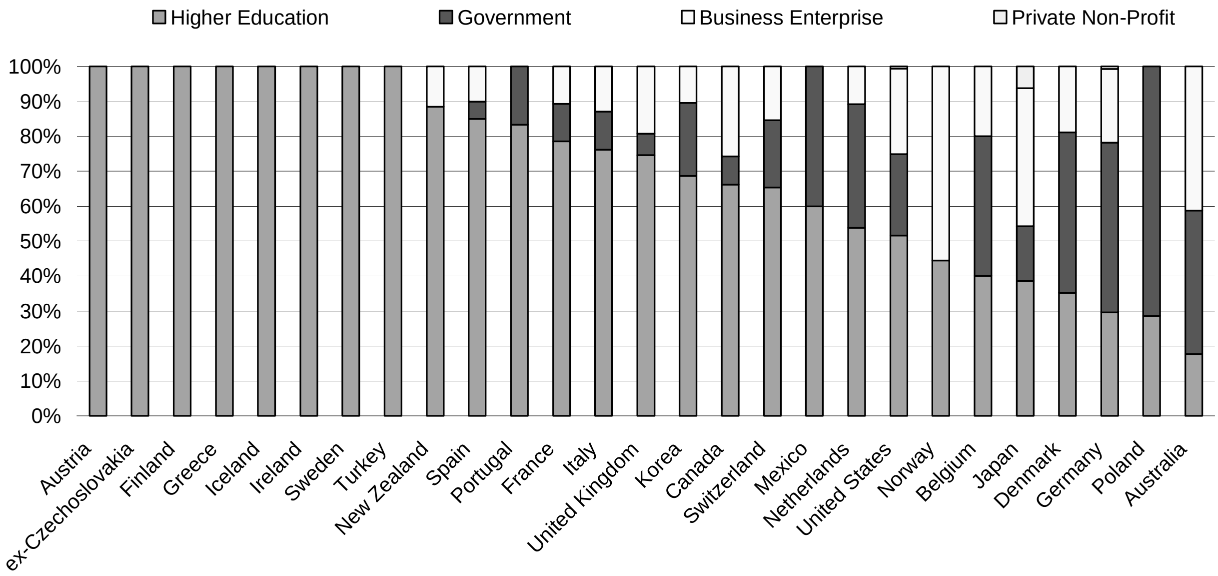
80. Figure 4.1 shows the overall distribution of publications among the main institutional sectors within the field of fuel cells in each OECD country over the 1990s. This measure provides a proxy of the division of scientific activities among the main institutional sectors within the OECD countries. The higher education sector was strongly involved in scientific publications during the 1990s in the OECD area. The average of national shares of this sector in the scientific publications of active OECD countries in the field amounted to around 70%. The government and business sectors ranked second and third, respectively, in terms of their average contributions to the scientific publications, with values of 17% and 13%. As a rule, the private non-profit sector played an insignificant role in the scientific publications of OECD countries within the field of fuel cells. These results more or less reflect the traditional division of labor among the main institutional sectors in the generation of scientific knowledge with a dominant role played by the higher education sector although the contribution of the business enterprise sector appears relatively high compared to that of the government sector.

81. However, there were marked differences among countries. First, the government sector contributed more than 50% of the publications in Australia, Belgium, Denmark, Germany, and Mexico, but it none in other active OECD countries during the 1990s, including Austria, Finland, Greece, Iceland, Ireland, Sweden, and Turkey. Second, the business enterprise sector appeared to be quite active in the scientific publications of several active OECD countries with shares of more 20% in the United States, Japan, Norway, Canada, Australia, and Germany. Finally, the private non-profit sector contributed more than 6% of the global scientific publications in Japan.

11 . The business enterprise sector may in addition formulate specific problems related to the technological development that should be resolved by universities or non-profit institutions in the framework of long-term research (Rosenberg, 1991).

Figure 4.1. Distribution of publications among the main institutional sectors, 1990-2000

In percentage



1. Only active OECD countries are shown in the figure.

2. Here, the total number of publications by country was measured by the sum of its publications in each sub-field.

Source: ETDE, ISI, OECD (treatments).

The institutional distribution of the scientific publications by sub-field

82. Admittedly, the high education sector appeared to be very active in the global scientific publications of the majority of OECD countries while the participation of both the government and business enterprise sectors seemed to be more limited. Nevertheless, a more detailed analysis of the institutional distribution of scientific publications in the past decade reveals substantial differences among the large and medium-sized publishing regions/countries from one sub-field to the next.

83. Generally, the higher education sector seemed very active on the science side in almost all the active OECD countries in AFCs during the 1990s, authoring more than 70% of publications (Table 4.1). Its contribution nevertheless was relatively low in Canada, the United States, and Germany. The government sector played a very limited role in almost all the active countries, contributing on average only around 7% of publications. Germany was the only exception to this pattern because the government sector generated nearly 60% of the country's scientific publications. The business enterprise sector, for its part, significantly contributed to scientific publications in the active OECD countries in AFCs over the past decade. Its average was about 19%. However, the involvement of the business enterprise sector was relatively strong in Canada and the United States where it contributed more than 40% of their scientific publications in fuel cells. Conversely, business did not account for any publications in Germany, Sweden, and Canada.

Table 4.1. Distribution of publications among the main institutional sectors in AFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Austria	0%	0%	100%	0%
Belgium	50%	50%	0%	0%
Canada	43%	0%	57%	0%
Finland	0%	0%	100%	0%
France	0%	0%	100%	0%
Germany	0%	60%	40%	0%
Japan	0%	0%	100%	0%
Korea	0%	0%	100%	0%
New Zealand	0%	0%	100%	0%
Spain	40%	0%	60%	0%
Sweden	0%	0%	100%	0%
Switzerland	0%	0%	100%	0%
Turkey	0%	0%	100%	0%
United Kingdom	100%	0%	0%	0%
United States	57%	0%	43%	0%

1. Only active OECD countries in AFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

84. In DMFCs, the average distribution of scientific publications among the main institutional sectors in the active OECD countries was roughly similar to that of the field of fuel cells as a whole. However, a further look at this distribution in the large and medium-sized publishing countries reveals substantial dissimilarities (Table 4.2). The contribution of the higher education sector was rather limited in Germany and the United States while it was very high in the United Kingdom and Italy. On the contrary, the relative share of the government sector in the publications of Germany, the United States, and Korea was quite substantial. The involvement of the business enterprise sector in the scientific publications of Italy, Korea, the United Kingdom, and the United States was rather low and even nil while it picked up to more than 20% in Germany. Finally, one can see that the share of the private non-profit sector climbed up to 6% in the publications of Germany in that sub-field while it was 0% in all other countries.

Table 4.2. Distribution of publications among the main institutional sectors in DMFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Denmark	50%	0%	50%	0%
France	0%	0%	100%	0%
Germany	24%	47%	24%	6%
Italy	0%	0%	100%	0%
Japan	100%	0%	0%	0%
Korea	0%	25%	75%	0%
Poland	0%	0%	100%	0%
Spain	0%	0%	100%	0%
Switzerland	0%	100%	0%	0%
United Kingdom	0%	7%	93%	0%
United States	11%	33%	56%	0%

1. Only active OECD countries in DMFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

85. In MCFCs, the average share of the higher education sector in the publications of the active OECD countries amounted to around 58%, compared to 25% for the business enterprise sector. The average contribution of the government sector in scientific publications wthin that sub-field did not significantly differ from its average contribution in all fuel cell publications (Table 4.3). At the level of large and medium-sized countries, one can see that the contribution of the higher education sector in the publications of Japan and the United Kingdom was relatively low in MCFCs with values below 30%, while the contribution of the business enterprise sector in these latter countries was high. The role of the government sector was significant in the Netherlands in comparison to the other large and medium-sized publishing countries. Lastly, the share of the private non-profit sector in the publications of Japan picked up to more than 14% while it was 0% in the other large and medium-sized publishing countries.

Table 4.3. Distribution of publications among the main institutional sectors in MCFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Austria	0%	0%	100%	0%
Canada	100%	0%	0%	0%
Denmark	33%	0%	67%	0%
ex-Czechoslovakia	0%	0%	100%	0%
France	17%	0%	83%	0%
Germany	17%	25%	58%	0%
Greece	0%	0%	100%	0%
Ireland	0%	0%	100%	0%
Italy	18%	5%	78%	0%
Japan	48%	11%	27%	14%
Korea	13%	22%	65%	0%
Netherlands	12%	33%	55%	0%
Norway	100%	0%	0%	0%
Poland	0%	100%	0%	0%
Portugal	0%	100%	0%	0%
Spain	0%	0%	100%	0%
Sweden	0%	0%	100%	0%
United Kingdom	86%	0%	14%	0%
United States	35%	13%	52%	0%

1. Only active OECD countries in MCFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

86. In PAFCs, the average share of the higher education sector in the publications of the active OECD countries climbed up to 65%. The government sector appeared to play a limited role in this sub-field with a contribution of 9%, compared to the business enterprise sector which contributed 26% (Table 4.4.). Among the large and medium-sized publishing countries in PAFCs, one can see that the involvement of the higher education sector was very low in Japan and to a lesser extent in the United States and Germany. The government sector did not published in Germany but produced a large share of the publications of Korea in comparison to the average. Finally, the participation of the business enterprise sector was also non-existent in Korea while it was quite high Japan, Germany, and the United States.

Table 4.4. Distribution of publications among the main institutional sectors in PAFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Canada	0%	0%	100%	0%
Denmark	20%	0%	80%	0%
Finland	0%	0%	100%	0%
Germany	56%	0%	44%	0%
Italy	6%	13%	81%	0%
Japan	74%	12%	12%	2%
Korea	0%	33%	67%	0%
Netherlands	60%	40%	0%	0%
New Zealand	0%	0%	100%	0%
Sweden	0%	0%	100%	0%
United Kingdom	50%	0%	50%	0%
United States	46%	13%	42%	0%

1. Only active OECD countries in PAFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

87. In PEMFCs, the higher education sector played a relatively less significant role, but government in the national scientific publications of the active OECD countries was significantly lower than its average contribution to global publications in fuel cells, conversely to the government sector whose contribution picked up to 34% (Table 4.5.). The business enterprise sector appeared somewhat behind the other in this sub-field with a participation that picked up to 14%. At the level of large and medium-sized publishing countries in PEMFCs, the higher education sector contributed to 24%, 29%, and 31% of the national publications of Germany, Japan, and Korea while its participation picked up to more than 70% in Canada. However, the involvement of the government sector in this latter country was quite low since it published 7% of all Canadian’s publications in PEMFCs.

Table 4.5. Distribution of publications among the main institutional sectors in PEMFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Australia	0%	67%	33%	0%
Belgium	0%	33%	67%	0%
Canada	22%	7%	71%	0%
Denmark	67%	0%	33%	0%
Finland	0%	0%	100%	0%
France	0%	25%	75%	0%
Germany	21%	55%	24%	0%
Iceland	0%	0%	100%	0%
Italy	7%	29%	64%	0%
Japan	42%	29%	29%	0%
Korea	31%	38%	31%	0%
Mexico	0%	40%	60%	0%
Netherlands	0%	100%	0%	0%
Spain	0%	50%	50%	0%
Sweden	0%	0%	100%	0%
Switzerland	14%	71%	14%	0%
United Kingdom	24%	29%	47%	0%
United States	21%	32%	47%	0%

1. Only active OECD countries in PEMFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

88. In RFCs, 59 % of publications originated from the government sector. The higher education and business enterprise sectors published nearly 36% and 5% of the total publications in that sub-field in the 1990s (Table 4.6.). Among the large and medium-sized publishing countries, the three main institutional sectors – namely the higher education, the government, and the business enterprise sectors – equally contributed to publications of the United States while most publications were produced by the business enterprise sector in Germany.

Table 4.6. Distribution of publications among the main institutional sectors in RFCs, 1990-2000

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
France	0%	100%	0%	0%
Germany	0%	80%	20%	0%
Italy	0%	100%	0%	0%
Japan	0%	100%	0%	0%
Sweden	0%	0%	100%	0%
United Kingdom	0%	0%	100%	0%
United States	33%	33%	33%	0%

1. Only active OECD countries in RFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

89. In SOFCs, the higher education sector, on average, was strongly involved in the national scientific publications of the active OECD countries with a share of 70%. The average share of business enterprise sector in the national publications of the OECD countries in that sub-field climbed up to 16%. Lastly, the government sector lagged behind the higher education and business enterprise sectors in terms of its participation to the publications at the national level (Table 4.7.). Even so, significant differences in the distribution of publications among the main institutional sectors can be highlighted at the level of large and medium-sized OECD countries. For instance, the involvement of the higher education sector seemed to be relatively weak in the national publications of Germany and Japan. Conversely, the share of the government sector in publications was very high in Germany in comparison to the other large and medium-sized countries in SOFCs. Its share effectively amounted to more than 50%. At the same time, this institutional sector was almost not involved in the production of scientific publications in the United Kingdom. Finally, the business enterprise sector was more implicated in the production of scientific publications in Japan than in any of the other large and medium-sized OECD countries.

Table 4.7. Distribution of publications among the main institutional sectors in SOFCs, 1990-2000

In percentage of row totals

	Business Enterprise	**Government**	**Higher Education**	**Private Non-Profit**
Australia	50%	36%	14%	0%
Austria	0%	0%	100%	0%
Canada	38%	25%	38%	0%
Denmark	12%	68%	20%	0%
France	22%	0%	78%	0%
Germany	21%	54%	25%	0%
Greece	0%	0%	100%	0%
Italy	20%	10%	70%	0%
Japan	30%	17%	48%	5%
Korea	0%	11%	89%	0%
Netherlands	20%	35%	45%	0%
New Zealand	13%	0%	88%	0%
Norway	50%	0%	50%	0%
Portugal	0%	0%	100%	0%
Spain	0%	0%	100%	0%
Sweden	0%	0%	100%	0%
Switzerland	17%	0%	83%	0%
Turkey	0%	0%	100%	0%
United Kingdom	15%	3%	82%	0%
United States	18%	20%	61%	2%

1. Only active OECD countries in SOFCs are shown in the table.

Source: ETDE, ISI, OECD (treatments).

The institutional division of labor on the technology side

The institutional distribution of the global EPO applications

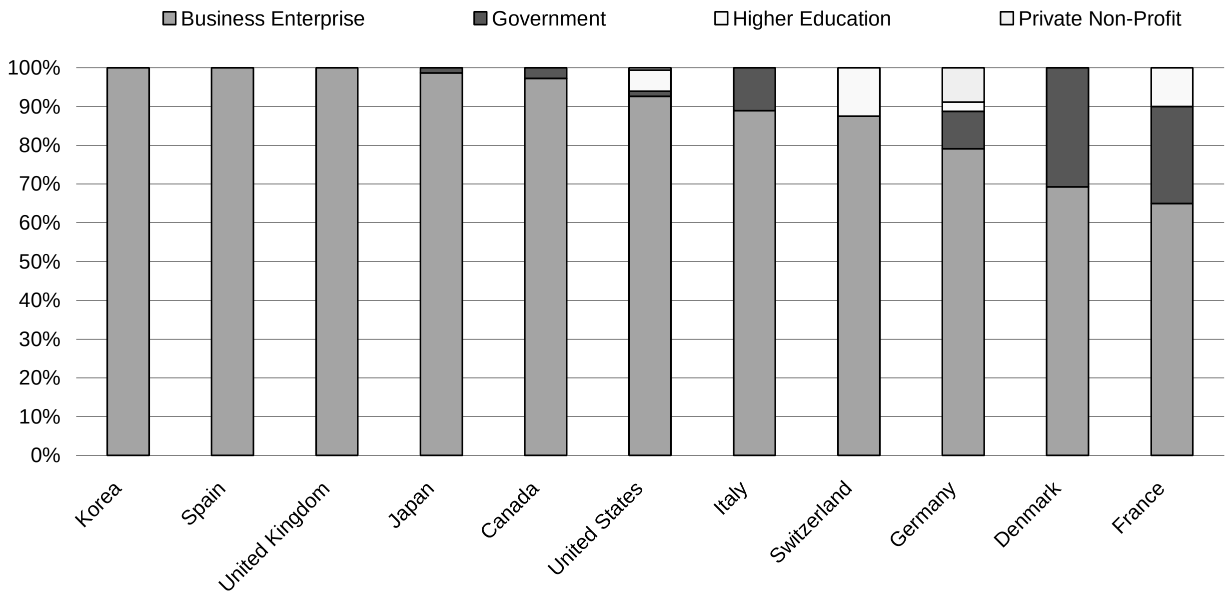
90. With regards to the distribution of the global EPO applications among the main institutional sectors over the period 1990-1999 (Figure 4.2.), the average contribution of the business enterprise sector in the national EPO applications was higher than 86% in the 1990s. On average, the share of the government sector in the national EPO applications of the patenting countries was 10%. Finally, the average

participation of the higher education and private non-profit sectors picked up to 4% and 1%. Even though these results reflected the traditional division of labor among the main institutional sector in the generation of technological knowledge, there were notable disparities across the active OECD countries.

91. The share of the business enterprise sector in the national EPO applications of Korea, Spain, and the United Kingdom climbed up to 100% while it was relatively lower than 70% in Denmark and the Netherlands. The government sector seemed to play a minor role in the generation of technological knowledge in Japan, Canada, and the United States as shown by its low share in their global EPO applications. Nonetheless, its share in the national EPO applications of Italy and Germany picked up to more than 10%. It was even exceeded 30% in Denmark and the Netherlands. In addition, several EPO applications also originated from the higher education sector, principally in the Netherlands, Switzerland, and in the United States. Lastly, the contribution of the private non-profit in the EPO applications of Germany was higher than 8% while it was 0% in the other patenting countries.

Figure 4.2. Distribution of EPO applications among the main institutional sectors, 1990-1999

In percentage



1. Only active OECD countries are shown in the figure.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

The institutional distribution of the EPO applications by sub-field

92. The examination of the distribution among the main institutional sectors of the global EPO applications of the patenting countries in the 1990s within the field of fuel cells underscored a dominant role played by the business enterprise sector in the generation of technological knowledge while the government, the higher education, and the private non-profit sectors were lagging behind. Nonetheless, the role played by these three latter institutional in the generation of technological knowledge within the main sub-fields of fuel cells was variable.

93. In AFCs, the business enterprise sector was clearly the principal contributor of EPO applications with an average of national shares of 83% while the contribution of the government and higher education sector amounted to around 0% and 18%, respectively (Table 4.8.). The higher education sector effectively took a stake of up to 20% in the national EPO applications of the United States, which constituted one of the largest patenting countries in AFCs.

Table 4.8. Distribution of EPO applications among the main institutional sectors in AFCs, 1990-1999

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
France	50%	0%	50%	0%
Germany	100%	0%	0%	0%
Japan	100%	0%	0%	0%
United States	80%	0%	20%	0%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

94. In DMFCs, the average national participation of the business enterprise sector in the national EPO applications of the active OECD countries in that sub-field climbed up to near 80% while the higher education and government sectors showed an average national of 13% and 7%, respectively (Table 4.9.). Interesting to note was the relative high contribution of the higher education sector in the national EPO applications of the largest patenting countries in that sub-field, namely Germany and the United States. In these countries, the share of the high education sector picked up to 25% and 40%, respectively.

Table 4.9. Distribution of EPO applications among the main institutional sectors in DMFCs, 1990-1999

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Canada	100%	0%	0%	0%
Germany	42%	33%	25%	0%
Japan	100%	0%	0%	0%
United Kingdom	100%	0%	0%	0%
United States	60%	0%	40%	0%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

95. In MCFCs, the average national share of the business enterprise sector amounted to near 84%. The average national shares of the government and higher education sectors were 10% and 7%, respectively (Table 4.10.). The share of the business enterprise sector was 88% and 100% in the largest patenting countries in that sub-field: Germany and Japan. In other respect, the government sector took a stake of up to 13% in the EPO applications of Germany.

Table 4.10. Distribution of EPO applications among the main institutional sectors in MCFCs, 1990-1999

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Germany	88%	13%	0%	0%
Italy	100%	0%	0%	0%
Japan	100%	0%	0%	0%
Netherlands	20%	40%	40%	0%
United Kingdom	100%	0%	0%	0%
United States	95%	5%	0%	0%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

96. The business enterprise sector appeared to be the only contributor to the national EPO applications of the active OECD countries in PAFCs during the past decade (Table 4.11.)

Table 4.11. Distribution of EPO applications among the main institutional sectors in PAFCs, 1990-1999

In percentage of row totals

	Business Enterprise	Government	Higher Education	Private Non-Profit
Denmark	100%	0%	0%	0%
Germany	100%	0%	0%	0%
Japan	100%	0%	0%	0%
United States	100%	0%	0%	0%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

97. In PEMFCs, the business enterprise sector showed an average national share of 91% in the national EPO applications of the active OECD countries in PEMFCs (Table 4.12). Its contribution was high in all the largest patenting countries in that sub-field, namely Canada, Germany, Japan, and the United States. However, the private non-profit sector also participated actively in the generation of technological knowledge in Germany within PEMFCs.

Table 4.12. Distribution of EPO applications among the main institutional sectors in PEMFCs, 1990-1999

	Business Enterprise	Government	Higher Education	Private Non-Profit
Canada	97%	3%	0%	0%
Denmark	100%	0%	0%	0%
France	53%	33%	13%	0%
Germany	84%	3%	3%	11%
Italy	82%	18%	0%	0%
Japan	98%	2%	0%	0%
Korea	100%	0%	0%	0%
Spain	100%	0%	0%	0%
Switzerland	100%	0%	0%	0%
United Kingdom	100%	0%	0%	0%
United States	88%	0%	11%	1%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

98. In RFCs, the average national share of the business enterprise in the EPO applications of the active OECD countries exceeded 97% (Table 4.13.).Among the leading patenting countries (*i.e*. Germany, Japan, the United Kingdom, and the United Kingdom) in that sub-field, only Germany was characterized by a contribution of its business enterprise sector lower than 90%. This was mainly due to the relatively high participation of its private non-profit sector in RFCs.

Table 4.13. Distribution of EPO applications among the main institutional sectors in RFCs, 1990-1999

	Business Enterprise	Government	Higher Education	Private Non-Profit
Canada	100%	0%	0%	0%
Germany	85%	4%	0%	12%
Italy	100%	0%	0%	0%
Japan	97%	3%	0%	0%
Netherlands	100%	0%	0%	0%
Switzerland	100%	0%	0%	0%
United Kingdom	100%	0%	0%	0%
United States	94%	2%	2%	1%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

99. The role of the business enterprise sector seemed more limited in SOFCs in comparison to the other main sub-fields of fuel cells (Table 4.14.). Its average share in the national EPO applications of the active OECD countries in that sub-field was effectively 82% during the past decade. However, its contribution to

the EPO applications of the two leading patenting countries in that sub-field, namely the United States and Japan, climbed up to more than 90%.

Table 4.14. Distribution of EPO applications among the main institutional sectors in SOFCs, 1990-1999

	Business Enterprise	Government	Higher Education	Private Non-Profit
Canada	100%	0%	0%	0%
Denmark	50%	50%	0%	0%
France	100%	0%	0%	0%
Germany	43%	57%	0%	0%
Italy	100%	0%	0%	0%
Japan	100%	0%	0%	0%
Korea	100%	0%	0%	0%
Netherlands	33%	67%	0%	0%
Switzerland	83%	0%	17%	0%
United Kingdom	100%	0%	0%	0%
United States	96%	1%	3%	0%

1. Only active OECD countries are shown in the table.

2. Here, the total number of EPO applications by country was measured by the sum of EPO applications by sub-field.

3. EPO applications are classified according to the earliest priority date and the countries of applications.

Source: EPO, OECD (treatments).

Patterns of sectoral cooperation

100. Recent years have shown a trend towards mounting interactions among the institutional sectors in terms of funding and performing of R&D activities. The tendency has been highlighted and examined by several scholars (Gibbons *et al.*, 1994; Etzkowitz and Leydesdorff, 1997). According to the latter, the increasing linkages among the various institutional sectors mainly steam from the falling gap between science and technology either from cognitive and institutional point of view.

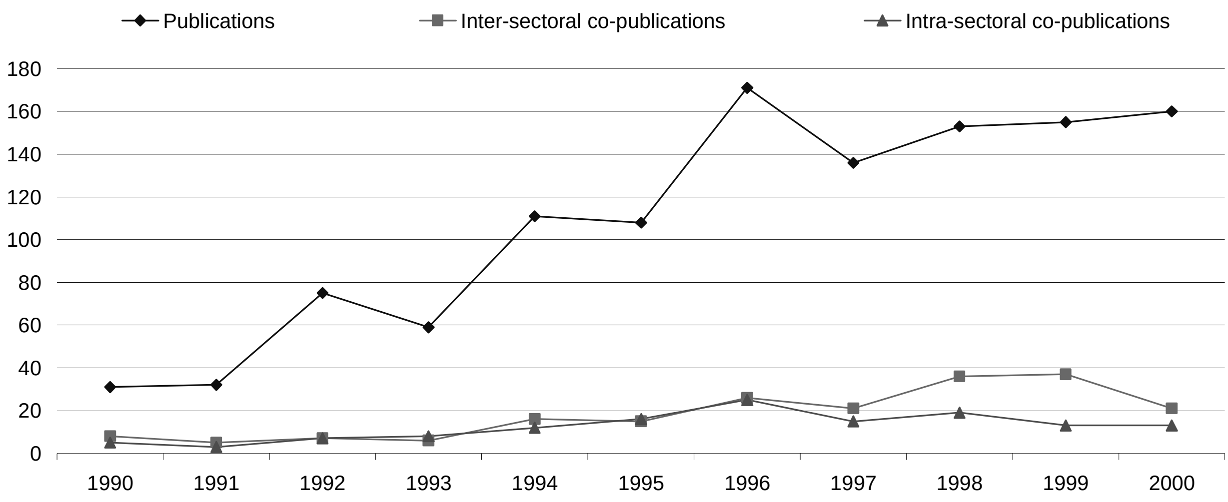
101. Notably, the rising scientific content of innovations in several fields of knowledge has lead firms towards intensifying cooperation with the traditional science systems. Mounting evidences have effectively demonstrated that public research has a significant impact on the S&T activities of private companies (Salter and Martin, *op. cit.*), especially in emerging fields of knowledge (Debackere and Rappa, 1994) where the uncertainty is high. However, not only have firms to undertake scientific research to be able to assimilate the results from public research, but they also need to collaborate with the public research sector (Zucker and Darby, *op. cit.*; Cockburn and Henderson, 1998) to ensure the transfer of tacit knowledge. In addition, numerous incentives have been created over the past decade by the governments of industrialized countries to spur interactions between the business enterprise sector and the higher education and governments sectors in order to turn public research into business (OECD, 2002*c*).

Worldwide trends in inter- and intra-sectoral cooperation

102. Figure 4.3. shows trends in intra- and inter-sectoral co-publications in the field of fuel cells during the period 1990-2000. Both intra- and inter-sectoral co-publications, which provide a proxy of cooperations within and among the main institutional sectors, followed an upward trend in the 1990s. Nevertheless, the rise of these co-publications was lower than the growth of total publications during the period under consideration. Both intra- and inter-sectoral co-publications grew at a compound annual

growth rate of 10% compared with 16% for the total publications. This pattern demonstrates that interactions among the main institutional sectors and within the latter were not strengthened in relative terms; so does the diffusion of scientific knowledge among these entities. In other words, the coordination between institutions in the production of scientific knowledge in the field of fuel cells appeared to be relatively fragmented at first sight over the past decade.

Figure 4.3. Publications, intra- and inter-sectoral co-publications, 1990-2000, worldwide



1. Inter-sectoral co-publications refer to publications that are co-authored by authors belonging to at least two different institutional sectors.

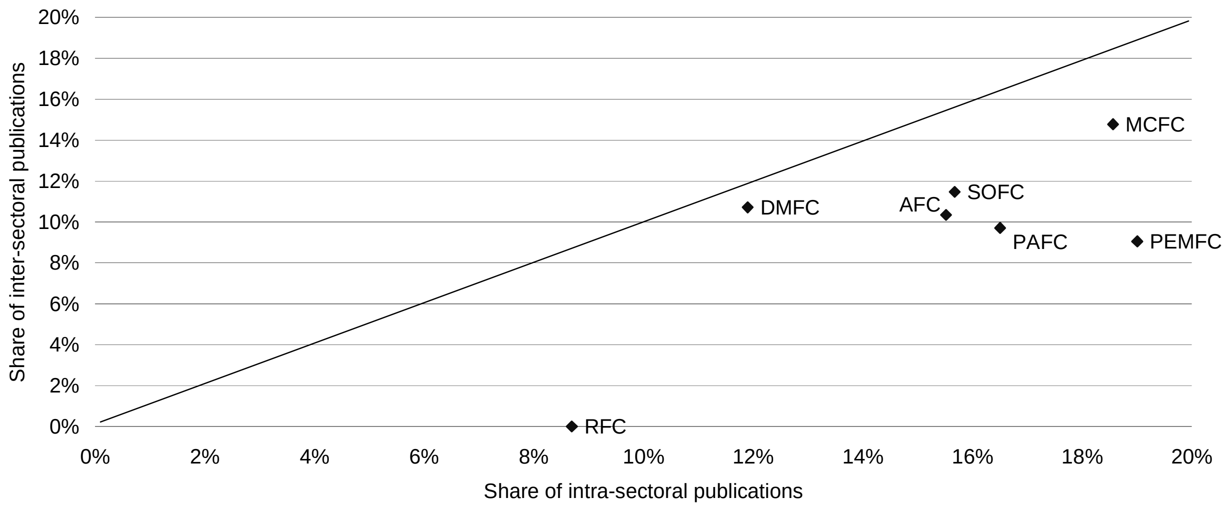
2.Intra-sectoral co-publications refer to publications that are co-authored by authors belonging to at least tow similar institutional sectors (but different main organizations).

Source: ETDE, ISI, OECD (treatments).

103. Nevertheless, the share of intra-sectoral co-publications and the share of inter-sectoral co-publications significantly fluctuated across the main sub-fields of fuel cells even though the former was higher than the latter in all the main sub-fields of fuel cells (Figure 4.4.). For instance, the share of inter-sectoral co-publications was near 0% in RFCs while it picked up to more than 14% in MCFCs. In the other sub-fields of fuel cells, the share of inter-sectoral co-publications fluctuated between 8% and 12%. The disparities across sub-fields were even more salient when looking at intra-sectoral publications. The share of intra-sectoral co-publications amounted to about 9 % and 12% in RFCs and DMFCs, respectively, while it picked up to more than 18% in PEMFCs and MCFCs. In the other sub-fields, the share of intra-sectoral publications oscillated between 15% and 17%.

Figure 4.4. Shares of inter- and intra-sectoral publications by sub-field, 1990-2000, worldwide

In percentage of publications



1. Inter-sectoral co-publications refer to publications that are co-authored by authors belonging to at least two different institutional sectors.

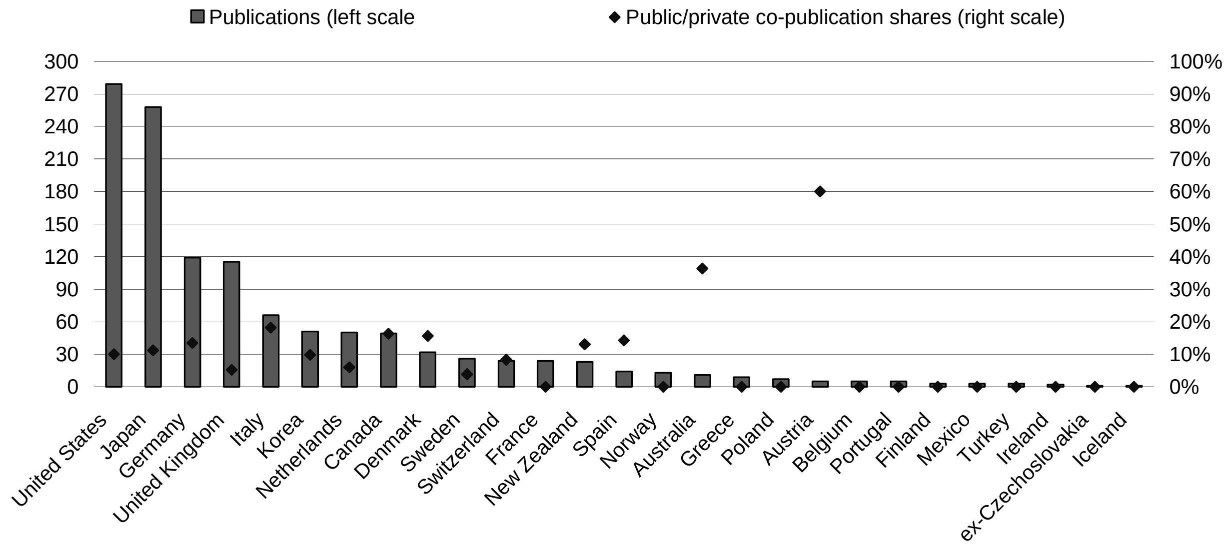
2.Intra-sectoral co-publications refer to publications that are co-authored by authors belonging to at least tow similar institutional sectors (but different main organizations).

Source: ETDE, ISI, OECD (treatments).

Public/private cooperation by country

104. Figure 4.5. provides further look at inter-sectoral cooperations in the field of fuel cells over the past decade. It shows the number of public/private co-publications in each OECD country as a percentage of industry publications. One can see that the percentage of industry publications co-authored with the public sector (*e.g*. higher education and government sectors) considerably varied from one country to the next. Generally, it appears that the less industry publishes publications, the more the latter are co-authored with either the higher education or the government sector. This concerns first France, the New Zealand, and Spain but also Switzerland, the Netherlands, Australia, Korea, and Denmark. With regards to the most active OECD countries in terms of industry publications, the share of public/private co-publications seemed to be low in Japan and the United Kingdom. In these countries, this share generally amounted to more than 40 % on average (Calvert and Patel, 2003; Pechter and Kakinuma, 1999). Conversely, this share seemed rather high in the United States (Hicks and Hamilton, 1999), Germany, Canada, Italy, and Norway.

Figure 4.5. Publications and public/private co-publication shares of OECD countries, 1990-2000



1. Public/private co-publications refer to publications that are co-authored by authors belonging to the business enterprise sector and the higher education and/or the government sectors.

2. Only countries whose business enterprise sector published during the 1990s are shown in the figure.

Source: ETDE, ISI, OECD (treatments).

Figure 4.6. Publications and public/private co-publication shares of OECD countries in AFCs, 1990-2000

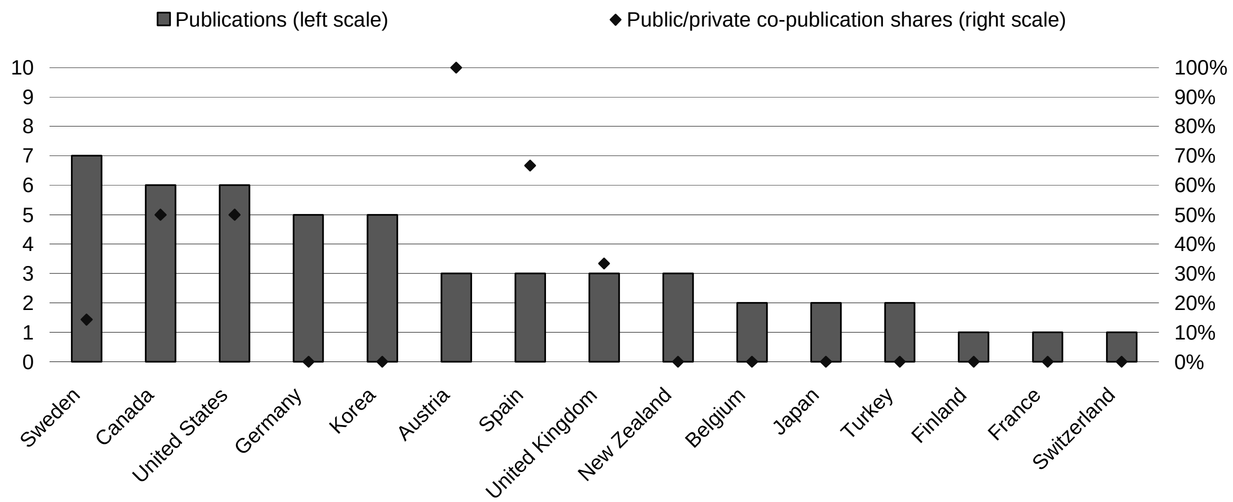


Figure 4.7. Publications and public/private co-publication shares of OECD countries in DMFCs, 1990-2000

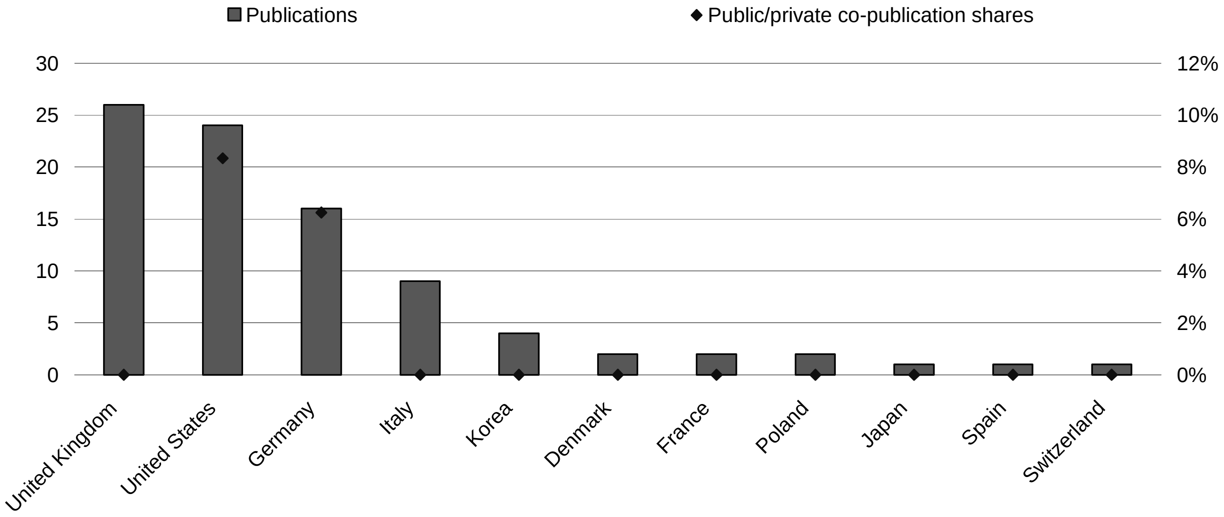


Figure 4.8. Publications and public/private co-publication shares of OECD countries in MCFCs, 1990-2000

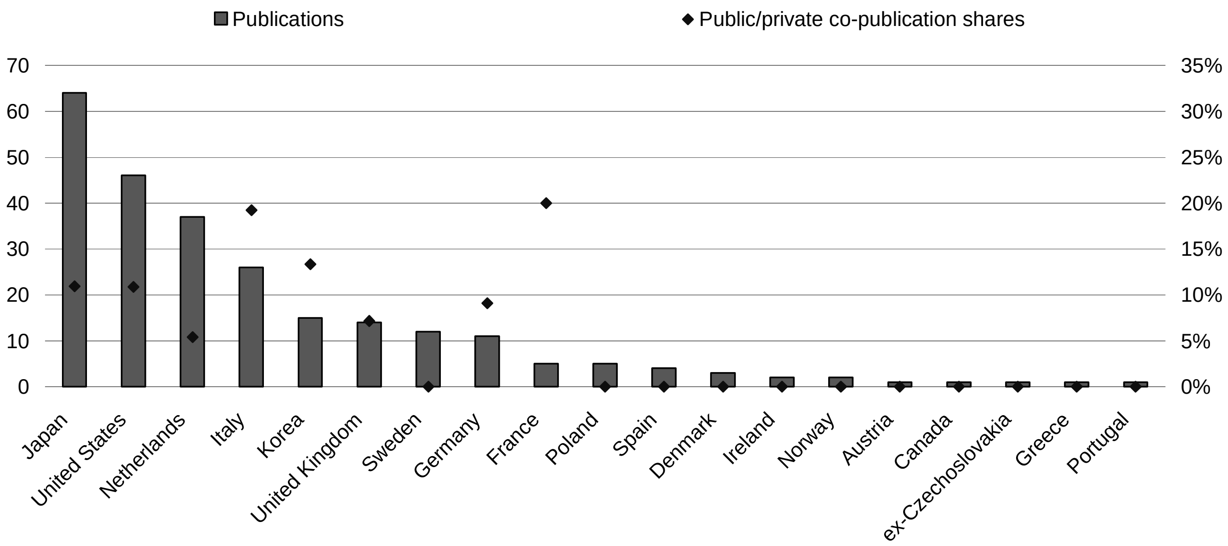


Figure 4.9. Publications and public/private co-publication shares of OECD countries in PAFCs, 1990-2000

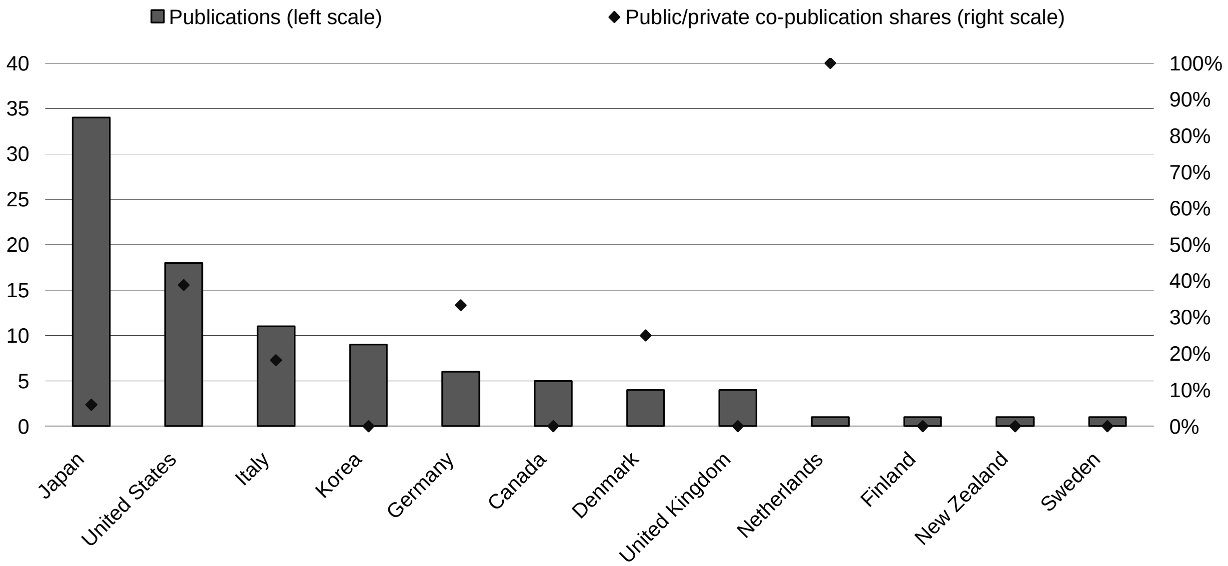


Figure 4.10. Publications and public/private co-publication shares of OECD countries in PEMFCs, 1990-2000

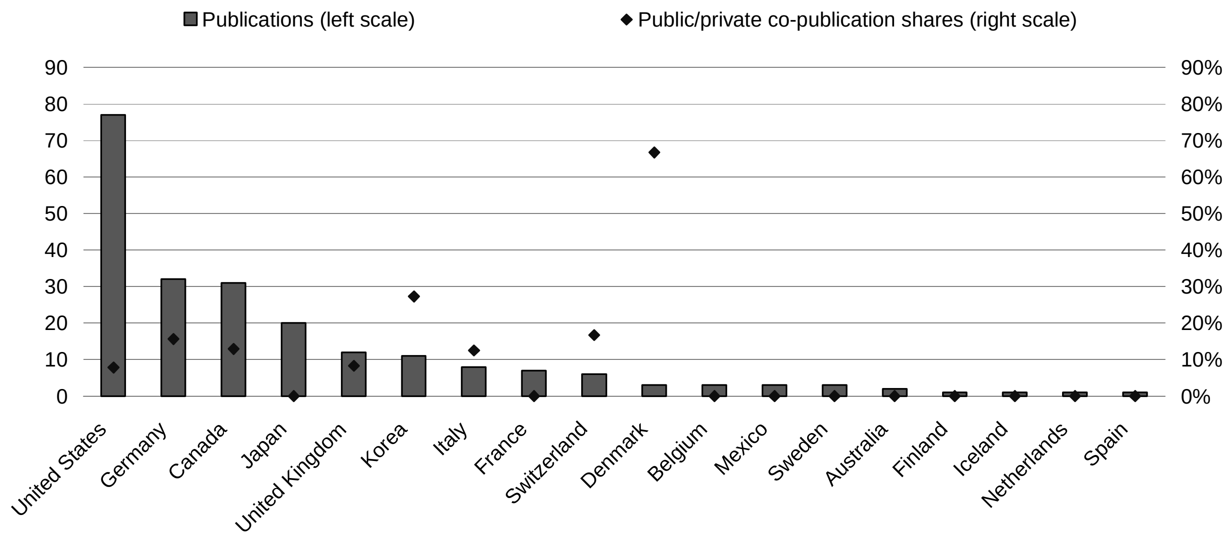


Figure 4.11. Publications and public/private co-publication shares of OECD countries in RFCs, 1990-2000

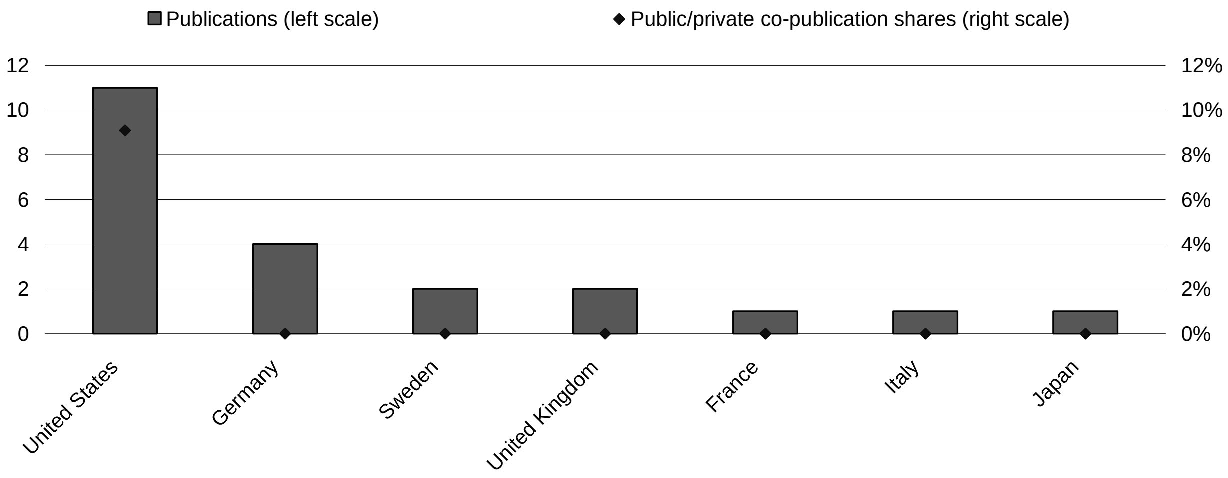
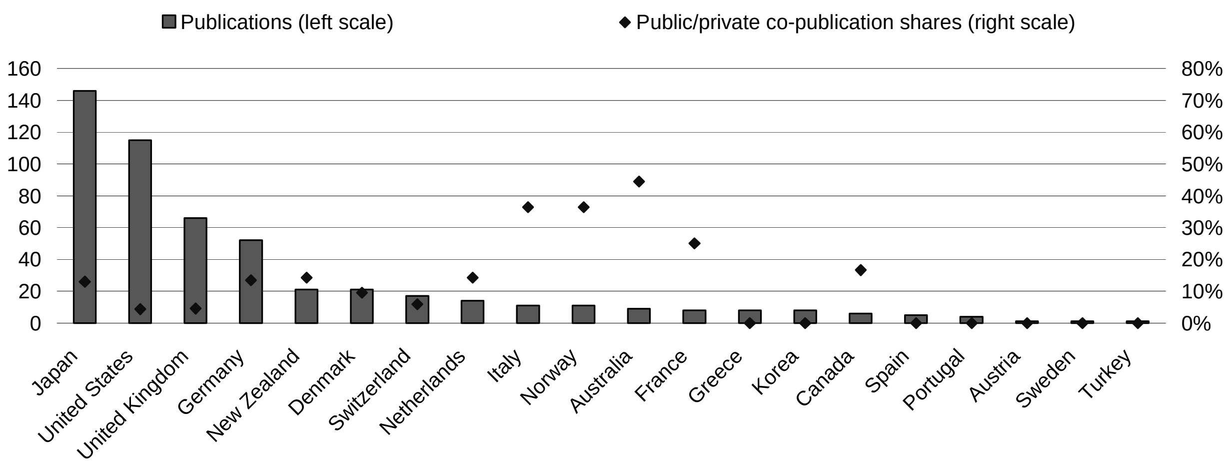


Figure 4.12. Publications and public/private co-publication shares of OECD countries in SOFCs, 1990-2000



CHAPTER 5. DISCUSSION AND GENERAL CONCLUSIONS

Methodological considerations

105. The mapping of the S&T knowledge base of the field of fuel cells in the OECD area over the past decade was conducted using both data on publications and patents. The latter enables quantitative analyses of the main features of the "fuel cells innovation system", including the division of labor among the actors (*i.e.* countries, institutional sectors, institutions) and the linkages between them in the production of S&T knowledge. The primary benefit of this methodological approach lies in its objective or transparent analysis of the organization of knowledge production and diffusion in the field in an internationally comparable perspective.

106. It is noteworthy to stress that publications and patents should be regarded as units of codified knowledge. As such, they can only reflect part of the underlying S&T activities that nevertheless extensively rely on tacit knowledge. One must therefore keep in mind that the volume of these publications and patents does not equate to the level of S&T output and research collaboration, although significant positive correlations are very likely to be found between these approximations and actual levels of S&T production and scientific cooperation at aggregate levels such as regions, countries, institutional sectors, and main organizations.

107. In addition, it should be noted that this bibliometric study on the field of fuel cells was based on journal articles published in peer-refereed international scientific and technical journals covered by both the ETDE's and Science Citation Index Expanded databases, most of which are English-language publication outlets, and on patent applications to the EPO, which might bias the results in favour of European countries and under-represent patenting by Asian and American inventors. Moreover, these data on publications and patent do not cover the whole spectrum of fuel cells S&T themes but only those dealing with alkaline, direct methanol, molten carbonate, phosphoric acid, proton exchange membrane, solid oxide, and regenerative (reversible) fuel cells.

108. Although bibliometric and patent data provide a useful quantitative framework for the mapping of knowledge base in specific technical fields or sectors (OECD, 2001*a*), one should take note that the numbers and measures derived from this approach should always be judged in terms of this restrictive universe. Bibliometric and patent findings should consequently preferably be accompanied by expert opinions, qualitative case studies, or other evaluate procedures to help assess their meaning and relevance. Therefore, one should be careful to use bibliometric and patent data for drawing strong policy conclusions in isolation of complementary information. In conclusion, the major added value of bibliometric and patent approaches should be sought in their comprehensive and systematic coverage, which enables one to address fuel cells R&D policy issues covering the whole range of OECD countries, their key research performing institutions and their inter-organizational collaboration linkages.

Key findings and questions

Scientific research and public funding

109. Despite a sharp worldwide growth of scientific publications in the field of fuel cells over the past decade, the world shares of the three triadic regions – the United States, European Union, and Japan

followed contrasted trends: the US share in total scientific publications declined rapidly while the EU-15 share grew rapidly and the Japanese share remained stable. Are these trends correlated with the amount of public funding in the field of fuel cells within these three regions, since most scientific publications originated from the higher education and government sector? Do these trends, especially in the United States and the European Union reflect changes in the objectives of public finding in terms of basic and applied research.

The relations between scientific research and technological development

110. In spite of the sharp growth of scientific publications at the worldwide level throughout the nineties, growth in the number of EPO patent applications was quite slow. Moreover, it appears that the scientific competencies were much more distributed among the OECD countries than the technological ones. In fact, most the leading OECD countries in terms of number of scientific developments were also the most active ones in terms of number of patent applications. Does this correlation mean that technological development in the field of fuel cells entails a strong scientific knowledge base?

S&T specialization profiles

111. Not only do OECD countries differ considerably in terms of their overall contribution to the S&T output within the field of fuel cells but they also perform very differently. Indeed, OECD countries had slightly different S&T specialization profiles with regards their involvement in the various types of fuel cells, namely AFC, DMFC, MCFC, PAFC, PEMFC, RFC and SOFC. S&T activity patterns also differed slightly within the leading OECD countries. Since most scientific publications originated from the public sector and nearly all patent applications come from the business enterprise sector in these countries, one can wonder whether there was a co-ordination between the public and private institutions in the generation of S&T knowledge within the field during the 1990s. In other words, did public research entirely respond to the needs of the business enterprise sector?

Scientific research and globalization

112. The data shows that the share of international co-publications in total publications and the density of the network of international co-publications in the field of fuel cells over the past decade were both relatively low in the 1990s compared with the situation of other specific technical fields. Does this mean an advanced division of labor in scientific activity among the OECD countries or rather a lack of public incentives for international collaboration over the past decade?

Private research and public/private cooperation

113. In several OECD countries, several firms were active in the generation of both S&T knowledge, as measured by publications and patent applications. Does this mean that their involvement in scientific research constituted a requisite to easily assimilate the results of public research or rather that the public sector did not respond to their needs? If these firms had the objective of creating absorptive capacity, why did they show a low propensity to co-publish with the public sector?

REFERENCES

Barré R. (1997), “Les outils bibliométriques, instruments essentials pour les recherches concernant les économies fondées sur la connaissance”, *Revue d’Economie Industrielle*, vol. 79

Bradford S. (1950), *Documentation*, Public Affairs Press, Washington, DC.

Braun *et al.* (1991), “The Bibliometric Assessment of UK Scientific Performance: Some Comments on Martin’s ‘Reply’”, *Scientometrics*, vol. 20

Callon M. *et al.* (1993), *La Scientométrie*, Presses Universitaires de France, Paris

Calvert J. and P. Patel (2003), University-industry research collaborations in the UK: bibliometric trends, *Science and Public Policy,* vol. 30

Cockburn I. and R. Henderson (1998), “Absorptive capacity, coauthoring behaviour, and the organization of research in drug discovery”, *The Journal of Industrial Economics*, vol. XLVI

Cohen W. and D. Levinthal (1989), “Innovation and Learning: the Two faces of R&D”, *Economic Journal*, September

Dasgupta P. and P. David (1994), “Toward a New Economics of Science”, *Research Policy*, vol. 23

David P. (1993), “Knowledge, property and the system dynamics of technological change”, *in* World Bank (ed.), *Proceedings of the World Bank Annual Conference on Development Economics 1992,* Washington D.C.

Debackere K. and M. Rappa (1994), “Technological communities and the diffusion of knowledge: a replication and validation”, *R&D Management*, vol. 24

European Commission (2003*a*), *Hydrogen Economy and Fuel Cells: a Vision of our Future*, report prepared on behalf of the High Level Group on Hydrogen and Fuel Cell Technologies.

European Commission (2003*b*), *Third Report on Science & Technology Indicators*, Luxembourg

Etzkowitz H. and L .Leydesdorff (eds.) (1997), *Universities in the Global Knowledge Economy: A Triple Helix of Academic-Industry-Government Relations*; Cassell, London

Fuel cells Canada and PricewatherhouseCoopers (2002), *Fuel Cells: The Opportunity for Canada,* June

Gambardella A. (1992), “Competitive Advantages from In-house Scientific Research: The US Pharmaceutical Industry in the 1980s, *Research Policy*, vol. 21

Garfield E. (1972), “The Design and Production of a Citation Index”, in *Citation Indexing-Its Theory and Application in Science, Technology and Humanities*, John Wiley & Sons, New York

Gibbons M. *et al.* (1994), *The New Production of Knowledge*, Sage Publications, London

Gibbons M. and R. Johnston (1974), “The Roles of Science in Technological Innovation”, *Research Policy,* vol. 3

Godin B. (1996), “Research and the Practice of Publications in Industries”, *Research Policy,* vol. 25

Godin B. and Y. Gindras (2000), “The Place of Universities in the System of Knowledge Production”, *Research Policy*, vol. 29

Hassan E. (2003), “Simultaneous Mapping of Interactions Between Scientific and Technological Bases: The Case of Space Communications”, *Journal of the American Society for Information Science and Technology,* vol. 54

Hicks D. (1995), “Tacit Competencies and Corporate Management of the Public/Private Character of Knowledge”, *Industrial and Corporate Change*, vol. 4

Hicks D. and K. Hamilton (1999), “Does University-Industry Collaboration Adversely Affect University Research”, *Issues in Science and Technology,* Summer

Hicks D. and S. Katz (1997), “A National Research Network Viewed from a Industrial Perspective”, *Revue d’Economie Industrielle,* vol. 79

Industry Canada *et al.* (2003), *Canadian Fuel Cells: Commercialization Roadmap*, Ottawa

IPTS (2003), Fuel Cells: Impact and Consequences of Fuel cells on Sustainable Development, Seville

Katz S. and B. Martin (1997), “What is Research Collaboration ?”, *Research Policy,* vol. 26

Kealey T. (1991), “Government-Funded Academic Science is a Consumer Good, Not a Producer Good: A Comparative Reassessment of Britain’s Scientific and Technological Achievements since 1794 and a Comment on the Bibliometry of B. Martin and J. Irvine”, *Scientometrics,* vol. 20

Kobayashi S. (1987), “Internationalisation of Japanese Journals and their Contribution to Basic Science”, *Daigaku Kenkyu,* vol. 1

Leydesdorff L. (1991), “On the ‘Scientometric Decline’ of British Science. One Additional Graph in Response to Ben Martin”, *Scientometrics,* vol. 20

Levin *et al.* (1987), “Appropriating the Returns from Industrial Research and Development”, *Brookings Papers on Economic Activity,* vol. 3

Narin F. and E. Noma (1985), “Is Technology Becoming Science”, Scientometrics, vol. 7

Martin B. (1991), “The Bibliometric Assessment of UK Scientific Performance. A Reply to Braun, Glänzel and Schubert, *Scientometrics,* vol. 20

National Science Board (2002), *Science and Engineering Indicators* -2002, National Science Foundation, Arlington

OECD (1994), *Patent Manual*, Paris

OECD (1996), *National Innovation Systems*, Paris

OECD (1997), *Indicateurs Bibliométriques et Analyse des Systèmes de Recherche: Méthodes et Exemples,* Document de Travail de la DSTI 1997/1

OECD (2001*a*), *Mapping the Knowledge Base of Specific Technological Fields or Sectors: A Bibliometric Approach*, DSTI/STP/TIP(2001)21

OECD (2001*b*), *OECD Science, Technology and Industry Scoreboard: Towards A Knowledge-based Economy*, Paris

OECD (2002*a*), *Frascati Manual*, Paris

OECD (2002*b*), *OECD Science, Technology and Industry: Outlook 2002*, Paris

OECD (2002*c*), *Benchmarking Industry-Science Relationships*, Paris

OECD (2003), *Turning Research into Business*; Paris

Otsu K. (1983), "A Bibliometric Study of Japanese Science and Social Science Publications", *Library and Information Science,* vol. 21

Pavitt K. (1991), "What Makes Basic Research Economically Useful", *Research Policy*, vol. 20

Pechter K. and S. Kakinuma (1999), "Coauthorship Linkages between University Research and Japanese Industry", *in* Branscomb *et al.* (eds.), *Industrializing Knowledge: University-Industry Linkages in Japan and the United States,* the MIT Press, Cambridge

Pigou (1932), The Economics of Welfare, 4th edition, Mac Millan, London

Rosenberg N. (1990), "Why Do Firms Do Basic Research (With Their Own Money)?", *Research Policy*, vol. 19

Rosenberg N. (1991), "Critical issues in Science Policy Research", *Science and Public Policy*, vol. 18

Salter A. and B. Martin (1999), "The Economics Benefits of Publicly Funded Basic Research: A Critical Review", *SPRU Working Papers Series*, 34

Siversten G. (1991), "Should a New Database for International Comparison be More Restricted in Journal Coverage?", *in Science and Technology in a Policy Context*, Acts of the EC-Leiden Colloquium on Science and Technology Indicators, DSWO Press, Leiden.

Stix E. (1994), "The Speed of Write", *Scientific American*, December

Tijssen and Leeuwen (2003), "Bibliometric Analysis of World Science", Extended technical annex to chapter 5 of the "Third European Report on S&T Indicators", CWTS

Tijssen and Van Wijk (1998), *The Global Science Base of Information and Communication Technologies*, CWTS Report 98-04

United States Department of Energy (2002), *National Hydrogen Energy Roadmap*, Washington D.C.

Van Raan A. and R. Tijssen (1990), "An Overview of Quantitative Science and Technology Indicators Based on Bibliometric Methods", Technology Economy Programme for the Development of Indicators, OECD, Paris.

Zucker L. and M. Darby (1995), "Virtuous Circles of Productivity: Star Bioscientists and the Institutional Transformation of Industry", *NBER Working Paper*, 5342

ANNEX A. METHODOLOGY AND INFORMATION SOURCES

114. This report is based on a large-scale application of a systematic method for quantifying information on fuel cells research and development activity. Data on patents and publications in the scientific and technical literature are used to create internationally comparable indicators that measure scientific and technological output and provide insight into the knowledge structure of the innovation system. The following developments provide extensive information on the methodology and data sources mobilized for this empirical study. First, the common strengths and weaknesses of bibliometric and patent indicators are discussed. Then, the content of the databases used for constructing and measuring of these indicators is described. Finally, both bibliometric and patent indicators used in this study are defined.

Strengths and weaknesses of bibliometric and patent indicators

115. Indicators based on bibliometric (*i.e.* scientific publications) and patent data satisfy four basic requirements to be considered in choosing quantitative indicators to examine the economics of knowledge production and diffusion in specific fields or sectors (Barré, 1997; OECD, 2001*a*):

- *International comparability*. The comparison between countries or regions is now at the heart of most studies on knowledge production and diffusion. This reduces the value of case studies based on *ad hoc* data that do not allow such comparisons.

- *Capturing the dynamics of knowledge production and diffusion at micro-level*. The knowledge base of different economic activities and knowledge linkages among them are complex and changing constantly. The use of conventional statistical categories such as "industry sector" may lead to overlook key policy-relevant aspects of such change, in both retrospective and prospective analysis.

- *Measuring inputs, outputs, and processes*. Innovation itself is difficult to measure directly. Relating measure of the inputs to innovation (*e.g.* R&D expenditures) to measures of the output from innovation often requires some measures of innovation processes themselves.

- *Timeless of data*. The relevance of case studies for policy-makers depends heavily on the availability of regularly updated data.

116. Publications and patents constitute one of the main outputs of scientific and technological activity and thus can be used to quantify its output. Moreover, when authors or inventors publish in journals (or other supports) or applied for patents, they not only reveal what they are doing but also with whom they did it, and when and where it was done. These indicators have become common tools to analyze the organization of research activity and its performance from a quantitative point of view (OECD, 1994, 1997; Callon *et al*., 1993; NSB, 2002; EC, 2003*b*). The main benefits of such indicators specifically applied to the mapping of the knowledge bases in particular fields or sectors remain the unique empirical characterization of the way actors (*i.e.* countries, institutional sectors, institutions) interact as a collective system of knowledge production and diffusion (OECD, 1996):

- *Division of labor among actors*. The identification of actors engaged in such fields/sectors and the measures of their contributions in the S&T knowledge production process lead to understanding how S&T activities are shared out among them.

- *Coordination between actors*. The identification of the different linkages between actors provides information on the ways knowledge is distributed within fields. Indeed, knowledge can be diffused through many channels, including physical collaborations, patents and papers, etc.

- *Structure performance*. Finally, once actors and linkages are identified, it becomes possible to analyze in depth the field's structure performance from a systemic point of view. Measures of density (*i.e.* intensity of linkages between actors), cohesion (*i.e.* subgroups of actors), actors' roles/positions (*i.e.* central/peripheral) are very helpful since "systemic failures" can be emphasized (*e.g.* a lack of public/private linkages, duplication in the innovation process among actors).

117. Indicators based on bibliometric and patent data are also subject, as other kinds of indicators, to several limits. The limitations of bibliometric data stem mainly from the various means of communication that scientists use to convey information to each other apart from the usual channel of scientific journals. *Inter alia*, oral communications between scientists is not captured in statistics, nor are internal reports between universities, laboratories or research groups and reports between countries working together through committees, programs or laboratories. Also slipping through the net are important monographs and, to an even greater extent, electronic communication between researchers, which is developing rapidly (Stix, 1994). All of the communication that is covered by bibliometric methods therefore consists of exchanges that have been "formalized" (*i.e.* codified knowledge); informal communication (*i.e*. embodied knowledge) is not incorporated. This approach is even more restrictive with regard to industrial or defense-related research. There are great lags in communication between science (primarily academic) and industry, because of industry's desire to protect its discoveries (prior to patent applications in particular) and the fact that its findings are generally published in an abridged form. Articles published by industrial laboratories often give a limited view of the aims of research, which are generally to create products or processes subject to commercial competition (OECD, 1997). Finally, it is well known that patents are not the only means to protect technological knowledge. Several other means such as lead-time or trade secrecy have to be taken into account (Levin *et al.*, 1987). Moreover, when using indicators based on patents, especially patent count to measure the technological output of an actor, it is necessary to assume that the propensity to patent does not vary from one actor to the next and that the value of all patents is equal.

The customized fuel cells database

118. Once the relevant kinds of quantitative indicators was chosen and the field of fuel cells delineated, a customized database was constructed in order to conduct both the bibliometric and patent analyses. This database contains relevant bibliographic data on scientific publications and patents on the global fuel cells S&T base.

Field delineation

119. A list of seven sub-fields was defined to delineate the field of fuel cells technologies either on the science or technology side. These seven sub-fields, which correspond to the most common types of fuel cells in accordance with the employed electrolytes, are the following (box 1.): Alkaline Fuel Cells (AFC); Direct Methanol Fuel Cells (DMFC); Molten Carbonate Fuel Cells (MCFC); Phosphoric Acid Fuel Cells (PAFC); Proton Exchange Membrane Fuel Cells (PEMFC); Solid Oxide Fuel Cells (SOFC); and Regenerative (Reversible) Fuel Cells (RFC).

120. This approach has for main consequence that not all publications and patents dealing with fuel cells or even related hydrogen-based technologies are considered to examine the knowledge base of the field. It nevertheless allows the simultaneous mapping of the scientific and technological bases of fuel cells since there are delimited according to a same definition. In addition, the approach allows the identification of the characteristics of the process of knowledge production and diffusion related to the different types of fuel cells in further analyses.

121. Each sub-field was then translated into a bibliographic search equation thanks to the technical experts from the European Patent Office (EPO) and the US Department of Energy (US DoE). Each equation comprised a set of significant keywords and/or indexing codes. This step was a requisite to select properly the relevant data on patents and scientific publications at the worldwide level.

122. Data on scientific publications were first downloaded from the ETDE’s database and then matched with an other database, namely the Science Citation Index Expanded. The characteristics of these two databases are described below. This methodology was adopted to obtain an accurate picture of the global science base of the field of fuel cells.

The ETDE’s database[12]

123. The ETDE's Energy Database is a database developed under the framework of the Energy Technology Data Exchange, a program of the International Energy Agency (IEA). The database contains the world's largest collection of energy literature with more than 3.8 million abstracted and indexed records. The database contains bibliographic references to and abstracts of journal articles, reports, conference papers, books, thesis/dissertation, and other miscellaneous document types. The database covers such varied subjects as environmental aspects of energy production and use and energy policy and planning, as well as the basic sciences that support energy research and development (R&D) (box 2.). In addition to the energy research and technology information from member countries, the database contains citations published worldwide regarding nuclear, coal, and global climate change information. This broader coverage comes through cooperation with other international organizations.

Box 2. How the ETDE’s Energy Database is built?

The construction of the ETDE database is as follows. Each member country[13] associated with the Energy Technology Data Exchange submits database records of the energy research and technology information published within their borders. This input is prepared by the country in a standardized form, adhering to agreed-upon cataloguing guidelines and subject analysis requirements. Members then electronically transmit the abstracted and indexed records (in English) via the Internet to the Operating Agent (OA). This electronic process enhances both the timeliness of available information and the efficiency in announcing results. ETDE's Energy Database also contains many citations from international organizations and their additional member countries. Nuclear literature published in non-ETDE countries is included in ETDE's database because all ETDE member countries also belong to the International Atomic Energy Agency's International Nuclear Information System (INIS). In addition, a cooperative venture with IEA Coal Research -- The Clean Coal Center provides worldwide coverage of energy-related coal data. This arrangement with The Clean Coal Center has supplemented ETDE's international coverage in the area of global climate change.

The Energy Technology Data Exchange employs several procedures to ensure the quality of the database. To assess how comprehensive the coverage is, annual database quality studies are conducted. Recent studies examined coverage of solar cells, the effects of transportation fuels on the depletion of the ozone layer, and biomass for power. Another quality assurance measure is that all database entries undergo a series of automated and manual quality checks when they arrive at the OA facility. Before the records are included in the database, fields such as journal title information and key words are computer checked against ETDE standards and authorities. To assist member countries in providing consistent, quality data, ETDE has developed a series of

12 . Most of the following developments are taken from the ETDE website (www.etde.org).

13 . ETDE has representatives in the 18 following countries: Belgium, Brazil, Canada, Denmark, Finland, France, Germany, Italy, Japan, South Korea, Mexico, the Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, and the United States.

reference publications and the ETDE Procedures Manual. Training sessions for new member countries are available on request from the OA. These sessions cover the full range of data processing procedures, including cataloguing, abstracting, and indexing.

Source: www.etde.org.

The Science Citation Index Expanded database[14]

124. The Science Citation Index Expanded (SCI Expanded) is compiled by the Institute for Scientific Information (ISI), a private company located in the United States. The bibliographic database encompasses the whole spectrum of scientific fields in the basic and applied sciences, providing a cover-to-cover indexing of more than 6,000 world's leading scholarly (*i.e.* peer reviewed) science and technical journals covering more than 150 disciplines international scientific and applied journals (box 3.).

Box 3. How are ISI journals selected?

The selection of journals incorporated in the ISI related databases (firstly, the Science Citation Index) mainly follows the subsequent principles. Its "inventor", Eugene Garfield, regarded cost-benefit considerations as paramount in defining the coverage of a database, conceding that it was not feasible to cover all existing journals. "One reason is that no one knows how many journals are published, because there is no agreement on what constitutes a journal" (Garfield, 1972). Garfield first calculated the number of scientific journals needed to optimize coverage of a maximum amount of scientific information. To do this he adopted a law that had been developed by information scientists on the basis of Bradford's work (1950). This law showed that between 500 and 1 000 journals were needed to cover 95 per cent of the "significant" literature published in a given field. Garfield subsequently combined Bradford's dispersion law with a concentration law he himself had developed (Garfield, 1972). Bradford's law defines a scientific field, but if a database is to cover several such fields, does the number of journals for one field have to be multiplied by the number of fields? According to Garfield, because a substantial proportion of disciplines overlap, the core literature for all of these disciplines can also be covered by approximately 500 to 1 000 journals. The first step was to develop a method for identifying these 500 to 1 000 journals. To do so, Garfield used the "number of citations" as one of the criteria for a "significant" search. Because authors cite earlier work in order to support, describe or develop a particular point in their own work, the citation of a scientific paper is an indication of the importance that the community attaches to the research. Thus, citations can be considered a criterion for selecting the most highly esteemed scientific journals on the basis of the articles they contain. First, a count was made of the number of times an article was cited in a given journal. Then, the impact factor was computed by dividing the number of citations by the number of articles contained in the journal. This made it possible to eliminate any bias stemming from a journal's size, rendering citation proportional to the number of articles. Thus the Science Citation Index database covers the most widely used, recognized and influential scientific journals in the world, as measured by their "citation indices". It limits the scope of coverage to world-class scientific journals, representing the "core" scientific output in specific fields and eliminating research not presented in the "mainstream", which is limited to a specific group of journals.

Source: OECD (1997).

125. Although the ISI related databases are the traditional information source for bibliometric analyses of scientific and technical research literature that is published in international scientific and technical journals, these data sets are nevertheless subject to limits. While these databases, especially the SCI Expanded, are quite large in terms of the number of indexed journals, the whole coverage of the ISI journals is not necessarily an accurate reflection of all worldwide research activities in all cases, notably in the social and behavioral sciences, law, and the humanities (Tijssen and van Wijk, 1998) as well as in engineering fields such as fuel cells. Secondly, one must consider the language factor. The ISI related databases clearly favor English-speaking scientists (Otsu, 1983; Kobayashi, 1987). As a consequence, researchers from non-English-speaking countries who publish in English enjoy a comparatively wider presence, as is the case in Scandinavia (Sivertsen, 1991).

Linking the Science Citation Index Expanded to the ETDE database.

126. ETDE journals whose scientific publications (*i.e.* journal articles in contrast to technical reports, book reviews, thesis dissertations, conference proceedings, etc.) dealing with fuel cells technologies where

14 . Most of the subsequent developments draw upon OCDE (1997).

published were matched with journals covered by the SCI Expanded thanks to the use of the ISSN codes. It is important to note that by excluding all publications that are not journal articles *per se*, the number of publications used in the analysis is significantly reduced. Secondly, considering only journal articles included in the SCI Expanded means that the journal articles of the ETDE database that have less to do with fundamental and technological advances are excluded from the analysis. Over the more than 2380 articles identified in the ETDE database for the period 1990-2000, only 1191 articles were considered for further analysis. In doing this, the most relevant (*i.e.* peer reviewed) articles related to fuel cells technologies were identified in the SCI Expanded since the identification process was completed at the level of individual scientific papers (Annex A)[15]. These articles were thus included in the bibliometric analysis. For each article, the following bibliographic information were used: title, abstract, name(s) of author(s), affiliation(s), journal name, date of publication, ISSN code, sub-field(s), and actor type (*i.e.* business enterprise, government, higher education, and private non-profit sectors).

Data on patents

127. Data on EPO patent applications related to fuel cells are incorporated in the OECD fuel cells database. For each patent, the following bibliographic information are classified: title, abstract, name(s) of inventor(s), affiliation(s), IPC code(s), dates of publication and priority, sub-field(s), actor type (*i.e*. business enterprise, government, higher education, and private non-profit sectors).

Data cleaning and additional data

128. Both data on scientific publications and patents were cleaned and unified. This principally concerns the names of institutions. Indeed, since many institutions had various spellings (institutions may appear with different names and abbreviations) in a same data set (*i.e.* ETDE database), it was necessary to clean their names and unified them into "standardized" ones. It is important to note that the unification process of the names of institutions has been done at the level of the main organization, including "umbrella organization". For instance, "Argonne National Lab." and "Lawrence Livermore National Lab." were unified under "US Department of Energy". Indeed, in many case, only the "umbrella organization" is mentioned in publications. Therefore, using different levels of analysis from one publication to the next may led to unsatisfactory results from methodology point of view. In addition, this technical constraint makes it more difficult or even impossible to perform more detailed bibliometric analysis, *e.g.* at the level of departments or laboratories.

129. In addition, valuable additional information not included in the raw data sets has been integrated in the customized fuel cells database, principally information on the type (*i.e*. business enterprise, government, higher education, and private non-profit sectors) of publishing and patenting institutions. The identification of the type of institutions was done in accordance with the definition of the institutional sectors given in the Frascati Manual (OECD, 2002*a*) and with the cooperation of the national experts participating in the TIP case study on energy technology. It is noteworthy to stress that the unification of the names of institutions and the identification of the type of these institutions (especially, those from non-participating countries) have been done to the best of our available knowledge. Moreover, the OECD secretariat cannot guarantee that the identification of type of institutions, especially patenting institutions, in the participating countries provides an accurate image of the technological contribution of the various institutional sectors in the field of fuel cells technologies. In fact, many patents originated from public research are own by individuals (e.g. professors, researchers), particularly in the European countries (Table 1.). Consequently, the number of patents from the public sectors in those countries may be largely underestimated in this report.

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15 . For a comparable methodology, see for instance Tijssen & van Wijk (1998), Hassan (2003).

Table 1. Ownership of intellectual property rights at Public Research Organizations (PROs) in OECD and non-member countries

	Universities			Non-university PROs		
	institution	inventor	government	institution	inventor	government
Australia	♦			♦		
Austria	♦			♦		
Belgium	♦			♦		
Canada[1]	♦	♦		♦		
Denmark	♦			♦		
Finland		♦		♦		
France	♦			♦		
Germany	♦			♦		
Iceland		♦		♦		
Ireland	♦			♦		
Italy		♦			♦	
Japan[2]		♦	◊	♦		
Korea	♦			♦		
Mexico	♦			♦		
Netherlands	♦			♦		
Norway		♦		♦		
Poland	♦			♦		
Russia			♦			♦
South Africa	♦			♦		
Sweden		♦		♦		
Switzerland	♦	◊		♦		
United Kingdom	♦			♦		
United States[3]	♦	◊	◊	♦	◊	

♦ = Legal basis or most common practice; ◊ = allowed by law/rule but less common.

1. In Canada, ownership of IP at universities generated through institutional funds varies, but IP generated through Crown procurement contracts devolves to the institution performing the contract research.

2. In Japan, the president of a national university or inter-university institution decides upon the right to ownership of inventions made by a staff member of the university/institution on the basis of discussions by the university invention committee.

3. In the United States, universities have the first right to elect title to inventions resulting from federally funded research. The government (*e.g.* federal agency) may claim title if the performer does not. In certain cases, the inventor may retain rights with the agreement of the university/federal partner and the government.

Source: OECD (2003).

Bibliometric and patent indicators used in this report

130. The following sections describe the bibliometric and patent indicators used in this report. Two main categories of bibliometric and patents indicators are used here for mapping the S&T knowledge bases of the field of fuel cells: activity indicators and relational indicators. Activity indicators are usually used to characterize knowledge production activities by examining the outputs of the innovation process. Relational indicators provide insight into knowledge diffusion activities by highlighting the interactions among actors or interrelations among research themes. Both activity and relational indicators are measured in the report using the "whole counting" schema (box 5.).

Box 5. Different counting schemas

One of the ambiguities of quantitative analysis based on scientific publications and patents is the diversity of counting methods. For example, the classification of "co-authored" publications (*i.e.* articles written by more than one person) or "co-invented" patents has long been a major subject of debate among bibliometricians (Martin, 1991; Braun *et al*., 1991; Leydesdorff, 1991; Kealey, 1991). How can the participation of authors/inventors in scientific and technical work be measured when the work is of a co-operative nature? Can individuals all be assigned "full credit" for their shares or, if an article/patent originate from nine other authors/inventors, for example, should they each be assigned only a tenth of a credit? Does a country engaged in three-country collaboration forge a "whole link" or only a "third of a link"? In practice, when an article/patent is co-authored/co-invented by researchers from different countries, bibliometricians basically have two ways of assigning credit to the countries concerned. Some assign full credit, *i.e.* count "1" for each co-author/co-inventor country (whole counting method); others divide co-authorship/co-inventorship by the number of countries of origin of the authors/inventors and assign a fractional credit to each country (fractional counting method).

Each counting method surely has its own logic, but the way credit is divided up must be totally understood by the people who use their output. For scientists and policy makers who use S&T indicators, whole counting tends to be more comprehensible and easy to interpret. "A share of 10 per cent [of a country] means in this sense, that 10 out of every 100 papers in the world have at least one contributor from [this country]. It is hard to explain, however, the 'meaning' of a 10 per cent share in the fraction scale", which may be the result of adding up ten or more papers (Braun *et al.*, 1991). Even more importantly, fractional counting assigns a lesser value to international co-authorship/co-inventorship than to authorship/inventorship of a national article/patent, when national performance is counted. The more international partners an article/patent has, the less credit is assigned to each of the countries involved. Why should a country be credited more, in bibliometric statistics, for a paper/patent by national authors/inventors than for a co-authored/co-invented article/patent during the course of international co-operation (Leydesdorff, 1991)? It is precisely for these reasons that some bibliometricians contend that fractional counting is an inferior procedure; especially when the volume of data is substantial, they maintain that "equal counting of all authors is in most cases the best solution" (Van Raan and Tijssen, 1990).

Source: adapted from OECD (1997).

Activity indicators

Output indicators

131. Numerical counts of scientific publications (*i.e.* journal articles) and patents provide a simple measure of the quantity of S&T knowledge produce by an actor (whether defined as a country, an institutional sector, or an institution) in a particular field. These indicators are measured here at the levels of countries, institutional sectors, and institutions and are expressed in both relative (as a percentage of total publications or patents, *i.e*. "world share") and absolute terms.

Productivity indicators

132. Numerical counts of scientific publications (papers) and patents by million population are used here as a proxy of the scientific and technological productivity of a country in the field of fuel cells.

Specialization indicators

133. Publication and patent counts can be used to calculate measures of S&T specialization that indicate the degree to which an actor's S&T outputs are concentrated in a particular scientific or technical field. This indicator is particularly useful since it minimizes distortions that can be introduced by comparing the world shares of actors, *i.e*. their respective contribution in the S&T output, notably the size effect of sub-fields. The specialization indicator is defined as follows:

$$\text{specialization index} = \tanh\left[\ln\left(CSR/WSR\right)\right]$$

where CSR is the percentage of scientific publications (or EPO patent applications) of an actor in a certain sub-field (e.g. alkaline fuel cells) and WSR accordingly calculated by the percentage of scientific publications (or EPO patent applications) of an actor in relation to all publications (or EPO patent applications) counted.

134. Taking the logarithm of that ratio leads to symmetry around the neutral value "0". Tanh gives the hyperbolic tangent. It is used in order to keep the values of the specialization index within the range of -1 and 1.

135. Both scientific and technological specialization indicators are measured in this report at the level of countries. They measure specialization within the field of fuel cells, but not in fuel cells versus other technological fields.

Relational indicators

Co-publications indicators

136. Scientific papers often bear the signatures of multiple authors from the scientific community reflecting cooperation during the research process. Co-signatures can therefore be used as an approximate measure of scientific collaboration between actors, especially if actors come from different organizations or countries. It is noteworthy to stress that using co-publications as an indicator of scientific cooperation is subject to certain limits since the notion of scientific cooperation is vague (Katz and Martin, 1997). First, not all cooperations result in a co-authored publication. Secondly, the relationships among actors can last several years but this will not reflected in co-authored publications in each of those years. In other terms, indicators based on co-publications better highlight the existence of cooperations than its duration over a time period. In spite of these limits, co-publications indicators are often be used to quantify collaborations at low costs (especially when the number of data is high) and following an invariable method.

137. Co-publications indicators are calculated in this report at the levels of countries, institutional sectors and institutions. Co-publications at the level of countries, which constitute international co-publications, involve authors from at least two different countries, *i.e*. at least two authors' addresses in different countries. Co-publications at the level of institutional sectors are either international or domestic co-publications involving at least two authors that are associated with different main organizations. This means that both intra-sectoral co-publications and inter-sectoral cooperations are taken into account in the measurement of the indicator at the level of institutional sectors. Co-publications at the level of institutions constitute either international or domestic co-publications involving at least two authors that belong to different main organizations. Consequently, co-publications involving at least two authors from different research groups, departments, or laboratories, which are nonetheless associated with the same main organization, are ignored.

ANNEX B. FUEL CELLS – RELEVANT INTERNATIONAL SCIENTIFIC AND TECHNICAL JOURNALS

Fuel cells journals covered by the SCI Expanded, and the number of publications per journal included in database, 1990-2000

Journals	Publications
JOURNAL OF THE ELECTROCHEMICAL SOCIETY	291
JOURNAL OF POWER SOURCES	278
SOLID STATE IONICS	138
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY	60
JOURNAL OF APPLIED ELECTROCHEMISTRY	55
ELECTROCHIMICA ACTA	38
JOURNAL OF THE AMERICAN CERAMIC SOCIETY	21
JOURNAL OF NEW MATERIALS FOR ELECTROCHEMICAL SYSTEMS	18
JOURNAL OF MATERIALS SCIENCE	15
CATALYSIS TODAY	13
INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH	13
INTERNATIONAL JOURNAL OF ENERGY RESEARCH	11
JOURNAL OF MATERIALS SCIENCE LETTERS	11
JOURNAL OF THE CERAMIC SOCIETY OF JAPAN	11
ENERGY CONVERSION AND MANAGEMENT	10
MATERIALS RESEARCH BULLETIN	8
CHEMICAL ENGINEERING SCIENCE	7
JOURNAL OF ALLOYS AND COMPOUNDS	7
MATERIALS SCIENCE FORUM	7
APPLIED CATALYSIS A-GENERAL	6
ENERGY	6
JOURNAL OF CHEMICAL ENGINEERING OF JAPAN	6
MATERIALS AND CORROSION-WERKSTOFFE UND KORROSION	6
MATERIALS CHEMISTRY AND PHYSICS	6
MATERIALS LETTERS	6
CHEMIE INGENIEUR TECHNIK	5
JOURNAL OF ENERGY RESOURCES TECHNOLOGY-TRANSACTIONS OF THE ASME	5
JOURNAL OF SOLID STATE CHEMISTRY	5
JOURNAL OF THE EUROPEAN CERAMIC SOCIETY	5
KAGAKU KOGAKU RONBUNSHU	5
SCRIPTA MATERIALIA	5
APPLIED ENERGY	4
CHEMISTRY & INDUSTRY	4
ENERGY & FUELS	4
NIPPON KAGAKU KAISHI	4
ADVANCED MATERIALS	3
AICHE JOURNAL	3

APPLIED SURFACE SCIENCE	3
IEEE TRANSACTIONS ON ENERGY CONVERSION	3
LANGMUIR	3
SCIENCE	3
THERMOCHIMICA ACTA	3
THIN SOLID FILMS	3
ACTA MATERIALIA	2
ACTUALITE CHIMIQUE	2
AMERICAN CERAMIC SOCIETY BULLETIN	2
CHEMISTRY OF MATERIALS	2
CHIMIA	2
CORROSION SCIENCE	2
ENERGY SOURCES	2
FUEL	2
IEEE TRANSACTIONS ON ELECTRON DEVICES	2
JOURNAL OF CATALYSIS	2
JOURNAL OF MATERIALS RESEARCH	2
MATERIALS SCIENCE AND ENGINEERING B-SOLID STATE MATERIALS FOR ADVANCED TECHNOLOGY	2
POLISH JOURNAL OF CHEMISTRY	2
POWDER TECHNOLOGY	2
SEA TECHNOLOGY	2
SURFACE & COATINGS TECHNOLOGY	2
APPLIED BIOCHEMISTRY AND BIOTECHNOLOGY	1
BIOMASS & BIOENERGY	1
BULLETIN OF ELECTROCHEMISTRY	1
CANADIAN JOURNAL OF CHEMICAL ENGINEERING	1
CHEMICAL ENGINEERING & TECHNOLOGY	1
CHEMICAL REVIEWS	1
CHEMISTRY LETTERS	1
COMBUSTION AND FLAME	1
ENVIRONMENTAL SCIENCE & TECHNOLOGY	1
FUEL PROCESSING TECHNOLOGY	1
INORGANIC MATERIALS	1
INTERNATIONAL JOURNAL OF MODERN PHYSICS B	1
JOURNAL DE PHYSIQUE IV	1
JOURNAL OF ANALYTICAL ATOMIC SPECTROMETRY	1
JOURNAL OF COLLOID AND INTERFACE SCIENCE	1
JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME	1
JOURNAL OF FLUID MECHANICS	1
JOURNAL OF MATERIALS ENGINEERING AND PERFORMANCE	1
JOURNAL OF NON-CRYSTALLINE SOLIDS	1
JOURNAL OF PHYSICS AND CHEMISTRY OF SOLIDS	1
JOURNAL OF PHYSICS-CONDENSED MATTER	1
JOURNAL OF PROPULSION AND POWER	1
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY	1
JOURNAL OF THE ATOMIC ENERGY SOCIETY OF JAPAN	1
JOURNAL OF THE INSTITUTE OF ENERGY	1
JOURNAL OF VACUUM SCIENCE & TECHNOLOGY A-VACUUM SURFACES AND FILMS	1

KERNTECHNIK	1
MATERIALS SCIENCE AND ENGINEERING A-STRUCTURAL MATERIALS PROPERTIES MICROSTRUCTURE AND PROCESSING	1
MECHANICAL ENGINEERING	1
NATURE	1
OXIDATION OF METALS	1
PRAKTISCHE METALLOGRAPHIE-PRACTICAL METALLOGRAPHY	1
PROCEEDINGS OF THE IEEE	1
PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	1
RENEWABLE ENERGY	1
SEPARATION SCIENCE AND TECHNOLOGY	1
SIAM JOURNAL ON APPLIED MATHEMATICS	1
SOLID STATE SCIENCES	1
SYNTHETIC METALS	1
TETSU TO HAGANE-JOURNAL OF THE IRON AND STEEL INSTITUTE OF JAPAN	1
VACUUM	1

ANNEX C. LIST OF PUBLISHING INSTITUTIONS BY OECD COUNTRY

Publishing institutions by country and the numbers of publications and co-publications in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Australia		
Ceramic Fuel Cells Ltd	7	4
Commonwealth Scientific and Industrial Research Organization	5	5
Queensland Univ.	2	2
Australian Nuclear Science and Technology Organisation	1	
Dept. of Defence	1	
Monash Univ.	1	1
Austria		
Graz Univ. of Technology	4	3
Technische Univ.	1	1
Belgium		
Univ. Catholique de Louvain	2	2
Vlaamse Instelling voor Technologisch Onderzoek (VITO)	2	
ZEVCO Belgium bvba	1	
Canada		
Inst. National de la Recherche Scientifique	12	8
Ecole Polytechnique de Montreal	8	1
Royal Military College of Canada	7	2
Ballard Power Systems Inc.	5	2
Hydro-Quebec	5	5
Natural Resources Canada	4	2
Toronto Univ.	4	1
Battery Technologies Inc.	2	2
Quebec Univ.	2	1
Queen's Univ.	2	2
Astris Energi Inc.	1	1
Concordia Univ.	1	1
H Power Enterprises of Canada Inc.	1	
Laval Univ.	1	
McMaster Univ.	1	
Memorial Univ. of Newfoundland	1	
Moli Energy Limited	1	
National Defence Headquarters	1	
Pulp and Paper Research Inst. of Canada (PAPRICAN)	1	1
Victoria Univ.	1	
Western Ontario Univ.	1	
Denmark		
Ministry of Science, Technology, and Innovation	17	6
Technical Univ. of Denmark	10	3

H. Topsoee A/S	5	4
Odense Univ.	3	1
Innovision A/S	1	
NKT	1	1
ex-Czechoslovakia		
Chemisch-Technische Hochschule	1	1
Finland		
Helsinki Univ. of Technology	3	
France		
Ecole Nationale Supérieure d'Electrochimie et d'Electrométallurgie (ENSEEG)	8	2
Ecole Nationale Superieure de Chimie de Paris	5	1
Commissariat à l'Energie Atomique	2	
Ecole Nationale Superieure des Mines	2	
Univ. de Poitiers	2	2
Air Liquide	1	1
Centre National de la Recherche Scientifique (CNRS)	1	
Gaz de France (GDF)	1	1
Inst. National Polytechnique	1	1
Pierre et Marie Curie Univ.	1	
Provence Univ.	1	1
Simulog	1	1
Univ. des Sciences et Technologies de Lille	1	1
Université du Maine	1	
Germany		
Forschungszentrum Juelich GmbH	47	14
Deutsches Zentrum fuer Luft- und Raumfahrt (DLR)	12	3
Siemens AG	10	4
Technical Univ. of Darmstadt	10	4
Center for Solar Energy and Hydrogen Research (ZSW)	6	3
The Max Planck Society for the Advancement of Science	5	3
Bonn Univ.	3	
DaimlerChrysler AG	3	1
Adam Opel AG	2	2
Degussa AG	2	
Dortmund Univ.	2	1
Duisburg Univ.	2	
Erlangen-Nuernberg Univ.	2	2
Fachhochschule Hamburg	2	
HEAG AG	2	2
Karlsruhe Research Center (FZK)	2	1
Regensburg Univ.	2	2
RWTH Aachen Univ.	2	2
Shell	2	2
Stuttgart Univ.	2	2
Technical Univ. of Munich	2	2
Ulm Univ.	2	2
ABB	1	
Burgenländische Elektrizitätswirtschafts-Aktiengesellschaft (BEWAG)	1	
EADS	1	
Fraunhofer-Gesellschaft	1	1
GfE Metalle und Materialien GmbH	1	

Hahn-Meitner Inst.	1	
Hamburg Univ.	1	1
Ingenieurkontor Luebeck	1	
Inst. fur Solarenergieforschung GmbH	1	1
Kassel Univ.	1	
Kernforschungszentrum Karlsruhe GmbH	1	
MTU Friedrichshafen GmbH	1	1
Ruhrgas AG	1	
SGL Technik GmbH	1	1
Technical Univ. Bergakademie Freiberg	1	
Technical Univ. of Clausthal	1	
Univ. of Applied Sciences-Fachhochschule Hamburg	1	
World Fuel Cell Council	1	
Greece		
National Technical Univ. of Athens	4	3
Patras Univ.	4	2
Aristotelian Univ. of Thessaloniki	1	
Ireland		
Limerick Univ.	2	2
Italy		
Consiglio Nazionale delle Ricerche	45	29
ENEA	9	5
Messina Univ.	9	9
Reggio Calabria Univ.	8	8
Ansaldo	7	5
Genova Univ.	7	5
CISE Spa	4	4
Pavia Univ.	4	4
Pisa Univ.	2	
Politecnico di Milano	2	2
Centro Informazioni Studi Esperienze (CISE)	1	1
Centro per la Ricerca Scientifica e Tecnologica (ITC-IRST)	1	1
De Nora Permelec Spa	1	1
Eniricerche SpA	1	
Japan		
National Inst. of Advanced Industrial Science and Technology (AIST)	28	10
Mitsubishi Corp.	19	3
Central Research Inst. for Electric Power Industry (CRIEPI)	17	11
Tohoku Univ.	16	9
Mie Univ.	14	12
Tokyo Univ.	14	3
Oita Univ.	11	
Tokyo Gas Co. Ltd.	10	3
Yamanashi Univ.	10	2
Yokohama National Univ.	10	9
Matsushita Battery Industrial Co., Ltd.	9	1
Nagoya Univ.	9	
Osaka Gas Co. Ltd.	9	3
SANYO Electric Co., Ltd.	9	2
Japan Fine Ceramics Center	8	5
Kyushu Univ.	7	

Toshiba Corporation	6	
Fuji Electric Co. Ltd.	5	1
Kansai Electric Power Co. Inc.	5	5
Kyoto Univ.	5	3
NTT Group	5	
Tokyo Electric Power Co. Inc.	5	
Kanden Kakou Co. Ltd.	4	4
Toho Gas Co. Ltd	4	4
Tokyo Inst. of Technology	4	2
Tonen Corp.	4	2
Aichi Inst. of Technology	3	2
Electric Power Industry	3	
Hitachi Ltd.	3	3
Ishikawajima harima Heavy Industries Co., Ltd.	3	3
Kawasaki Heavy Industries Ltd.	3	3
MCFC Research Association	3	2
National Chemical Lab. for Industry	3	2
New Energy and Industrial Technology Development Organisation (NEDO)	3	3
Okayama Prefectural Univ.	3	
Electrotechnical Lab.	2	2
Gifu Prefectural Industrial Research Technical Center	2	2
Gifu Univ.	2	2
Government Industrial Research Inst.	2	
Kyushu Refractories Co. Ltd.	2	
Mitsui Engineering and Shipbuilding Co., Ltd.	2	
Muroran Inst. of Technology	2	
Nippon Oil Company	2	2
Nisshin Steel Co. Ltd.	2	1
Osaka Prefecture Univ.	2	
Shikoku Research Inst.	2	2
Tokyo Univ. of Agriculture and Technology	2	2
Tokyo Univ. of Science	2	2
Toto Ltd.	2	2
Toyo Engineering Corp.	2	2
Yuasa Corp.	2	
Asahi Chemical Industry Co. Ltd.	1	
Chiba Univ.	1	1
Chubu Electric Power Company	1	1
Ehime Univ.	1	1
Global Industrial and Social Progress Research Inst. (GISPRI)	1	
Gunma Univ.	1	
Hokkaido Univ.	1	1
Ibaraki Prefectural Industrial Technology Center	1	1
Japan Atomic Energy Research Inst.	1	
Kagoshima Univ.	1	
Kansai Research Inst.	1	1
Kobe Univ.	1	
Mizusawa Industrial Chemicals	1	1
Nagaoka Univ. of Technology	1	
Nagoya Inst. of Technology	1	
National Inst. for Materials Science	1	

Nippon Chemical Industrial Co. Ltd.	1	1
Nippon Inst. of Technology	1	1
NKK Corporation	1	1
Osaka Prefectural College of Technology	1	1
Panosonic EV Energy Co. Ltd.	1	1
Saibu Gas	1	1
Saitama Univ.	1	1
Shibaura Inst. of Technology	1	1
Tanaka Kikinzoku Kogyo	1	1
The Japan Research and Development Center for Metals	1	1
Toray Group	1	1
Tosoh Corp.	1	
Toyohashi Univ. of Technology	1	1
Toyota Motor Corp.	1	
Yamagata Univ.	1	1
Korea		
Hanyang Univ.	10	3
Korea Inst. of Energy Research	9	2
Seoul National Univ.	9	6
Korea Univ.	8	4
Korea Advanced Inst. of Science and Technology	3	2
Korea Gas Corporation	3	3
Korea Inst. of Science and Technology	3	2
Woosuk Univ.	3	3
Yonsei Univ.	3	2
Pohang Univ. of Science and Technology	2	
Samsung	2	2
Seoul City Univ.	2	1
Ajou Univ.	1	
Choongbuk National Univ.	1	1
Chungnam National Univ.	1	1
Korea Atomic Energy Research Inst.	1	1
Korea Basic Science Inst.	1	1
Korea Electric Power Research Inst.	1	
Korea Military Academy	1	1
Pukyong National Univ.	1	1
Pusan National Univ.	1	1
SK Corporation	1	
Mexico		
National Autonomous Univ. of Mexico (UNAM)	3	2
Centro de Investigación y de Estudios Avanzados del Inst. Politécnico Nacional (Cinvestav)	2	2
Netherlands		
Delft Univ. of Technology	29	13
Netherlands Energy Research Foundation (ECN)	19	10
Twente Univ.	6	3
BCN - Dutch Fuel Cell Corp.	3	2
Stork Product Engineering BV	2	2
TNO	2	2
KEMA Nederland BV	1	1
Netherlands Agency for Energy and the Environment (NOVEM)	1	1

Royal Netherlands Navy's Gravenhage	1	1
Shell	1	1
New Zealand		
Waikato Univ.	21	11
Canterbury Univ.	2	
Industrial Research Ltd.	2	2
New Zealand Inst. for Industrial Research and Development	1	1
Norway		
SINTEF	7	4
Norwegian Univ. of Science and Technology	5	4
Norsk Hydro ASA	2	
Kongsberg College of Engineering	1	1
Oslo Univ.	1	1
Senter for Industriforskning	1	
Trondheim Univ.	1	
Poland		
Polish Academy of Sciences	5	
Warsaw Univ. of Technology	2	2
Portugal		
Aveiro Univ.	3	2
Inst. Nacional de Engenharia e Tecnologia Industrial Electroquimica de Materials	1	1
Minho Univ.	1	1
The Technical Univ. of Lisbon	1	1
Spain		
Consejo Superior de Investigaciones Cientificas	5	2
Barcelone Univ.	3	2
Univ. Autónoma de Madrid	3	3
Carburos Metalicos S.A.	2	2
Univ. Complutense de Madrid	2	1
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicasv (CIEMAT)	1	1
Inst. de Ceramica y Vidrio	1	
Madrid Univ.	1	1
Sevilla Univ.	1	1
Tecnologia Grupo INI	1	1
Sweden		
KTH-Royal Inst. of Technology	22	6
Lund Univ.	5	2
Uppsala Univ.	1	
Switzerland		
ETH	8	3
Ecole Polytechnique Federale de Lausanne	7	
Paul Scherrer Inst.	5	2
Eidgenoessische Technische Hochschule	1	
Marek Consulting	1	1
Plasma-Technik AG	1	1
Sulzer Bros Ltd.	1	1
Sulzer Innotec Ltd.	1	1
Université de Geneve	1	1
Turkey		

Middle East Technical Univ.	3	1
United Kingdom		
Imperial College of Science, Technology and Medicine	29	5
Keele Univ.	14	6
Newcastle upon Tyne Univ.	14	4
BG Group plc	10	2
Newcastle Univ.	10	3
Johnson Matthey plc	8	3
Aberdeen Univ.	4	2
Ministry of Defence	4	3
Cambridge Univ.	3	1
Edinburgh Univ.	3	1
Loughborough Univ.	3	3
St Andrews Univ.	3	1
Birmingham Univ.	2	
Harwell Lab.	2	2
Oxford Univ.	2	1
Brunel Univ.	1	
Ceram Research Ltd	1	1
DRA Haslar	1	1
Electrochemical Power Sources Centre	1	
Energy Policy Research	1	1
Essex Univ.	1	
ICI Runcorn	1	
Intensys	1	1
Liverpool Univ.	1	1
London Univ.	1	
Napier Univ.	1	1
Rolls-Royce plc	1	
Sheffield Univ.	1	1
Strathclyde Univ.	1	
Tioxide Specialties	1	1
Ulster Univ.	1	
Univ. College London	1	1
Vickers Shipbuilding and Engineering Ltd.	1	
W. Lavers Consultancy	1	1
Warwick Univ.	1	
United States		
Dept. of Energy	56	12
Texas A & M Univ.	20	10
Case Western Reserve Univ.	14	1
Illinois Inst. of Technology	14	5
Georgia Inst. of Technology	13	
Massachusetts Inst. of Technology	9	3
Northwestern Univ.	8	
ONSI Corp.	8	4
Texas Univ.	8	3
Utah Univ.	8	2
California Univ.	7	4
Ceramatec Inc.	7	4
Environmental Protection Agency	6	5

Missouri-Rolla Univ.	6	1
South California Univ.	6	1
Westinghouse Electric Corp.	6	2
Dartmouth College	5	
Stonehart Associates Inc.	5	4
Dept. of Defense	4	
Energy Research Corp.	4	1
Pennsylvania Univ.	4	1
California Inst. of Technology	3	1
Colorado Univ.	3	2
General Motors	3	
Humboldt State Univ.	3	1
Kansas Univ.	3	
M-C Power Corp.	3	1
Physical Sciences Inc.	3	1
Siemens AG	3	1
Connecticut Univ.	2	2
Electric Auto Corporation (EAC)	2	2
Eltron Research Inc.	2	
EPRI	2	
Exxon	2	1
Giner Inc.	2	1
Iowa State Univ.	2	1
New Mexico Inst. of Mining and Technology	2	
Pennsylvania State Univ.	2	
Research Triangle Inst.	2	1
SOFCo	2	
SRI international	2	
Tufts Univ.	2	
US Army Communications Electronics Command (CECOM)	2	
Washington Univ.	2	
AeroVironment, Inc.	1	1
American Academy of Science	1	
Arthur D. Little, Inc.	1	
Babcock Wilcox Co.	1	
BCS Technology Inc.	1	
Bolder Technologies Corp.	1	
BP	1	
Central Florida Univ.	1	
Dept. of the Navy	1	
Directed Technologies Inc.	1	
Dow Chemical Co.	1	
DuPont	1	
Eltech Systems Corporation	1	
Energy Signature Associates	1	1
Engelhard Corporation	1	
General Electric Co.	1	
Gilbert/Commonwealth Inc.	1	1
Global Energen Corp.	1	
Harvard Univ.	1	
Hawaii Univ.	1	1

Hoechst Celanese Corporation	1	
Honeywell	1	
Houston Univ.	1	
Iowa Univ.	1	
Kansas State Univ.	1	
Lamar Univ.	1	1
Lynntech, Inc.	1	
Minnesota Univ.	1	1
Morgantown Energy Technology Center	1	1
National Inst. of Health	1	
National Inst. of Standards and Technology	1	1
New Jersey Inst. of Technology	1	1
Ohio State Univ.	1	
PPG Industries Inc.	1	1
Proton Energy Systems Inc.	1	
Rutgers, The State Univ. of New Jersey	1	
San Diego Gas and Electric	1	
Southern California Univ.	1	1
Southern Illinois Univ.	1	1
Stanford Univ.	1	1
Tri-State Univ.	1	1
Worcester Polytechnic Inst.	1	1

Publishing institutions by country and the numbers of publications and co-publications in AFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Austria		
Graz Univ. of Technology	2	2
Technische Univ.	1	1
Belgium		
Vlaamse Instelling voor Technologisch Onderzoek (VITO)	1	
ZEVCO Belgium bvba	1	
Canada		
Battery Technologies Inc.	2	2
Ecole Polytechnique de Montreal	2	
Toronto Univ.	2	1
Astris Energi Inc.	1	1
Finland		
Helsinki Univ. of Technology	1	
France		
Ecole Nationale Superieure des Mines	1	
Germany		
Deutsches Zentrum fuer Luft- und Raumfahrt (DLR)	2	
Kassel Univ.	1	
Kernforschungszentrum Karlsruhe GmbH	1	
Technical Univ. of Darmstadt	1	
Japan		
Tokyo Univ.	2	
Korea		

Hanyang Univ.	4	3
Woosuk Univ.	3	3
Choongbuk National Univ.	1	1
Korea Univ.	1	
Seoul City Univ.	1	1
New Zealand		
Canterbury Univ.	2	
Waikato Univ.	1	
Spain		
Barcelone Univ.	3	2
Carburos Metalicos S.A.	2	2
Sweden		
KTH-Royal Inst. of Technology	7	3
Switzerland		
ETH	1	
Turkey		
Middle East Technical Univ.	2	
United Kingdom		
ICI Runcorn	1	
Johnson Matthey plc	1	
W. Lavers Consultancy	1	1
United States		
Texas A & M Univ.	3	1
Electric Auto Corporation (EAC)	2	2
Physical Sciences Inc.	1	
PPG Industries Inc.	1	1

Publishing institutions by country and the numbers of publications and co-publications in DMFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Denmark		
Innovision A/S	1	
Odense Univ.	1	
France		
Ecole Nationale Supérieure d'Electrochimie et d'Electrométallurgie (ENSEEG)	1	
Inst. National Polytechnique	1	1
Univ. de Poitiers	1	1
Germany		
Forschungszentrum Juelich GmbH	5	
Bonn Univ.	3	
DaimlerChrysler AG	2	1
Siemens AG	2	
The Max Planck Society for the Advancement of Science	2	2
Fraunhofer-Gesellschaft	1	1
Hahn-Meitner Inst.	1	
RWTH Aachen Univ.	1	1
Italy		
Consiglio Nazionale delle Ricerche	7	5
Pisa Univ.	2	

Reggio Calabria Univ.	1	1
Japan		
Matsushita Battery Industrial Co., Ltd.	1	
Korea		
Seoul National Univ.	3	3
Korea Inst. of Energy Research	1	
Poland		
Warsaw Univ. of Technology	2	2
Spain		
Madrid Univ.	1	1
Switzerland		
Paul Scherrer Inst.	1	
United Kingdom		
Newcastle upon Tyne Univ.	13	4
Newcastle Univ.	10	3
Cambridge Univ.	2	
DRA Haslar	1	1
Imperial College of Science, Technology and Medicine	1	
Ministry of Defence	1	1
Oxford Univ.	1	
United States		
Case Western Reserve Univ.	8	
Dept. of Energy	8	
Illinois Inst. of Technology	3	
California Inst. of Technology	2	1
Colorado Univ.	1	1
Dept. of the Navy	1	
Eltron Research Inc.	1	
Giner Inc.	1	1
ONSI Corp.	1	1
Southern California Univ.	1	1

Publishing institutions by country and the numbers of publications and co-publications in MCFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Austria		
Graz Univ. of Technology	1	
Canada		
Moli Energy Limited	1	
ex-Czechoslovakia		
Chemisch-Technische Hochschule	1	1
Denmark		
Technical Univ. of Denmark	2	
France		
Ecole Nationale Superieure de Chimie de Paris	5	1
Gaz de France (GDF)	1	1
Germany		
Technical Univ. of Darmstadt	5	1
The Max Planck Society for the Advancement of Science	2	

Center for Solar Energy and Hydrogen Research (ZSW)	1	
EADS	1	
Forschungszentrum Juelich GmbH	1	1
MTU Friedrichshafen GmbH	1	1
Technical Univ. of Clausthal	1	
Greece		
Aristotelian Univ. of Thessaloniki	1	
Ireland		
Limerick Univ.	2	2
Italy		
Consiglio Nazionale delle Ricerche	17	10
Messina Univ.	9	9
Ansaldo	7	5
Genova Univ.	3	3
ENEA	2	
Pavia Univ.	2	2
Japan		
Central Research Inst. for Electric Power Industry (CRIEPI)	9	5
Mitsubishi Corp.	8	2
Tohoku Univ.	7	3
Hitachi Ltd.	3	3
Kawasaki Heavy Industries Ltd.	3	3
Kyoto Univ.	3	3
Matsushita Battery Industrial Co., Ltd.	3	
MCFC Research Association	3	2
National Inst. of Advanced Industrial Science and Technology (AIST)	3	1
Okayama Prefectural Univ.	3	
SANYO Electric Co., Ltd.	3	2
Tokyo Electric Power Co. Inc.	3	
Toshiba Corporation	3	
Yokohama National Univ.	3	2
Government Industrial Research Inst.	2	
Japan Fine Ceramics Center	2	
Kyushu Refractories Co. Ltd.	2	
New Energy and Industrial Technology Development Organisation (NEDO)	2	2
Nisshin Steel Co. Ltd.	2	1
Tokyo Univ.	2	
Tonen Corp.	2	2
Toyo Engineering Corp.	2	2
Electric Power Industry	1	
Fuji Electric Co. Ltd.	1	
Hokkaido Univ.	1	1
Ishikawajima harima Heavy Industries Co., Ltd.	1	1
Kansai Electric Power Co. Inc.	1	1
Nagoya Univ.	1	
Nippon Chemical Industrial Co. Ltd.	1	1
Osaka Prefectural College of Technology	1	1
The Japan Research and Development Center for Metals	1	1
Toyohashi Univ. of Technology	1	1
Yamagata Univ.	1	1
Korea		

Korea Univ.	6	4
Hanyang Univ.	3	
Korea Inst. of Science and Technology	3	2
Korea Advanced Inst. of Science and Technology	2	2
Samsung	2	2
Korea Atomic Energy Research Inst.	1	1
Korea Basic Science Inst.	1	1
Korea Electric Power Research Inst.	1	
Korea Military Academy	1	1
Pukyong National Univ.	1	1
Pusan National Univ.	1	1
Seoul National Univ.	1	1
Netherlands		
Delft Univ. of Technology	25	12
Netherlands Energy Research Foundation (ECN)	15	9
BCN - Dutch Fuel Cell Corp.	3	2
Stork Product Engineering BV	2	2
Twente Univ.	2	2
KEMA Nederland BV	1	1
Netherlands Agency for Energy and the Environment (NOVEM)	1	1
Norway		
Norsk Hydro ASA	2	
Poland		
Polish Academy of Sciences	5	
Portugal		
Inst. Nacional de Engenharia e Tecnologia Industrial Electroquimica de Materials	1	1
Spain		
Consejo Superior de Investigaciones Cientificas	2	2
Univ. Autónoma de Madrid	2	2
Univ. Complutense de Madrid	2	1
Tecnologia Grupo INI	1	1
Sweden		
KTH-Royal Inst. of Technology	12	3
Lund Univ.	2	2
United Kingdom		
BG Group plc	7	1
Johnson Matthey plc	4	1
Imperial College of Science, Technology and Medicine	1	
Rolls-Royce plc	1	
Ulster Univ.	1	
United States		
Illinois Inst. of Technology	9	4
Dept. of Energy	6	3
Texas A & M Univ.	4	1
California Univ.	3	3
Energy Research Corp.	3	1
M-C Power Corp.	3	1
EPRI	2	
Massachusetts Inst. of Technology	2	2
Research Triangle Inst.	2	1

Dartmouth College	1	
Eltech Systems Corporation	1	
Energy Signature Associates	1	1
Environmental Protection Agency	1	
General Electric Co.	1	
Georgia Inst. of Technology	1	
Gilbert/Commonwealth Inc.	1	1
Global Energen Corp.	1	
Hawaii Univ.	1	1
Hoechst Celanese Corporation	1	
Iowa State Univ.	1	
Kansas State Univ.	1	
Minnesota Univ.	1	1
ONSI Corp.	1	
Pennsylvania State Univ.	1	
San Diego Gas and Electric	1	
Southern Illinois Univ.	1	1
Worcester Polytechnic Inst.	1	1

Publishing institutions by country and the numbers of publications and co-publications in PAFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Canada		
Ecole Polytechnique de Montreal	3	
Toronto Univ.	2	
Denmark		
Technical Univ. of Denmark	4	1
NKT	1	1
Finland		
Helsinki Univ. of Technology	1	
Germany		
Technical Univ. of Darmstadt	3	3
HEAG AG	2	2
Center for Solar Energy and Hydrogen Research (ZSW)	1	1
Degussa AG	1	
Ruhrgas AG	1	
World Fuel Cell Council	1	
Italy		
Consiglio Nazionale delle Ricerche	10	5
Reggio Calabria Univ.	3	3
Centro Informazioni Studi Esperienze (CISE)	1	1
CISE Spa	1	1
ENEA	1	
Japan		
Mitsubishi Corp.	9	
Fuji Electric Co. Ltd.	4	1
NTT Group	3	
SANYO Electric Co., Ltd.	3	
Tokyo Gas Co. Ltd.	3	2

Toshiba Corporation	3	
New Energy and Industrial Technology Development Organisation (NEDO)	2	2
Osaka Gas Co. Ltd.	2	2
Osaka Prefecture Univ.	2	
Shikoku Research Inst.	2	2
Tokyo Electric Power Co. Inc.	2	
Ehime Univ.	1	1
Japan Fine Ceramics Center	1	1
Kyushu Univ.	1	
MCFC Research Association	1	1
Saibu Gas	1	1
Tanaka Kikinzoku Kogyo	1	1
Toho Gas Co. Ltd	1	1
Yamanashi Univ.	1	1
Korea		
Korea Inst. of Energy Research	3	
Pohang Univ. of Science and Technology	2	
Hanyang Univ.	1	
Korea Advanced Inst. of Science and Technology	1	
Seoul National Univ.	1	1
Yonsei Univ.	1	
Netherlands		
BCN - Dutch Fuel Cell Corp.	1	1
KEMA Nederland BV	1	1
Netherlands Agency for Energy and the Environment (NOVEM)	1	1
Netherlands Energy Research Foundation (ECN)	1	1
Stork Product Engineering BV	1	1
New Zealand		
Waikato Univ.	1	
Sweden		
KTH-Royal Inst. of Technology	1	
United Kingdom		
Johnson Matthey plc	2	
Energy Policy Research	1	1
Imperial College of Science, Technology and Medicine	1	1
Ulster Univer.	1	
United States		
ONSI Corp.	5	3
Stonehart Associates Inc.	4	3
Environmental Protection Agency	3	3
Connecticut Univ.	2	2
Texas A & M Univ.	2	
California Univ.	1	
Case Western Reserve Univ.	1	1
Colorado Univ.	1	
Energy Research Corp.	1	
Illinois Inst. of Technology	1	
Iowa State Univ.	1	1
Lamar Univ.	1	1
Physical Sciences Inc.	1	1

Publishing institutions by country and the numbers of publications and co-publications in PEMFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Australia		
Commonwealth Scientific and Industrial Research Organization	1	1
Dept. of Defence	1	
Monash Univ.	1	1
Belgium		
Univ. Catholique de Louvain	2	2
Vlaamse Instelling voor Technologisch Onderzoek (VITO)	1	
Canada		
Inst. National de la Recherche Scientifique	12	8
Royal Military College of Canada	7	2
Ballard Power Systems Inc.	4	1
Hydro-Quebec	4	4
Ecole Polytechnique de Montreal	2	
Natural Resources Canada	2	2
Quebec Univ.	2	1
Queen's Univ.	2	2
Concordia Univ.	1	1
H Power Enterprises of Canada Inc.	1	
Laval Univ.	1	
Memorial Univ. of Newfoundland	1	
National Defence Headquarters	1	
Victoria Univ.	1	
Denmark		
H. Topsoee A/S	2	2
Technical Univ. of Denmark	1	
Finland		
Helsinki Univ. of Technology	1	
France		
Ecole Nationale Supérieure d'Electrochimie et d'Electrométallurgie (ENSEEG)	3	2
Commissariat à l'Energie Atomique	2	
Ecole Nationale Superieure des Mines	1	
Pierre et Marie Curie Univ.	1	
Univ. de Poitiers	1	1
Germany		
Forschungszentrum Juelich GmbH	11	2
Deutsches Zentrum fuer Luft- und Raumfahrt (DLR)	8	3
Adam Opel AG	2	2
Center for Solar Energy and Hydrogen Research (ZSW)	2	1
Duisburg Univ.	2	
Karlsruhe Research Center (FZK)	2	1
Stuttgart Univ.	2	2
Ulm Univ.	2	2
Burgenländische Elektrizitätswirtschafts-Aktiengesellschaft (BEWAG)	1	
Degussa AG	1	
GfE Metalle und Materialien GmbH	1	
Ingenieurkontor Luebeck	1	
SGL Technik GmbH	1	1

Siemens AG	1	1
Technical Univ. of Darmstadt	1	
Italy		
Consiglio Nazionale delle Ricerche	8	6
ENEA	4	4
De Nora Permelec Spa	1	1
Reggio Calabria Univ.	1	1
Japan		
National Inst. of Advanced Industrial Science and Technology (AIST)	7	3
Matsushita Battery Industrial Co., Ltd.	4	1
Yamanashi Univ.	3	1
SANYO Electric Co., Ltd.	2	
Tokyo Univ. of Science	2	2
Asahi Chemical Industry Co. Ltd.	1	
Fuji Electric Co. Ltd.	1	
Nagoya Inst. of Technology	1	
Panosonic EV Energy Co. Ltd.	1	1
Saitama Univ.	1	1
Toyota Motor Corp.	1	
Korea		
Korea Inst. of Energy Research	5	1
Korea Gas Corporation	3	3
Yonsei Univ.	2	2
Ajou Univ.	1	
Hanyang Univ.	1	
SK Corporation	1	
Mexico		
National Autonomous Univ. of Mexico (UNAM)	3	2
Centro de Investigación y de Estudios Avanzados del Inst. Politécnico Nacional (Cinvestav)	2	2
Netherlands		
Royal Netherlands Navy's Gravenhage	1	1
TNO	1	1
Spain		
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicasv (CIEMAT)	1	1
Univ. Autónoma de Madrid	1	1
Sweden		
KTH-Royal Inst. of Technology	2	
Uppsala Univ.	1	
Switzerland		
Paul Scherrer Inst.	5	2
Marek Consulting	1	1
Université de Geneve	1	1
United Kingdom		
Ministry of Defence	4	3
Johnson Matthey plc	3	2
Loughborough Univ.	2	2
Newcastle Univ.	2	1
Cambridge Univ.	1	1
Electrochemical Power Sources Centre	1	

Essex Univ.	1	
Imperial College of Science, Technology and Medicine	1	
Liverpool Univ.	1	1
Vickers Shipbuilding and Engineering Ltd.	1	
United States		
Dept. of Energy	20	4
Texas A & M Univ.	14	9
Case Western Reserve Univ.	7	
South California Univ.	6	1
California Univ.	4	2
Dept. of Defense	3	
General Motors	3	
Kansas Univ.	3	
Exxon	2	1
Humboldt State Univ.	2	1
US Army Communications Electronics Command (CECOM)	2	
AeroVironment, Inc.	1	1
American Academy of Science	1	
Arthur D. Little, Inc.	1	
Babcock Wilcox Co.	1	
BCS Technology Inc.	1	
Bolder Technologies Corp.	1	
California Inst. of Technology	1	
Central Florida Univ.	1	
Directed Technologies Inc.	1	
Dow Chemical Co.	1	
DuPont	1	
Energy Research Corp.	1	1
Engelhard Corporation	1	
Environmental Protection Agency	1	1
Illinois Inst. of Technology	1	
Iowa Univ.	1	
Lynntech, Inc.	1	
National Inst. of Standards and Technology	1	1
Northwestern Univ.	1	
Physical Sciences Inc.	1	
Stonehart Associates Inc.	1	1

Publishing institutions by country and the numbers of publications and co-publications in RFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
France		
Centre National de la Recherche Scientifique (CNRS)	1	
Germany		
Deutsches Zentrum fuer Luft- und Raumfahrt (DLR)	3	
Hamburg Univ.	1	1
Inst. fur Solarenergieforschung GmbH	1	1
Italy		
ENEA	1	

Japan		
National Inst. of Advanced Industrial Science and Technology (AIST)	1	
Sweden		
Lund Univ.	2	
United Kingdom		
London Univ.	1	
Newcastle upon Tyne Univ.	1	
United States		
Dept. of Energy	3	1
BCS Technology Inc.	1	
Case Western Reserve Univ.	1	
Ceramatec Inc.	1	1
Colorado Univ.	1	
Giner Inc.	1	
Harvard Univ.	1	
Humboldt State Univ.	1	
National Inst. of Health	1	
Proton Energy Systems Inc.	1	

Publishing institutions by country and the numbers of publications and co-publications in SOFCs in the customized database, 1990-2000

Main Organizations	Publications	Co-publications
Australia		
Ceramic Fuel Cells Ltd	7	4
Commonwealth Scientific and Industrial Research Organization	4	4
Queensland Univ.	2	2
Australian Nuclear Science and Technology Organisation	1	
Austria		
Graz Univ. of Technology	1	1
Canada		
Natural Resources Canada	2	
Ballard Power Systems Inc.	1	1
Ecole Polytechnique de Montreal	1	1
Hydro-Quebec	1	1
McMaster Univ.	1	
Pulp and Paper Research Inst. of Canada (PAPRICAN)	1	1
Western Ontario Univ.	1	
Denmark		
Ministry of Science, Technology, and Innovation	17	6
H. Topsoee A/S	3	2
Technical Univ. of Denmark	3	2
Odense Univ.	2	1
France		
Ecole Nationale Supérieure d'Electrochimie et d'Electrométallurgie (ENSEEG)	4	
Air Liquide	1	1
Provence Univ.	1	1
Simulog	1	1
Univ. des Sciences et Technologies de Lille	1	1
Université du Maine	1	

Germany		
Forschungszentrum Juelich GmbH	33	11
Siemens AG	8	3
Center for Solar Energy and Hydrogen Research (ZSW)	3	1
Dortmund Univ.	2	1
Erlangen-Nuernberg Univ.	2	2
Fachhochschule Hamburg	2	
Regensburg Univ.	2	2
Shell	2	2
Technical Univ. of Munich	2	2
ABB	1	
DaimlerChrysler AG	1	
GfE Metalle und Materialien GmbH	1	
RWTH Aachen Univ.	1	1
Technical Univ. Bergakademie Freiberg	1	
The Max Planck Society for the Advancement of Science	1	1
Univ. of Applied Sciences-Fachhochschule Hamburg	1	
Greece		
National Technical Univ. of Athens	4	3
Patras Univ.	4	2
Italy		
Genova Univ.	4	2
CISE Spa	3	3
Consiglio Nazionale delle Ricerche	3	3
Reggio Calabria Univ.	3	3
Pavia Univ.	2	2
Politecnico di Milano	2	2
Centro per la Ricerca Scientifica e Tecnologica (ITC-IRST)	1	1
ENEA	1	1
Eniricerche SpA	1	
Japan		
National Inst. of Advanced Industrial Science and Technology (AIST)	17	6
Mie Univ.	14	12
Oita Univ.	11	
Tokyo Univ.	10	3
Tohoku Univ.	9	6
Central Research Inst. for Electric Power Industry (CRIEPI)	8	6
Nagoya Univ.	8	
Osaka Gas Co. Ltd.	8	2
Tokyo Gas Co. Ltd.	8	2
Yokohama National Univ.	7	7
Kyushu Univ.	6	
Yamanashi Univ.	6	
Japan Fine Ceramics Center	5	4
Kanden Kakou Co. Ltd.	4	4
Kansai Electric Power Co. Inc.	4	4
SANYO Electric Co., Ltd.	4	
Tokyo Inst. of Technology	4	2
Aichi Inst. of Technology	3	2
Mitsubishi Corp.	3	1
National Chemical Lab. for Industry	3	2

Toho Gas Co. Ltd	3	3
Electric Power Industry	2	
Electrotechnical Lab.	2	2
Fuji Electric Co. Ltd.	2	
Gifu Prefectural Industrial Research Technical Center	2	2
Gifu Univ.	2	2
Ishikawajima harima Heavy Industries Co., Ltd.	2	2
Kyoto Univ.	2	
Mitsui Engineering and Shipbuilding Co., Ltd.	2	
Muroran Inst. of Technology	2	
Nippon Oil Company	2	2
NTT Group	2	
Tokyo Univ. of Agriculture and Technology	2	2
Tonen Corp.	2	
Toto Ltd.	2	2
Yuasa Corp.	2	
Chiba Univ.	1	1
Chubu Electric Power Company	1	1
Global Industrial and Social Progress Research Inst. (GISPRI)	1	
Gunma Univ.	1	
Ibaraki Prefectural Industrial Technology Center	1	1
Japan Atomic Energy Research Inst.	1	
Kagoshima Univ.	1	
Kansai Research Inst.	1	1
Kobe Univ.	1	
Matsushita Battery Industrial Co., Ltd.	1	
MCFC Research Association	1	1
Mizusawa Industrial Chemicals	1	1
Nagaoka Univ. of Technology	1	
National Inst. for Materials Science	1	
New Energy and Industrial Technology Development Organisation (NEDO)	1	1
Nippon Inst. of Technology	1	1
NKK Corporation	1	1
Shibaura Inst. of Technology	1	1
Toray Group	1	1
Tosoh Corp.	1	
Korea		
Seoul National Univ.	4	1
Chungnam National Univ.	1	1
Hanyang Univ.	1	
Korea Inst. of Energy Research	1	1
Korea Univ.	1	
Seoul City Univ.	1	
Netherlands		
Delft Univ. of Technology	5	1
Netherlands Energy Research Foundation (ECN)	5	2
Twente Univ.	4	1
BCN - Dutch Fuel Cell Corp.	1	1
KEMA Nederland BV	1	1
Netherlands Agency for Energy and the Environment (NOVEM)	1	1
Shell	1	1

Stork Product Engineering BV	1	1
TNO	1	1
New Zealand		
Waikato Univ.	21	11
Industrial Research Ltd.	2	2
New Zealand Inst. for Industrial Research and Development	1	1
Norway		
SINTEF	7	4
Norwegian Univ. of Science and Technology	5	4
Kongsberg College of Engineering	1	1
Oslo Univ.	1	1
Senter for Industriforskning	1	
Trondheim Univ.	1	
Portugal		
Aveiro Univ.	3	2
Minho Univ.	1	1
The Technical Univ. of Lisbon	1	1
Spain		
Consejo Superior de Investigaciones Cientificas	3	
Inst. de Ceramica y Vidrio	1	
Sevilla Univ.	1	1
Sweden		
Lund Univ.	1	
Switzerland		
Ecole Polytechnique Federale de Lausanne	7	
ETH	7	3
Eidgenoessische Technische Hochschule	1	
Plasma-Technik AG	1	1
Sulzer Bros Ltd.	1	1
Sulzer Innotec Ltd.	1	1
Turkey		
Middle East Technical Univ.	1	1
United Kingdom		
Imperial College of Science, Technology and Medicine	27	5
Keele Univ.	14	6
BG Group plc	7	1
Aberdeen Univ.	4	2
Edinburgh Univ.	3	1
St Andrews Univ.	3	1
Birmingham Univ.	2	
Harwell Lab.	2	2
Brunel Univ.	1	
Ceram Research Ltd	1	1
Energy Policy Research	1	1
Intensys	1	1
Loughborough Univ.	1	1
Napier Univ.	1	1
Oxford Univ.	1	1
Rolls-Royce plc	1	
Sheffield Univ.	1	1
Strathclyde Univ.	1	

Tioxide Specialties	1	1
Univ. College London	1	1
Warwick Univ.	1	
United States		
Dept. of Energy	22	5
Georgia Inst. of Technology	12	
Northwestern Univ.	8	
Texas Univ.	8	3
Utah Univ.	8	2
Massachusetts Inst. of Technology	7	1
Ceramatec Inc.	6	3
Missouri-Rolla Univ.	6	1
Westinghouse Electric Corp.	6	2
Dartmouth College	4	
Pennsylvania Univ.	4	1
Illinois Inst. of Technology	3	1
Siemens AG	3	1
New Mexico Inst. of Mining and Technology	2	
SOFCo	2	
SRI international	2	
Texas A & M Univ.	2	
Tufts Univ.	2	
Washington Univ.	2	
Babcock Wilcox Co.	1	
BP	1	
Colorado Univ.	1	1
Dept. of Defense	1	
Eltron Research Inc.	1	
Environmental Protection Agency	1	1
Honeywell	1	
Houston Univ.	1	
Morgantown Energy Technology Center	1	1
New Jersey Inst. of Technology	1	1
Ohio State Univ.	1	
ONSI Corp.	1	
Pennsylvania State Univ.	1	
Rutgers, The State Univ. of New Jersey	1	
Stanford Univ.	1	1
Tri-State Univ.	1	1

ANNEX D. LIST OF PATENTING INSTITUTIONS BY OECD COUNTRY

Patenting institutions by country and the numbers of EPO applications in the customized database, 1990-1999

Main organizations	Patents
Canada	
Ballard Power Systems Inc.	33
Global Thermoelectric Inc.	1
Hydrogenics Corporation	1
Ministry of National Defence	1
Denmark	
H. Topsoee A/S	5
Ministry of Science, Technology, and Innovation	4
Danacell A/S	1
Danish Power Systems APS	1
France	
PSA Peugeot Citroën	6
Commissariat à l'Energie Atomique	5
RENAULT s.a.s.	3
Centre National de la Recherche Scientifique	2
SERSEN	2
SORAPEC S.A.	2
Conservatoire National des Arts et Metiers	1
Electricité de France (EDF)	1
Institut Français du Pétrole (IFP)	1
Rhodia Group	1
S.E.R.E.G.I.E.	1
SNECMA	1
SNPE	1
Transports Recherches Etudes Groupement d'Intérêt Economique (T.R.E.G.I.E.)	1
Germany	
Siemens AG	31
OMG AG & Co. KG	14
Celanese AG	11
Fraunhofer-Gesellschaft	11
Ballard Power Systems Inc.	8
Forschungszentrum Juelich GmbH	7
BASF Aktiengesellschaft	6
MTU Friedrichshafen GmbH	6
Aventis	4
DaimlerChrysler AG	4
Proton Motor Fuel Cell GmbH	4
Degussa AG	3
Stuttgart Univ.	3
Xcellsis GmbH	3
ENEA	2

FRIEMANN & WOLF Batterietechnik GmbH	2
Magnet-Motor (MM) GmbH	2
Deutsches Zentrum für Luft- und Raumfahrt (DLR)	1
H2-Interpower Brennstoffzellensysteme GmbH	1
Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF)	1
Piller GmbH	1
SGL Carbon Group	1
Vodafone Holding GmbH	1
Wissenschaftsgemeinschaft Gottfried Wilhelm Leibniz e.V.	1
Italy	
Gruppo De Nora	5
Nuvera Fuel Cells Europe S.R.L.	4
Eniricerche SpA	3
Finmeccanica	2
ENEA	1
Roen Est s.r.l.	1
SAES Getters Group	1
Snam SpA.	1
STMicroelectronics S.r.l.	1
Japan	
Matsushita Battery Industrial Co., Ltd.	41
NKG Insulators Ltd.	30
Honda Motor Co., Ltd	18
Hitachi Ltd.	13
Toyota Motor Corporation	13
Ishikawajima-Harima Heavy Industries Co., Ltd.	12
Asahi Glass Co., Ltd.	9
Mitsubishi Heavy Industries, Ltd.	8
Sumitomo Corporation	8
Kashima Kita Electric Power Corporation	6
Murata Manufacturing Co., Ltd.	6
Japan Gore-Tex Inc.	5
Tanaka Kikinzoku Kogyo K.K.	5
Nissan Motor Co., Ltd.	4
Toshiba Corporation	4
Kabushiki Kaisha Equos Research	3
National Inst. of Advanced Industrial Science and Technology (AIST)	3
NTT Group	3
SANYO Electric Co., Ltd.	3
Japan Storage Battery Co., Ltd.	2
Mitsubishi Materials Corp.	2
N.E. CHEMCAT Corp.	2
Nisshinbo Industries, Inc.	2
Osaka Gas Co., Ltd.	2
Petroleum Energy Center	2
The Kansai Electric Power Co., Inc.	2
Toho Gas Co., Ltd.	2
Toyo Boseki Kabushiki Kaisha	2
Bridgestone Corporation	1
Daido Tokushuko Kabushiki Kaisha	1
Ebara Corporation	1
Idemitsu Petrochemical Co., Ltd.	1
Kabushiki Kaisha Meidensha	1

Kabushiki Kaisha Toyota Chuo Kenkyusho	1
Mazda Motor Corporation	1
Micro Colloid Co., Ltd.	1
Mitsubishi Chemical Corp.	1
Nichias Corp.	1
Nippon Oil Company, Ltd.	1
Nippon Pillar Packing Co., Ltd.	1
Nippon Shokubai Co., Ltd.	1
Onoda Cement Company, Ltd.	1
Permelec Electrode Ltd.	1
Railway Technical Research Institute	1
Sekisui Chemical Co., Ltd.	1
Shin-Estu Chemical Co., Ltd.	1
Sony Corporation	1
Tonen Corporation	1
Toray Industries, Inc.	1
Ube Industries, Ltd.	1
YKK Corporation	1
Korea	
Samsung	6
Korea Electric Power Corporation	1
Korea Hydro & Nuclear Power Co., Ltd.	1
Netherlands	
Stichting Energieonderzoek Centrum Nederland (ECN)	4
Stork Screens B.V.	3
Delft Univ. of Technology	2
Shell B.V.	2
ASA BV	1
Turboconsult B.V.	1
Spain	
David Fuel Cell Components SL	2
Switzerland	
Sulzer Ltd.	6
ABB	1
Ecole Polytechnique Fédérale de Lausanne	1
United Kingdom	
Johnson Matthey plc	11
Regenesys Technologies Limited	9
National Power Plc.	6
Ineos Chlor Limited	3
Victrex Manufacturing Limited	3
British Nuclear Fuels PLC (BNFL)	2
Northrop Grumman	2
Rolls-Royce Plc.	2
BG Group plc	1
Huntsman Tioxide Specialties Ltd.	1
Keele Univ.	1
Prutec Ltd.	1
The Morgan Crucible Company Plc.	1
United States	
Westinghouse Electric Corporation	43
General Motors	19
International Fuel Cells Corporation	16
Gas Technology Institute	15

Siemens AG	15
Delphi Corporation	13
DuPont	10
Honeywell	10
3M	9
Raytheon Company	9
The Dow Chemical Company	9
Energy Research Corp.	8
United Technologies Corporation	7
California Univ.	6
Corning Incorporated	6
ExxonMobil	6
California Institute of Technology	4
Ceramatec Inc.	4
ECD Ovonics	4
Technology Management, Inc.	4
ZTEK Corporation	4
Avista Laboratories Inc.	3
Dept. of Energy	3
Dow Chemical Co.	3
Foster-Miller, Inc.	3
GrafTech International Ltd.	3
IdaTech, LLC.	3
Lockheed Martin Corp.	3
Proton Energy Systems, Inc.	3
Reveo, Inc.	3
Sofco	3
Southern California Univ.	3
Viacom Inc.	3
Acumentrics Corporation	2
Aquanautics Corp.	2
Case Western Reserve Univ.	2
Engelhard Corporation	2
Finmeccanica	2
General Electric Co.	2
IGR Enterprises, Inc.	2
International Business Machines Corporation	2
Lynntech, Inc.	2
Manhattan Scientifics, Inc.	2
State Univ. of New York	2
Stonehart Associates Inc.	2
Univ. of Chicago	2
W.L. Gore & Associates, Inc.	2
AER Energy Reources, Inc.	1
Air Products and Chemicals, Inc.	1
D. C. Voltage Gradient Technology and Supply Ltd.	1
ElectroChem, Inc.	1
Eltech Systems Corporation	1
Energy Conversion Devices, Inc.	1
Energy Partners, Inc.	1
Fucellco, Inc.	1
Fuelcell Energy, Inc.	1
Gel Incorporated	1
Giner, Inc.	1

Gore Enterprise Holdings, Inc.	1
H Power Corporation	1
Matsushita Battery Industrial Co., Ltd.	1
M-C Power Corporation	1
MicroCoating Technologies, Inc.	1
Millennium Cell Inc.	1
Motorola, Inc.	1
NASA	1
Pennsylvania Univ.	1
Physical Sciences, Inc.	1
Pittsburgh Electric Engines, Inc.	1
Polyfuel, Inc.	1
Praxair Technology, Inc.	1
The Scripps Research Institute	1
Solar Reactor Technologies, Inc.	1
SRI International	1
Syntroleum Corporation	1
T & G corporation	1
Teledyne Energy Systems, Inc.	1
University Patents, Inc.	1
Valence Technology, Inc.	1

Patenting institutions by country and the numbers of EPO applications in AFCs in the customized database, 1990-1999

Main organizations	Patents
France	
Conservatoire National des Arts et Métiers (CNAM)	1
Electricité de France (EDF)	1
Germany	
Celanese AG	1
Japan	
Ebara Corporation	1
United States	
International Business Machines Corporation	2
Energy Conversion Devices, Inc.	1
Giner, Inc.	1
Univ. of Chicago	1

Patenting institutions by country and the numbers of EPO applications in DMFCs in the customized database, 1990-1999

Main organizations	Patents
Canada	
Ballard Power Systems Inc.	3
Germany	
Forschungszentrum Juelich GmbH	3
Siemens AG	3
Stuttgart Univ.	3
Celanese AG	1
Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF)	1
OMG AG & Co. KG	1

Japan	
Honda Motor Co., Ltd	3
Korea	
Samsung	2
United Kingdom	
Ineos Chlor Limited	1
Johnson Matthey plc	1
Victrex Manufacturing Limited	1
United States	
Foster-Miller, Inc.	2
California Institute of Technology	1
Case Western Reserve Univ.	1
DuPont	1
Southern California Univ.	1

Patenting institutions by country and the numbers of EPO applications in MCFCs in the customized database, 1990-1999

Main organizations	Patents
Germany	
MTU Friedrichshafen GmbH	6
DaimlerChrysler AG	1
Forschungszentrum Juelich GmbH	1
Italy	
Finmeccanica	2
Japan	
Ishikawajima-Harima Heavy Industries Co., Ltd.	10
Hitachi Ltd.	8
Toshiba Corporation	2
Mitsubishi Heavy Industries, Ltd.	1
Netherlands	
Delft Univ. of Technology	2
Stichting Energieonderzoek Centrum Nederland (ECN)	2
ASA BV	1
Turboconsult B.V.	1
United Kingdom	
BG Group plc	1
Johnson Matthey plc	1
United States	
Gas Technology Institute	10
Energy Research Corp.	3
General Electric Co.	2
United Technologies Corporation	2
Dept. of Energy	1
International Fuel Cells Corporation	1
M-C Power Corporation	1
Westinghouse Electric Corporation	1

Patenting institutions by country and the numbers of EPO applications in PAFCs in the customized database, 1990-1999

Main organizations	Patents
Denmark	

H. Topsoee A/S	1
Germany	
Siemens AG	1
Japan	
Honda Motor Co., Ltd	5
Hitachi Ltd.	2
Japan Gore-Tex Inc.	1
Toshiba Corporation	1
United States	
Engelhard Corporation	1
Gas Technology Institute	1
International Fuel Cells Corporation	1

Patenting institutions by country and the numbers of EPO applications in PEMFCs in the customized database, 1990-1999

Main organizations	Patents
Canada	
Ballard Power Systems Inc.	31
Hydrogenics Corporation	1
Ministry of National Defence	1
Denmark	
Danacell A/S	1
Danish Power Systems A/S	1
France	
PSA Peugeot Citroën	6
Commissariat à l'Energie Atomique	5
RENAULT s.a.s.	3
Centre National de la Recherche Scientifique	2
SORAPEC S.A.	2
Conservatoire National des Arts et Metiers	1
Electricité de France (EDF)	1
Institut Français du Pétrole (IFP)	1
SNECMA	1
SNPE	1
Germany	
Siemens AG	21
OMG AG & Co. KG	14
Celanese AG	10
Fraunhofer-Gesellschaft	8
Aventis	4
BASF Aktiengesellschaft	4
Proton Motor Fuel Cell GmbH	4
Degussa AG	3
Magnet-Motor (MM) GmbH	2
Stuttgart Univ.	2
Xcellsis GmbH	2
Ballard Power Systems Inc.	1
Deutsches Zentrum für Luft- und Raumfahrt (DLR)	1
Forschungszentrum Juelich GmbH	1
H2-Interpower Brennstoffzellensysteme GmbH	1
SGL Carbon Group	1
Italy	

Gruppo De Nora	5
Nuvera Fuel Cells Europe S.R.L.	4
ENEA	1
Roen Est s.r.l.	1
STMicroelectronics S.r.l.	1
Japan	
Matsushita Battery Industrial Co., Ltd.	40
Honda Motor Co., Ltd	12
Asahi Glass Co., Ltd.	9
Toyota Motor Corporation	8
Tanaka Kikinzoku Kogyo K.K.	5
Japan Gore-Tex Inc.	4
Sumitomo Corporation	4
Kabushiki Kaisha Equos Research	3
Hitachi Ltd.	2
Japan Storage Battery Co., Ltd.	2
N.E. CHEMCAT Corp.	2
National Inst. of Advanced Industrial Science and Technology (AIST)	2
Nisshinbo Industries, Inc.	2
SANYO Electric Co., Ltd.	2
Daido Tokushuko Kabushiki Kaisha	1
Idemitsu Petrochemical Co., Ltd.	1
Kabushiki Kaisha Toyota Chuo Kenkyusho	1
Mazda Motor Corporation	1
Mitsubishi Chemical Corp.	1
Nichias Corp.	1
Nippon Pillar Packing Co., Ltd.	1
Nissan Motor Co., Ltd.	1
Permelec Electrode Ltd.	1
Sekisui Chemical Co., Ltd.	1
Shin-Estu Chemical Co., Ltd.	1
Sony Corporation	1
Toray Industries, Inc.	1
Toshiba Corporation	1
Ube Industries, Ltd.	1
Korea	
Samsung	5
Spain	
David Fuel Cell Components SL	2
Switzerland	
ABB	1
United Kingdom	
Johnson Matthey plc	8
Victrex Manufacturing Limited	3
Ineos Chlor Limited	2
National Power Plc.	1
The Morgan Crucible Company Plc.	1
United States	
General Motors	16
DuPont	10
The Dow Chemical Company	9
3M	8
International Fuel Cells Corporation	7
United Technologies Corporation	5

California Institute of Technology	4
Avista Laboratories Inc.	3
California Univ.	3
Dow Chemical Co.	3
Foster-Miller, Inc.	3
GrafTech International Ltd.	3
Southern California Univ.	3
Case Western Reserve Univ.	2
Gas Technology Institute	2
Lynntech, Inc.	2
Manhattan Scientifics, Inc.	2
Raytheon Company	2
State Univ. of New York	2
Stonehart Associates Inc.	2
W.L. Gore & Associates, Inc.	2
Delphi Corporation	1
ElectroChem, Inc.	1
Eltech Systems Corporation	1
Energy Partners, Inc.	1
Fucellco, Inc.	1
Gore Enterprise Holdings, Inc.	1
H Power Corporation	1
Lockheed Martin Corp.	1
MicroCoating Technologies, Inc.	1
Physical Sciences, Inc.	1
Polyfuel, Inc.	1
SRI International	1
Teledyne Energy Systems, Inc.	1

Patenting institutions by country and the numbers of EPO applications in RFCs in the customized database, 1990-1999

Main organizations	**Patents**
Canada	
Ballard Power Systems Inc.	1
France	
SERSEN	2
S.E.R.E.G.I.E.	1
Transports Recherches Etudes Groupement d'Intérêt Economique (T.R.E.G.I.E.)	1
Germany	
Ballard Power Systems Inc.	7
Siemens AG	7
DaimlerChrysler AG	3
Fraunhofer-Gesellschaft	3
BASF Aktiengesellschaft	2
FRIEMANN & WOLF Batterietechnik GmbH	2
Piller GmbH	1
Vodafone Holding GmbH	1
Wissenschaftsgemeinschaft Gottfried Wilhelm Leibniz e.V.	1
Xcellsis GmbH	1
Italy	
Gruppo De Nora	1

SAES Getters Group	1
Japan	
Kashima Kita Electric Power Corporation	6
Toyota Motor Corporation	5
Ishikawajima-Harima Heavy Industries Co., Ltd.	3
Sumitomo Corporation	3
Matsushita Battery Industrial Co., Ltd.	2
The Kansai Electric Power Co., Inc.	2
Toyo Boseki Kabushiki Kaisha	2
Bridgestone Corporation	1
Hitachi Ltd.	1
Micro Colloid Co., Ltd.	1
Mitsubishi Heavy Industries, Ltd.	1
National Inst. of Advanced Industrial Science and Technology (AIST)	1
NTT Group	1
Osaka Gas Co., Ltd.	1
Railway Technical Research Institute	1
Netherlands	
Stork Screens B.V.	3
Shell B.V.	1
Switzerland	
Sulzer Ltd.	1
United Kingdom	
Regenesys Technologies Limited	9
National Power Plc.	6
Lattice Intellectual Property Limited	2
Ineos Chlor Limited	1
Johnson Matthey plc	1
Prutec Ltd.	1
United States	
Raytheon Company	9
International Fuel Cells Corporation	7
Westinghouse Electric Corporation	7
Energy Research Corp.	5
ExxonMobil	5
ECD Ovonics	4
General Motors	3
IdaTech, LLC.	3
Proton Energy Systems, Inc.	3
Reveo, Inc.	3
Viacom Inc.	3
ZTEK Corporation	3
Aquanautics Corp.	2
California Univ.	2
Finmeccanica	2
Siemens AG	2
3M	1
Acumentrics Corporation	1
AER Energy Reources, Inc.	1
D. C. Voltage Gradient Technology and Supply Ltd.	1
Delphi Corporation	1
Dept. of Energy	1
Engelhard Corporation	1
Fuelcell Energy, Inc.	1

Gas Technology Institute	1
Gel Incorporated	1
Honeywell	1
IGR Enterprises, Inc.	1
Lockheed Martin Corp.	1
Materials and Electrochemical Research Corporation	1
Millennium Cell Inc.	1
Motorola, Inc.	1
NASA	1
The Scripps Research Institute	1
Solar Reactor Technologies, Inc.	1
Syntroleum Corporation	1
T & G corporation	1
University Patents, Inc.	1
Valence Technology, Inc.	1

Patenting institutions by country and the numbers of EPO applications in SOFCs in the customized database, 1990-1999

Main organizations	Patents
Canada	
Global Thermoelectric Inc.	1
Denmark	
H. Topsoee A/S	4
Ministry of Science, Technology, and Innovation	4
France	
Rhodia Group	1
Germany	
Forschungszentrum Juelich GmbH	4
Siemens AG	3
Italy	
Eniricerche SpA	3
Snam SpA.	1
Japan	
NKG Insulators Ltd.	30
Mitsubishi Heavy Industries, Ltd.	7
Murata Manufacturing Co., Ltd.	6
Nissan Motor Co., Ltd.	3
NTT Group	2
Petroleum Energy Center	2
Toho Gas Co., Ltd.	2
Kabushiki Kaisha Meidensha	1
Mitsubishi Materials Corp.	1
Nippon Oil Company, Ltd.	1
Nippon Shokubai Co., Ltd.	1
Onoda Cement Company, Ltd.	1
Osaka Gas Co., Ltd.	1
SANYO Electric Co., Ltd.	1
Sumitomo Corporation	1
Tonen Corporation	1
YKK Corporation	1
Korea	
Korea Electric Power Corporation	1

Korea Hydro & Nuclear Power Co., Ltd.	1
Samsung	1
Netherlands	
Stichting Energieonderzoek Centrum Nederland (ECN)	2
Shell B.V.	1
Switzerland	
Sulzer Ltd.	5
Ecole Polytechnique Fédérale de Lausanne	1
United Kingom	
British Nuclear Fuels PLC (BNFL)	2
Rolls-Royce Plc.	2
Huntsman Tioxide Specialties Ltd.	1
Keele Univ.	1
United States	
Westinghouse Electric Corporation	39
Siemens AG	15
Delphi Corporation	13
Honeywell	9
Corning Incorporated	6
Ceramatec Inc.	4
Technology Management, Inc.	4
Sofco	3
Gas Technology Institute	2
Acumentrics Corporation	1
Air Products and Chemicals, Inc.	1
California Univ.	1
Dept. of Energy	1
Energy Research Corp.	1
ExxonMobil	1
IGR Enterprises, Inc.	1
Internaional Fuel Cells Corporation	1
Lockheed Martin Corp.	1
Pennsylvania Univ.	1
Pittsburgh Electric Engines, Inc.	1
Praxair Technology, Inc.	1
Univ. of Chicago	1
ZTEK Corporation	1