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Sustainable Chemistry: Evidence on Innovation from Patent Data

Series on Risk Management

No.25

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OECD Environment, Health and Safety Publications

Series on Risk Management

No. 25

SUSTAINABLE CHEMISTRY: EVIDENCE ON INNOVATION FROM PATENT DATA

IOMC

INTER-ORGANIZATION PROGRAMME FOR THE SOUND MANAGEMENT OF CHEMICALS

A cooperative agreement among FAO, ILO, UNEP, UNIDO, UNITAR, WHO, World Bank and OECD

Environment Directorate

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FOREWORD

Sustainable chemistry is a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. The concept of Sustainable Development was established at the 1992 UN Conference on Environment and Development in Rio de Janeiro. It has been further elaborated in 2002 at the Johannesburg World Summit on Sustainable Development.

Sustainable chemistry encompasses the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes. Within the broad framework of sustainable development, government, academia and industry should strive to maximise resource efficiency through activities such as energy and non-renewable resource conservation, risk minimisation, pollution prevention, minimisation of waste at all stages of a product life-cycle and the development of products that are durable and can be reused and recycled.

Sustainable chemistry is also a process that stimulates innovation across all sectors to design and discover new chemicals, production processes, and product stewardship practices that will provide increased performance and increased value while meeting the goals of protecting and enhancing human health and the environment.

The OECD's work on Sustainable Chemistry was initiated in 1998. The Issue Team on Sustainable Chemistry was established in 1999 and focused largely on developing guidance for "Establishing Research and Development Programmes in Sustainable Chemistry". In 2006, the Issue Team established a Sustainable Chemistry Network for information exchange, review of new developments and further elaboration of incentives for sustainable chemistry. In 2007, the Issue Team started to develop a Sustainable Chemistry Platform to serve as a networking resource and a place to disseminate information about workshops, training courses, and other capacity building opportunities (see http://www.oecd.org/env_sustainablechemistry_platform/).

This report was initiated by the OECD's Sustainable Chemistry Issue Team and uses patent data to investigate green chemistry innovation trends. Due to the nature of the International Patent Classification (IPC) system it was not possible to identify a broad all-encompassing green chemistry indicator. As a consequence we have investigated selected technologies which can be identified reliably using IPC classes. While these are by no means intended to be representative of Sustainable Chemistry as a whole, we believe that they do provide a cross-section of relevant areas.

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INTRODUCTION

1. Modern lifestyles have been made possible through a vast range of chemicals that improve many aspects of our lives including the medicines we consume, the dyes in our clothes and the fertiliser used to grow our food. Unfortunately, in some cases these same chemicals have also led to undesirable environmental and health consequences. Chemical releases into the atmosphere, water bodies and land can be harmful to ecosystems and human health.

2. Nature uses a narrow range of environmentally common elements, while the chemical industry utilizes the broad spectrum of elements in the periodic table for chemical transformations. The effect of these environmentally rare chemicals on natural systems is often unknown (Collins, 2001). Many chemicals which have been released into receiving environments have later been shown to be toxic or to cause unseen environmental damage. For instance, phthalates used widely in plastics are believed to cause hormonal disruption. In the past, CFCs (chlorofluorocarbons) were widely used in aerosol cans and for refrigeration. It was not until 1970s that CFCs were linked to the hole in the ozone layer, and eventually phased out under the Montreal Protocol.

3. Green chemistry[1] holds the promise of providing significant environmental and health benefits relative to standard chemical practices. It aims to avoid harm to people and the environment by changing chemical products and processes: it strives to achieve sustainability through design at the molecular level, focusing on inherent hazards of chemicals rather than the circumstances of exposures. Green chemistry principles address the root causes of physical, toxicological, and global hazards, including fires, explosions, acute and chronic toxicity, depletion of limited resources, and greenhouse gas emissions.

4. The OECD started working in the area of green chemistry in 1998 with the aim of providing guidance to member and non-member countries in the development of national programs. An OECD workshop in 1998 identified what work was being done in the field of sustainable chemistry and what could further its development and use. An "Issues Team" was established in 1999 with 10 OECD countries represented. The Sustainable Chemistry Platform was started in 2007 to assist information exchange, to monitor new developments and to investigate the drivers of sustainable development.

5. Formally, the OECD defines 'green' chemistry as 'the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes.'[2] Green chemistry contributes to sustainable development through the manufacture of products that are less harmful to human health and the environment: i) by the use of less hazardous and harmful feedstocks and reagents; ii) by improving the energy and material efficiency of chemical

[1] For the purposes of this report 'green' and 'sustainable' chemistry are used interchangeably.
[2] http://www.oecd.org/dataoecd/16/25/29361016.pdf

processes; iii) by using renewable feedstocks or wastes in preference to fossil fuels or mined resources; and, iv) by designing chemical products for better reuse or recycling. These categories encompass all parts of a chemical lifecycle, from the raw materials and manufacturing to use and end of life.

6. The twelve principles of green chemistry written by Anastas and Warner (1998) provide a practical definition below in Table 1. These are a set of principles that help chemists to evaluate existing methodologies, and more importantly, design new chemical solutions to achieve the goals of sustainability. The goal of these design criteria is to provide guidelines for sustainable design. Green chemistry is distinct from environmental chemistry. While green chemistry concentrates on avoiding pollution, environmental chemistry focuses on monitoring the fate and transport of chemicals in ecosystems and the clean-up of chemical pollution.

Table 7.Twelve principles of green chemistry (Anastas and Warner)

1. **Prevention**
   It is better to prevent waste than to treat or clean up waste after it has been created.
2. **Atom Economy**
   Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **Less Hazardous Chemical Syntheses**
   Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. **Designing Safer Chemicals**
   Chemical products should be designed to effect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries**
   The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. **Design for Energy Efficiency**
   Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.
7. **Use of Renewable Feedstocks**
   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **Reduce Derivatives**
   Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.
9. **Catalysis**
   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **Design for Degradation**
    Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.
11. **Real-time analysis for Pollution Prevention**
    Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. Inherently Safer Chemistry for Accident Prevention
Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

* Anastas, P. T. et al (1998).

Green Chemistry Initiatives

7. The notion of making production processes less polluting through innovations in the use of chemicals has been around a long time. The origins of green chemistry can be traced to the late 1980s when governments shifted the focus of their environmental policies. For instance, in the mid 1980s, the United States Environmental Protection Agency (EPA) began to shift its focus from pollution control to pollution prevention (Linthorst 2010). This was formalised with the passage of the 1990 Pollution Prevention Act. In 1988 the American Chemistry Council launched the Responsible Care initiative, which encourages industry-wide adoption of environmental management practices and information disclosure. In Europe, the 1996 Integrated Pollution Prevention and Control Directive (IPPC) illustrated the move towards pollution prevention. [http://eippcb.jrc.es/]

8. The growing interest in green chemistry can be seen to have emerged from this increased emphasis on pollution prevention rather than control. In the US, the Environmental Protection Agency started the Green Chemistry Program officially in 1993. This program continues to promote green chemistry with grants, education and with the Presidential Green Chemistry Challenge Awards.[3] Other recognition efforts include the Green and Sustainable Chemistry Awards in Japan (http://www.gscn.net/awardsE/index.html), the European Sustainable Chemistry Award (http://www.euchems.org/esca/) and the Royal Australian Chemical Institute Green Chemistry Challenge awards (http://www.raci.org.au/national/awards/greenchemistry.html).

9. Networks have aided the growth of green chemistry internationally. In 1997 the Green Chemistry Institute, a non-profit institution, was launched to promote green chemistry (http://www.epa.gov/gcc/pubs/gcinstitute.html). It became part of the American Chemical Society in 2001. The Green Chemistry Institute has chapters in more than 20 countries, including Argentina, China, India, South Africa and Taiwan. In addition there are green chemistry networks in a number of countries for the purposes of information dissemination and education. In the UK the Green Chemistry Network was established within the Royal Society of Chemistry. From here, the successful journal *Green Chemistry* emerged in 1999. In Italy, INCA (International Network for Culture and Arts) a multi-university consortium of universities established in 1993 consolidated links between research teams, with green chemistry one of their key areas (Hjeresen 1999). Initially 5 universities were involved, now there are 31 Italian university members.

10. In Japan, the Green and Sustainable Chemistry Network (GSCN) was launched in 2000 with the focus of promoting research and development in green chemistry (http://www.gscn.net). In 2005, the Mediterranean Green Chemistry Network (MEGREC) was established to encourage research and education links between European and Arab countries. That same year, the G8

[3] For the list of winners see: http://www.epa.gov/greenchemistry/pubs/pgcc/past.html

nations established the International Green Network linking eight research centres, one in each country, with the aim of improving research, education, regulation and public policy in the green chemistry area.

11. Other specialised research centres have been established worldwide. In China, there are more than a dozen universities with "key labs" in green chemistry that are supported at national or provincial levels. Many of the key labs are associated with a specialty area, for example green polymer materials, clean energy from biomass, or green synthetic techniques. Host universities include Qinghua University, Peking University, Sichuan University, Zhejiang University of Technology, Wuhan Institute of Technology, and Tianjin University. In the United States, the National Science Foundation has funded research centers focusing on green chemistry challenges such as environmentally benign solvents (http://www.nsfstc.unc.edu/).

12. Monash University in Australia has a Green chemistry research centre funded by the government for basic research and for establishing combined industry and university projects. The Danish government has funded a Center for Green Chemistry and Sustainability. In Canada, Queen's University has recently inaugurated the GreenCentre Canada, funded by government and industry partners, which is devoted to the "development and commercialization of green chemistry technologies."[4]

13. Green chemistry has been incorporated into the curriculum of standard chemistry courses. The first college-level course in green chemistry was offered at Carnegie Mellon University in 1992 (Collins 1995). Specialist undergraduate and postgraduate courses are also offered at a number of universities, including McGill, the University of Oregon, Toronto, and Yale in North America, University of York, Leeds, Notthingham, and ELTE-Budapest in Europe as well as at Monash in Australia. Degree programs in green chemistry have been offered at the University of Massachusetts (Lowell and Boston campuses, Ph.D. level), University of York (M.Sc.), University of Leicester (M.Sc. and Ph.D.), University of Zaragoza (Ph.D.), Sichuan University (M.Sc. and Ph.D.) and the University of Western Australia (B.Sc.).

14. A green chemistry summer school supported by the European Commission began in 1998 in Venice, where students have the chance to visit lectures of scientific leaders in this particular field (http://www.incaweb.org/education/summer_school_on_green_chemistry/index.php). The American Chemical Society Green Chemistry Institute has run an annual summer program for graduate and postdoctoral students from North and South America. Numerous workshops have been organized by academic, industrial, and government sponsors in Asia and Africa as well. (ACS 2009).

15. There has also been increasing focus on green chemistry in the academic literature. In 2009, its tenth year of publication, the RSC journal *Green Chemistry* was ranked #15 out of 140 chemistry journals according to highest impact factor.[5] In 2008 *ChemSusChem* was established as a sister journal of *Angewandte Chemie* and focuses on new sustainable processes. Also in 2008, *Green Chemistry Letters and Reviews* emerged. The journal Environmental Science and Technology solicits manuscripts for each issue under the heading "Sustainability Engineering and

[5] ISI Web of Knowledge Journal Citation Reports.

Green Chemistry". *Journal of Chemical Education* has solicited green chemistry manuscripts for more than a decade. Many renowned journals have dedicated special issues on recent green chemistry developments. [6]

16. The chemicals sector has also actively encouraged the growth of green chemistry. Companies have introduced green principles into their production and invested in sustainable research and development. Various measurement tools for eco-efficiency or sustainability of chemical products such as Corporate Carbon footprint or Eco-Efficiency analysis play an increasingly important role in corporate policies. In Europe, two industry groups Cefic and EuropaBio along with the EC have established the European Technology Platform for Sustainable Chemistry [http://www.suschem.org/] to encourage chemical research and development in Europe. In Germany, DECHEMA founded a working group "Sustainable Chemistry Measurement and Metrics" integrating key industrial players.

[6] The June 2007 issue of *Chemical Reviews* in 2007 [Ref: 2007, 107, 6, 2167-2820] edited by Paul Anastas and Istvan T. Horvath discussed recent developments in green chemistry. Other special issues have been published in *Tetrahedron* [2010, 66(5)], *Journal of Physical Chemistry A* [2010, 114(11)], *Chimia* [2000, Vol 54(9)], *Accounts of Chemical Research* [2002, 35(9)], *Industrial and Engineering Chemistry Research* [2002, 41(18)] the IUPAC journal *Pure and Applied Chemistry* [2007, 79(11) and 2000, 72(7)].

IMPORTANT AREAS OF GREEN CHEMISTRY

17. Given the breadth of the areas covered by green chemistry it is difficult to completely circumscribe the field. Key areas of green chemistry include the efficient exploitation of alternative feedstocks, the development of novel, environmentally benign synthetic pathways and the use of alternative solvents.

Feedstocks

18. Petroleum-based feedstocks are the current basis of the chemical industry with 90% of all organic chemicals derived from oil. Furthermore, 90% of the worlds energy needs are met by non-renewable resources. [http://www.eia.doe.gov/emeu/international/] Indeed, it has been estimated that the energy demand is to grow by more than 50% by 2025 simultaneous with depletion of petroleum reserves (Ragauskas 2006). Thus, there is enormous interest in covering future energy demands by using alternative, renewable energy sources. Environmental concerns associated with the use of petroleum and coal also include their contribution to climate change through CO_2 emissions. One of the benefits of using renewable resources is that they are potentially carbon neutral, and their use would mitigate greenhouse gas burdens in the atmosphere.

19. In order to achieve sustainability, chemistry requires a paradigm shift in the chemical industry to move from oil to renewable resources. Comparable transformations have occurred in the past with a shift from wood to coal and then to oil; these were largely responsible for the industrial revolution. The switch to oil required significant innovation to create new technologies and investment in capital infrastructure. A shift to a “bio-refinery” will also require chemical innovations of a similar or even higher impact. These innovations will need to be efficient and commercially viable if they are to be widely adopted (King 2010).

20. Recently, advanced biofuels have been developed that use food crops such as corn or sugarcane. This edible biomass, rich in carbohydrates, is most commonly converted to ethanol by fermentation (McMillan 1997, Kim and Dale 2004). Central to future research are alternative waste feedstocks that avoid competition with food production. They include agricultural waste, lignocelluloses, lignin (e.g. waste parts of plants and trees after paper production) and chitin (e.g. shells). For example, lignin is usually burned to support the energy need of other processes. However, the useful carbon content of this material and woody biomass in general should be more efficiently exploited by converting them to either liquid transportation fuels or useful chemicals. These materials are however, chemically complex in nature, so new technology is required for their effective utilization. Although the possibility of ethanol production (Galbe and Zacchi 2007) or liquefaction by pyrolysis Carlson et al. 2009) represent recent progress in this field , further new solutions are needed in order to achieve desired product streams (Huber et al. 2009, Gazelot 2007, and Huber et al. 2007).

21. Apart from chemically converting non-edible biomass, some of its components can potentially be also used as value added chemicals. For example, waxes have been extracted from wheat straw using supercritical CO_2. The waxes can be used as a base for cosmetics, while other chemicals have pharmaceutical and agrochemical potential (Deswarte et al. 2006). Chitin is an abundant biodegradable material that can be processed into chitosan. This biopolymer has a wide range of current and potential uses such as crop pest control, water treatment and as a substitute for traditional polymers in industrial applications (Rinaudo et al. 2006). Bio-based feedstock can also be used for the production of non-toxic, biodegradable plastics (Belgacem and Gandini 2008).

Solvents

22. Solvents are a great challenge for green chemistry, since in production of fine chemicals and pharmaceuticals they frequently account for the vast majority of waste. Many conventional solvents are harmful to health and the environment. They are often toxic, flammable and/or corrosive and volatile. To reuse or recycle these solvents in order to minimize waste, energy-intensive operations are required, such as distillation. Therefore green chemistry focuses on the use of alternative solvents that are non-toxic and represent no additional waste (Anastas and Eghbali 2010). Green chemistry also encourages the development of solvent-free processes, or the use of biphasic systems which allow for immobilization of catalysts and recycling of products. In principle, any green solvent needs to be a functional replacement for conventional organic solvents, in addition to reductions in intrinsic hazard (Beach et al. 2009).

23. Water, because of its obviously non-toxic nature is a very popular green solvent. A variety of reactions (oxidation, reduction, C-C bond forming) have shown to be compatible with this medium (Li 1993, Li 2005, Li 2006). Water is a good polar solvent which is often shown to be beneficial for reactivity, in addition and it offers the possibility of easy separation of organic product phases. In some cases, for example in biomass transformations, supercritical water is used.

24. Supercritical solvents are a suitable alternative to classical organic solvents. Especially supercritical carbon dioxide has proven to be a unique and safe reaction medium (Leitner 1999, Jessop and Subramaniam 2007, DeSimone 2010, Leitner 2000). Due to its critical point, the supercritical state is easy to achieve and the removal of solvent occurs just by cooling and depressurising the reaction vessel. In addition, by variation of temperature/pressure parameters, its density, and the outcome of reactions, can be easily tuned (Leitner 2002). This medium has already found its commercial applications in decaffeination of coffee (replacing the toxic and hazardous solvent dichloromethane) and as an alternative to harmful perchloroethylene in dry-cleaning of clothing.

25. Ionic liquids are likely to replace conventional solvents in many applications (Rogers and Seddon 2003). They are considered “designer solvents” in green chemistry because a huge variety of different structures can be explored to tune their physical and chemical properties. They are liquid salts at room temperature with practically no vapour pressure, which also makes them ideal candidates for liquid-liquid biphasic reactions, and immobilization of catalysts (Welton 1999, Wasserscheid and Welton 2007). Another example of biphasic mixtures are perfluorinated solvents. Usually, they are not miscible with organic solvents at room temperature, but form a

single phase at slightly higher temperatures, allowing for the reactions to take place. The separation of the products will then occur by subsequent cooling, largely simplifying the purification process (Gladysz et al. 2004).

Alternate synthetic pathways and catalysis

26. In order to achieve sustainability through design at the molecular level, significant innovation is necessary on a fundamental scientific level. To meet the challenges described in the 12 principles of green chemistry, new energy-efficient reaction pathways should be designed. At the same time, generation of large amounts of side products and unnecessary functionalization should be avoided and the number of reaction steps minimized. The definition of Atom Economy (AE) (Trost 1991, Trost 1995) and the Environmental Impact factor (E-factor) (Sheldon 1992, Sheldon 2007) are numerical tools that help assess chemical reactions in terms of waste prevention. The Environmental Impact Factor is a metric to quantify total amounts of waste generated, and Atom Economy measures how efficiently starting materials are incorporated into the final product.

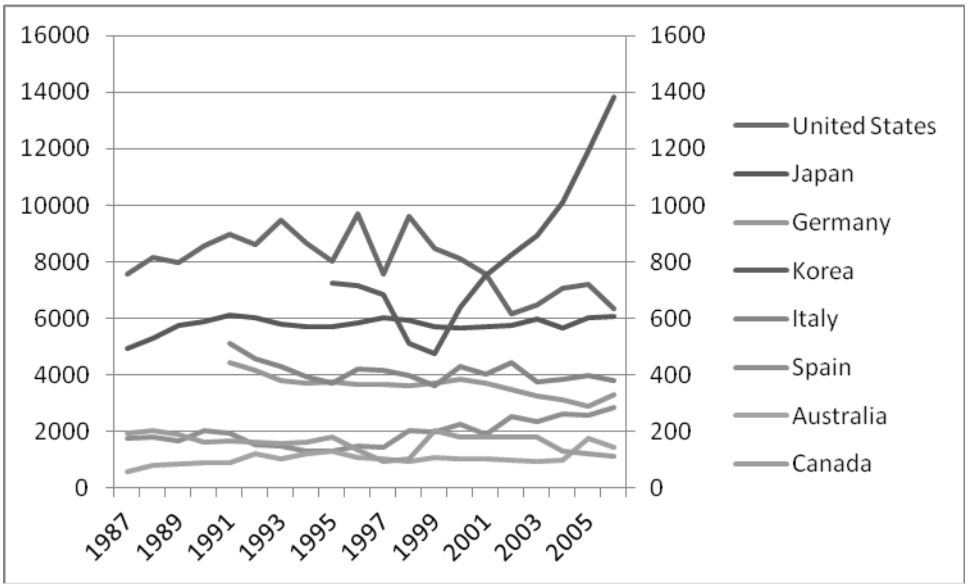
27. Molecular catalysis plays a central role in design of novel green reactions (Anastas 2009). The use of catalysts instead of stoichiometric reagents greatly reduces waste and in most cases improves product selectivity, atom economy and energy efficiency. The most powerful catalytic processes include hydrogenations (Noyori 1987), C-H activation (Crabtree 2001), C-C coupling reactions (Bower and Krische 2009), and olefin-metathesis (Vougioukalakis and Grubbs 2010 and Trnka and Grubbs 2001). Two Nobel Prizes were awarded for catalysis during the past decade: in 2001 for hydrogenation, and in 2005 for olefin metathesis. Biocatalysis is another green strategy, relying on natural or modified enzymes (Silverman 2002, Bommarious and Riebelin 2004) More recently, white biotechnology offers attractive catalytic routes to useful chemicals (Schaefer 2010).

28. Stoichiometric reactions can also be designed to meet green chemistry criteria. Highly atom economical reactions include Diels-Alder reactions (Brummond and Wach 2007), multicomponent reactions (Domling and Ugi 2000) and various rearrangements (Leung et al. 2007). Click chemistry (Kolb eta. 2001) strives to develop reactions with no side products and a 100% utilization of starting materials. A number of chemical engineering technologies for the use of microwave or ultrasound in chemical synthesis have emerged to improve yields and facilitate reactions (Strauss and Varma 2006). Advances have also been made in the field of microreactor technology and high throughput screening that allow for efficient catalysis and process optimization and testing (Mason 2007).

MEASURING INNOVATION IN GREEN CHEMISTRY

29. As noted in OECD (2009), there are a number of measures which can be used to document innovation trends, including R&D expenditures, scientific personnel, publications, and patents. Figure 1 provides data on R&D expenditures by the chemicals sectors (ISIC 24) in the time period from 1987-2007. Germany (the biggest EU producer) and the US have declining R& D expenditures in the sector starting from 2001. Korea has been rapidly increasing since 1999, while Japan can be viewed as constant.

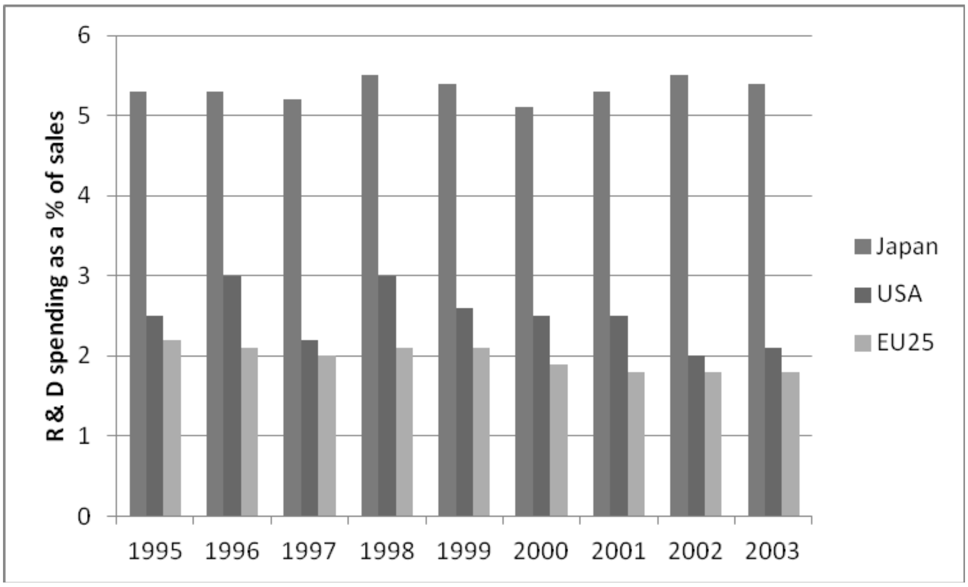
Figure 22. STAN R&D in Chemicals (excluding pharmaceuticals) (Million $2000 PPP)



Source: OECDSTAT ANBRED Statistics

30. CEFIC provides data on R&D spending as a percentage of sales for the EU25, the United States and Japan over the period 1995-2003. Japan has the highest ratio, followed by the United States and then Europe. There has been a degree of convergence between the latter two (see Figure 2.)

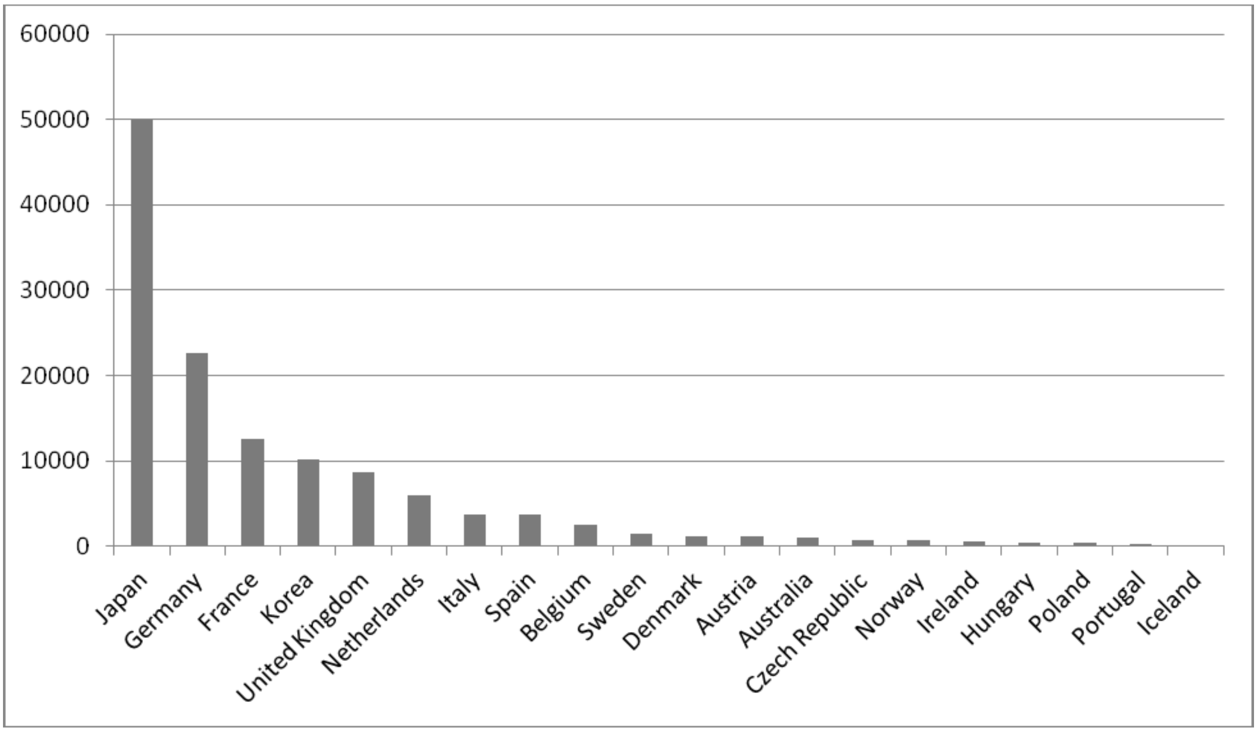
Figure 23. Chemical industry R & D Spending in EU25, the US and Japan 1995-2003



Source: http://www.cefic.be/factsandfigures/level02/investment_index.html

31. Data on scientific personnel by industrial sector is also available. Figure 3 gives the number of full-time employee equivalents who are classified as R&D personnel or researchers in the ISIC 24 sector (excluding pharmaceuticals).

Figure 24. Number of R&D Personnel and Researchers in the Chemicals Sector (excluding pharmaceuticals) in 2006[7]



Source OECDSTAT ANBRED Statistics

32. However, in all these cases the data refers to all R&D activities within the sector, and not that which is specifically related to 'green' chemistry. While there is data on public R&D expenditures by socio-economic objective (including control and care for the environment), this is not disaggregated by sector. However, the classification systems used when delimiting the claims of patent applications allows for the identification of inventions which relate specifically to 'green' chemistry. As such, the remainder of this section addresses the following questions:

- Why are patents a good way to measure innovation?
- Why use patents to measure chemical innovation?
- What are the overall trends in patenting, and how do these related to current trends and drivers in the chemical industry?
- Which sustainable chemistry indicators can be created from patent data?

[7] 2005 for Norway and Switzerland.

Why are patents a good way to measure innovation?

33. Patents are a useful (although not all-encompassing) measure of innovation.[8] Patent data is preferable to many other measures of innovation in that it measures the outputs of innovation. Other commonly-used measures focus on inputs, such as Research and Development expenditures (capital invested) and numbers of scientific personnel (labour input). The classification of patents into technological categories allows specific innovation indicators to be created. As part of the OECD Environmental Policy and Technological Innovation project, a number of technologies have been investigated, such as air pollution abatement, waste water effluent treatment and various climate mitigation technologies.[9]

34. Applicants are able to protect their intellectual property for a specified period - usually 20 years at most offices - if maintenance fees are paid on a granted patent. Applicants must disclose detailed descriptions of their invention, which must be considered novel and useful in order to be granted protection. Once a patent application is submitted to an office, the details are kept confidential for approximately 18 months after which they become available to the public and competitors. Thus patents act not only as a method of protecting intellectual property, but also as a stimulus to invention, as detailed technical knowledge is publicly available.

35. Since intellectual property protection is sought as a means to capture the rents for new inventions which are thought to be commercially viable, patent counts can be used as a proxy for innovation. More specifically, in the context of a globalising world economy, there are three other pieces of information which can be gleaned from patent datasets:

- Firstly, data on patent citations gives an indication of the international diffusion of knowledge, by providing a trace of the geographical origins of relevant previous innovations.

- Second, data on foreign co-inventors gives an indication of the role played by international collaboration in the invention process.

- Third, data on patent families gives an indication of the potential for technology adoption, that is, the markets in which innovators feel they are likely to be able to export their technologies.

36. Patents are not a perfect measure of innovation as companies use other methods to protect their inventions: secrecy and lead-time being the most notable. However, patenting, lead-time and secrecy can be used as complementary strategies. Furthermore a firm’s patent portfolio can act as an important signal and subsequently used as leverage for take-overs, to boost share prices, raise capital and firm ‘branding’.

[8] For a discussion of indicators of innovation, including patent data, see Johnstone and Hascic (2009)..

[9] See www.oecd.org/environment/innovation

Why use patents to measure chemical innovation?

37. Patenting is an important strategy for the chemical industry. The propensity to patent both product and process innovations is higher in the chemical industry than in other sectors. A Carnegie Mellon survey on Industrial R & D in the US manufacturing sector (Cohen 2000). carried out in 1994 found that on average manufacturers applied for patents for 49% of their product innovations and 31% of their process innovations. However the propensity to patent varied widely between different manufacturing sectors. For the chemical industry the rates were 65% and 54% respectively.[10]

38. Three reasons have been forwarded as to why patenting is a particularly common strategy for the chemical industry. First, the chemicals industry has used patents to protect their inventions for well over a century, and so there is a high degree of familiarity with the use of IPRs (Arora and Gambardella 1998). Second, chemical inventions are considered suitable to IP protection because they are easy to define - and thus defend legally- since chemical inventions can be described using engineering principles and physical and chemical laws (Arora and Gambardella 1998). For instance, reaction pathways and operating conditions can be clearly specified.

39. Third, patents are vital for licensing agreements and licensing is widely used as an industrial strategy in the chemical sector. Licensing is also a significant source of revenue and used as a way to earn rents from Research and Development expenditure. (Arora and Gambardella 1998)[11] For instance, in 2008 DOW Chemicals earned $307 million from patent and technology royalties.[12]

Trends in chemistry patenting

40. Data for this report has been extracted from the EPO World Patent Statistical (PATSTAT) database (EPO 2009)[13] using search algorithms based on a selection of International Patent Classification (IPC) codes. The IPC is a hierarchical classification assigned by patent examiners to applications identifying the technical nature of inventions. There are approximately 60,000 different codes. Using IPC classes to identify patents is the preferred method as it is far more accurate than key word searches of titles or abstracts which are moreover restricted to those written in English.

[10] The figure for the chemical industry have been calculated using table A1 and includes 2400 Chemicals, nec, 2411 Basic Chemicals, 2413 Plastic Resins, 2423 Drugs and 2429 Miscellaneous Chemicals. The rate of patenting varied across these categories, with 2423 Drugs having the highest product patent rate at 95.5% and 2400 Chemicals nec having the highest process patenting rate at 61.49%. Note that when the 2423 Drugs category is removed, the product and process patenting rates are still above average.

[11] Part of the reason behind the importance of licensing is the role that SEFs (specialized engineering firms) have played in the chemical industry. SEFs specialise in process innovations and by licensing their technology have spread the latest technologies throughout the world.

[12] Figure from 2008 Annual Report. http://www.dow.com/financial/pdfs/161-00720.pdf

[13] version SEP 2009.

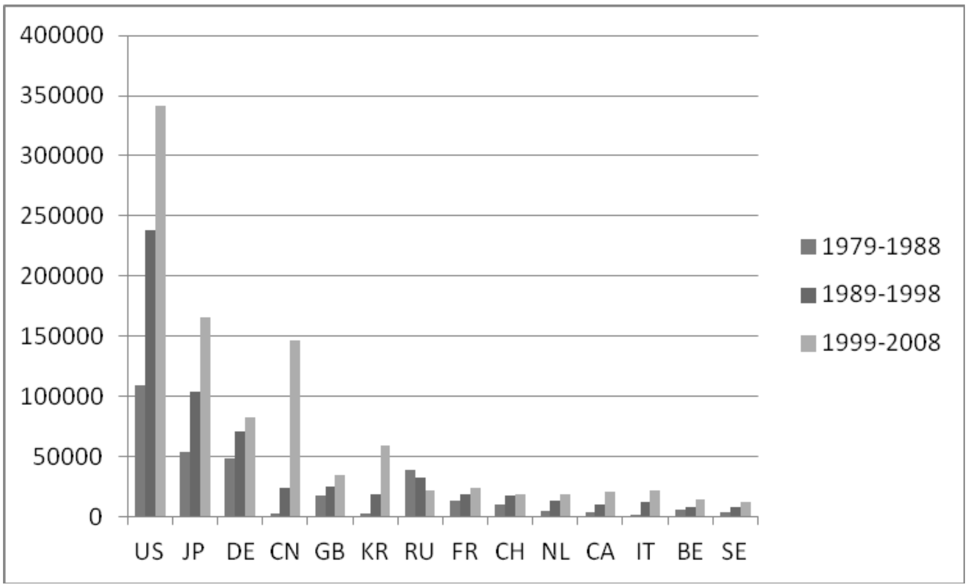
41. The data is disaggregated by *application office*, *priority date* (based on the first application filing date world-wide), *inventor country* (country of residence of the inventors, generated as fractional counts), *applicant* (often a company seeking rights to protection) and *document type*.

42. Some clarification on the meaning of “document type” is required. When patent protection is sought for an invention from just one office, i.e. in one country, this is called a singular (SING). When protection is sought in multiple offices, the first application that is submitted is called a claimed priority (CP) while further applications are referred to as duplicates (DUPL). Considering claimed priority and singular applications (CP+SING) allows us to quantify each new invention (without double counting when protection is sought for an identical invention in a second country).

43. Counts based on CPs would generally focus on higher value inventions, since they have been filed in at least two countries.[14] The decision to use patent counts based on claimed priorities only (CP) as compared to claimed priorities and singulars combined (CP+SING) can make a difference to the results since the relative proportion of CP to SING applications varies widely across countries. For example, China has a relatively small number of claimed priorities in relation to singulars, and thus will be far more prominent relative to other countries when using CP+SING counts as compared to CP only counts. Finally, counts based on all application types (CP, SING and DUPL) allows us to see in which markets protection is sought. This might be relevant for an analysis of industry adoption.

44. An indicator of patent counts for all chemical inventions (*ALL CHEMISTRY*) has been drawn from the PATSTAT database. Figure 4 gives the count of patent applications (CPs and SING) for each of the last three decades for the most important inventor countries. As in most fields the United States, Japan and Germany dominate. Moreover, the Japanese figures are under-estimates since there many patent applications filed at the JPO data for which the inventor country is missing in PATSTAT. China and Korea have shown particularly rapid growth. Other important chemical product manufacturing countries (e.g. Switzerland, Belgium and Italy) also feature.

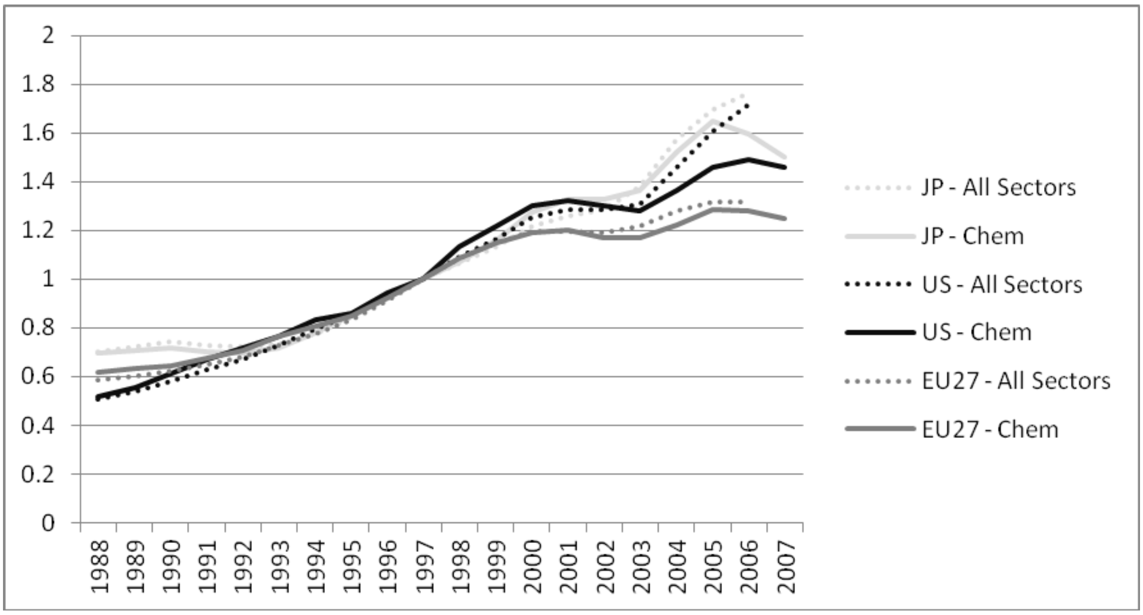
Figure 25. Patent counts (CP + SING) by Inventor Country



[14] See Guellec and von Pottlesbergh (2000) and Harhoff et al. (2003).

45. Normalised trends are shown in Figure 5. Note that the rate of applications for chemistry has followed a similar pattern to that for all technology field (*ALL SECTORS*), with approximately 50% more applications in the 2000s than in 1988. However, *ALL SECTORS* has increased nearly 20% since 2000 while *ALL CHEMISTRY* has remained static.

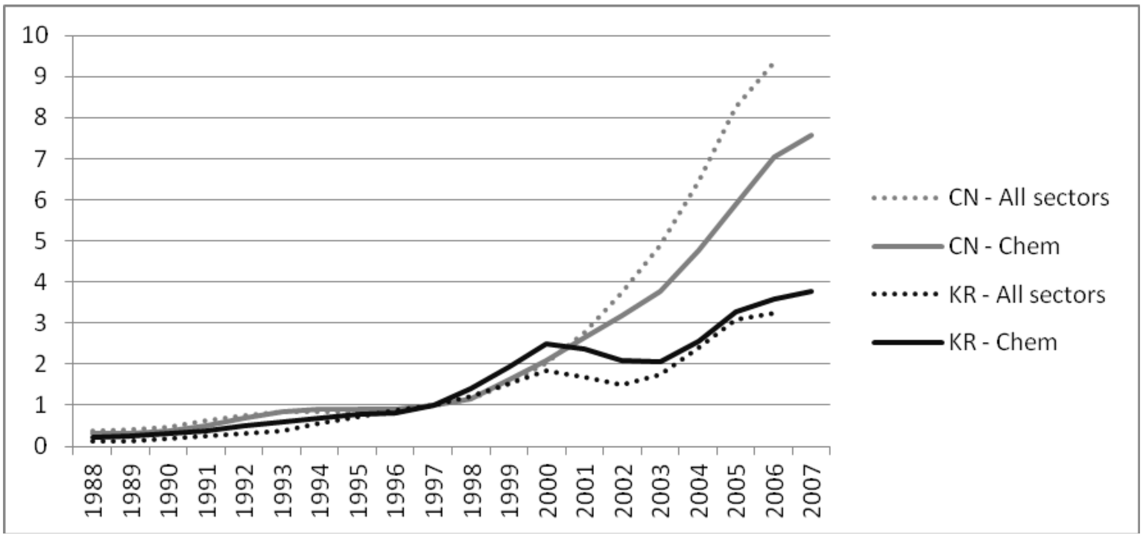
Figure 26. Patent counts (CP + SING) – 3 year moving average indexed on 1997 (= 1.0)



46. In February 2001 the EU published a White Paper entitled 'A Strategy for a Future Chemicals Policy' (http://www.isopa.org/isopa/uploads/Documents/documents/White%20Paper.pdf) which suggested that the uncertainty associated with the negotiations leading up to the passage of REACH had slowed innovaton in the field. While it is true that prior to 2001 chemicals patents were rising faster than for all sectors combined, but slower afterward. This may have been due to other factors.

47. For Japan, the chemical patenting rates have stayed in line with overall patenting – but have diverged since 2005. In the US, chemical and overall patenting had a similar pattern until 2003 where subsequently chemical patenting has not kept pace with overall patenting. For Europe, chemical patenting has been in line with overall patenting, however, neither has attained the growth rates of both Japan and the US.

Figure 27. Patent counts (CP + SING) – 3 year moving average indexed on 1997 (= 1.0)



48. The picture differs markedly for Korea and China, where the growth in patenting rates have been spectacular. For China overall patent counts were 9 times higher in 2006 than in 1997. Although the rate of growth of chemical patents has fallen short of that of all patents, there is still impressive growth. For Korea, chemical and overall patenting rates follow a similar pattern; growing overtime but stagnating for a short period after 2000. The chemical patenting rates were nearly 4 times the level in 2007 than in 1997.

Green chemistry patents

49. For this report, patent data is used to investigate green chemistry innovation trends. The following section describes how the patent indicators are constructed along with details on the specific indicators developed for this report.

50. The search algorithms are based on a selection of International Patent Classification (IPC) codes, with the exception of the *green Plastics* area which uses a key word search based on patent application titles. For each of the selected areas covered in this report, data is disaggregated by *application office*, *priority date* (based on the first application filing date world-wide), *inventor country* (country of residence of the inventors, generated as fractional counts), *applicant* (often a company seeking rights to protection) and *document type*. Patent families were identified allowing document type to define applications as claimed priorities, duplicates or singulars.

51. Nameroff (2004) conducted a study of green chemistry patents study using a detailed abstract and title search on key words such as 'benign'. While the study covered a wide range of Sustainable Chemistry patents, it was restricted to the United States Patent Office and thus did not allow for cross-country comparisons. For international comparisons, data drawn from PATSTAT using the International Patent Classification system (IPC) is more appropriate.

52. Unfortunately we are not able to identify a broad all-encompassing green chemistry indicator due to the nature of the IPC system. As a consequence we have investigated selected technologies which can be identified reliably using IPC classes. While these are by no means intended to be representative of Sustainable Chemistry as a whole, they do provide a cross-section of relevant areas . (The areas investigated in this paper are summarised in Table 2)

Table 8. Sustainable Chemistry areas covered in the report

Area	Notes (including International Patent Classes IPC used to select patents)[15]	Applications 1970-2007
Biochemical Fuel Cells	Biochemical Fuel Cells, also known as Microbial fuel cells (MFCs), drive a current from bio-electrochemical systems which mimic bacterial interactions. They are a clean and efficient way of producing energy. Many organic materials can be used to feed the fuel cell including waste material such as wastewater.[16] (IPC = H01M8/16)	572
Biodegradable packaging	Biodegradable packaging covers packaging that involve disintegrable, dissolvable or edible materials and thus are designed so they do not accumulate in the environment. (IPC = B65D65/46)	4823
Aqueous solvents	Many solvents are damaging to the environment (from water to the ozone layer) and harmful to humans. Organic solvents are prevalent in paint thinners, nail polish removers, glue solvents, industrial and household cleaning products, printing inks and in extractive processes. Sustainable Chemistry encourages the replacement of organic solvents with aqueous solvents along with supercritical fluids, ionic liquids or by using solvent free processes. (IPC = C08F2/10)	3347
Selected White Biotech	This falls into the white biotechnology/catalysis area and involves the preparation of oxygen containing compounds using fermentation (or similar). (IPC = C12P7/00 i.e. including all subcategories)	31959
TCF Bleaching Technologies	Totally chlorine free bleaching technologies used in the pulp paper industry removes dioxins found in both paper products and wastewater when using pre-existing technologies. TCF technologies involve no chlorine compounds and remove all but naturally present Adsorbable Organic Halides (AOX), dioxins and furans. (IPC = D21C9/153 or D21C9/16)	4176
Green plastics	Unlike the other categories which use IPC codes to identify patents, Green Plastics applications have been identified using key word searches on titles. Specifically, this involves looking for polylactide, polylactic acid, PLA, Polyhydroxybutyrate, PHB, Polycaprolactone and PCL in application titles in relevant areas as defined broadly using IPC codes. These are biodegradable polymers that are also derived from renewable feedstocks in the case of PLA and PHB. This search was restricted to patents with English titles. [17] Due to varying quality of data from different patent offices and the fragile nature of key word searches, the Green plastics figure should be treated with care.	508

[15] Technical descriptions of IPC codes can be found on the WIPO website: http://www.wipo.int/ipc8earlypub/ipcpub/index.php?lang=en&menulang=EN. To look at patent applications corresponding to certain IPC codes, please refer to the Esp@cenet website: http://ep.espacenet.com/advancedSearch?locale=en_EP.

[16] The Biochemical Fuel cell and the Selected White Biotech categories were defined with the help of Prof. James Clark at York University.

[17] In the future we hope to improve this search by ensuring all family members are included even when they fail to have a title with the correct key words.

53. A related project has examined innovation in climate change mitigation technologies (see Haščič et al. 2010). Some of the fields examined as part of this work relate to sustainable chemistry, including carbon capture and storage (CCS) (e.g. by chemical separation or adsorption), solar photovoltaic cells (e.g. dye-sensitised solar cells, microcrystalline solar PV cells) and cellulosic ethanol. The search algorithms for these areas were developed by patent examiners at the European Patent Office. See text boxes below.

MAJOR TRENDS IN SELECTED SUSTAINABLE CHEMISTRY INVENTIVE ACTIVITY

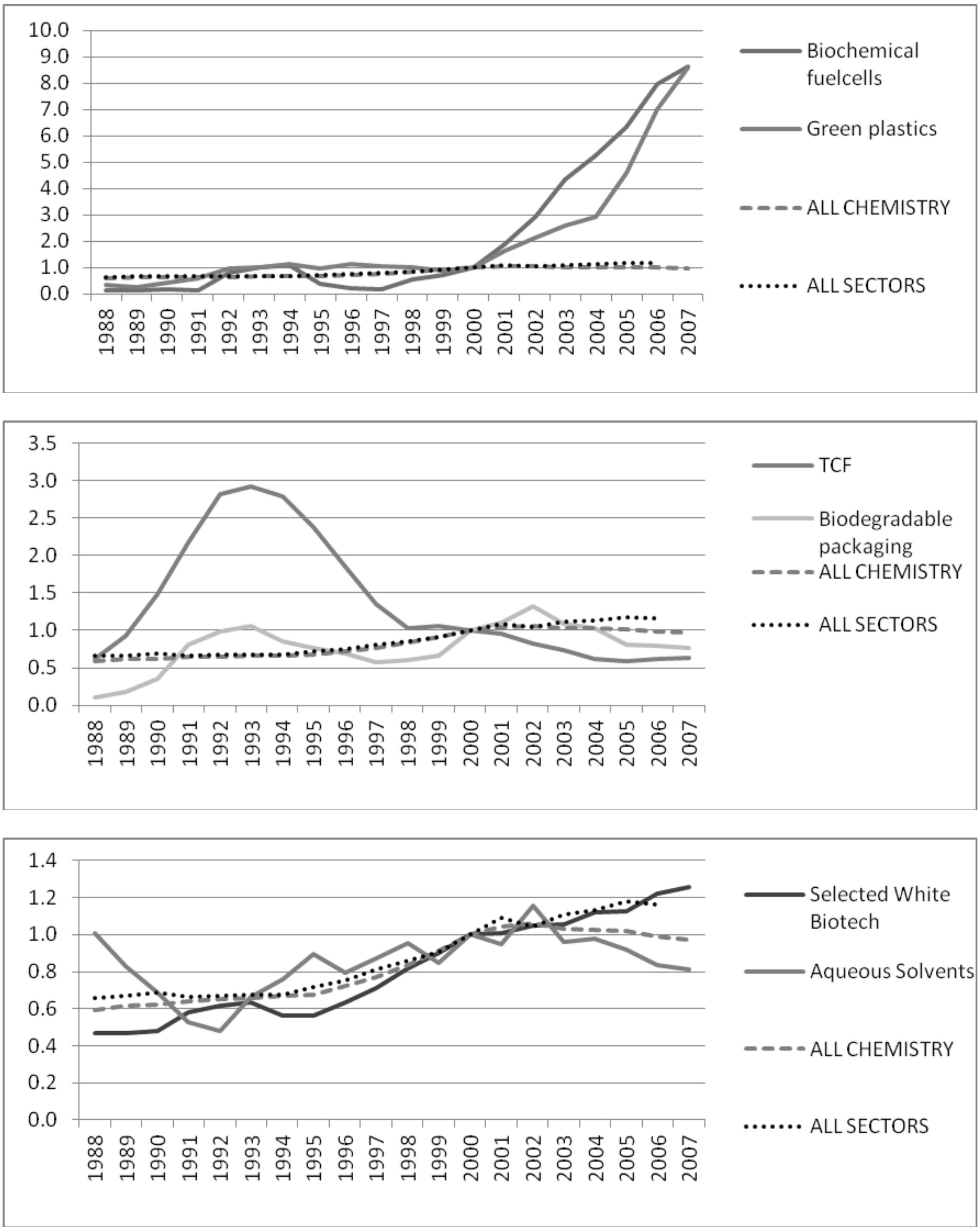
Patent Counts for Sustainable Chemistry

54. Figure 7 shows general invention trends in selected green chemistry areas by looking at application counts (CP+SING) by year as indexed on the year 2000. Since patenting activity in general has increased over time, the *ALL SECTORS* indicator is included for purposes of comparison, as well as the *ALL CHEMISTRY* indicator which encompasses all chemistry patents. Note that the rate of applications for chemistry has followed a similar pattern to that for *ALL SECTORS*, with approximately 50% more applications in the 2000s than in 1988. However, *ALL SECTORS* has increased nearly 20% since 2000 while *ALL CHEMISTRY* has remained static.

55. Biochemical fuel cells have shown rapid growth since 1988 when compared to the other areas, but note that the counts for this category are relatively low, with approximately 600 applications (including duplicates) in the 1970-2007 period. Similarly, *green plastics* has shown rapid growth, but again has relatively small counts. Furthermore, the *green plastics* comparison is imprecise as the applications have been selected from those with English titles, and preferably the comparison groups would also be derived from the same population.

56. Biodegradable packaging shows two peaks, first in the early 1990s and then later in 2002. Since 2002, rates have fallen slightly. *Totally Chlorine Free* (TCF) peaked in 1993 at nearly 3 times the 2000 level. In 2007 TCF applications were at same level as they were in 1988. *Selected white biotech* has increased steadily since 1988. In 2007 it was more than 20% higher than in 2000 however it is in line with the *ALL SECTOR* application trend. Invention in the *aqueous solvents* area has stagnated since 1988 and has not kept pace with the overall growth in patent applications.

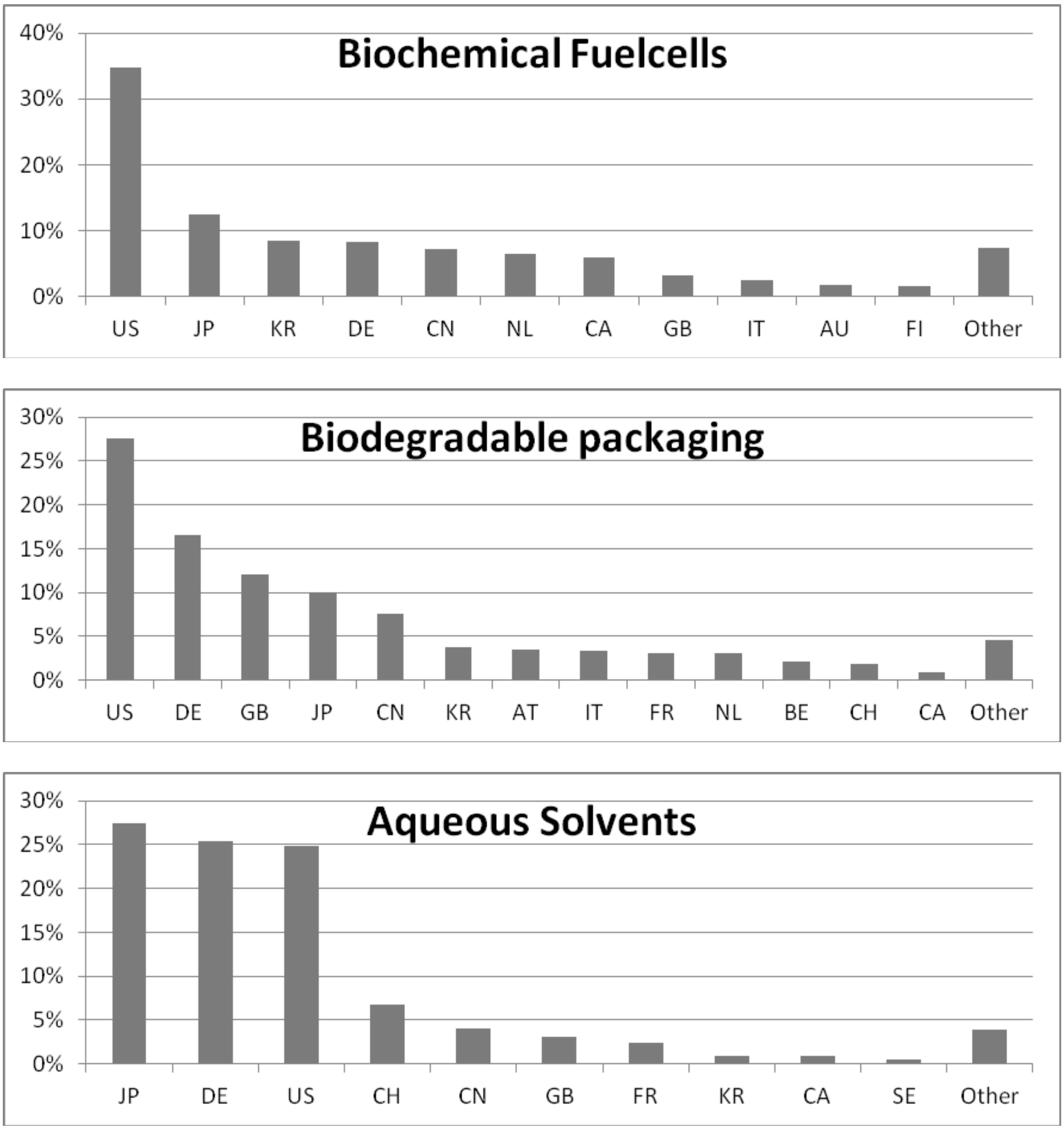
Figure 28. Growth rate of selected Sustainable Chemistry area (Count of CPs and SINGs worldwide, 3-year moving average, indexed on 2000=1)

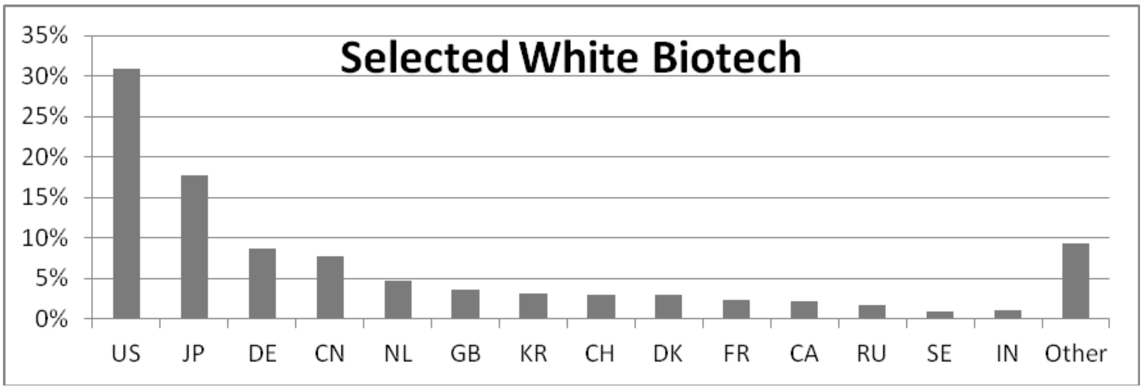


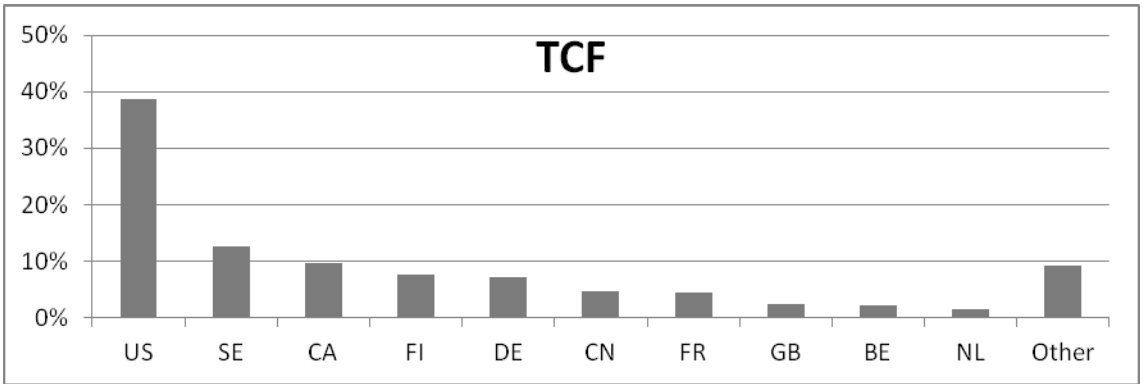
57. Figure 8 shows the proportion of applications (claimed priorities and singular) by inventor country over the 1988-2007 period. The United States dominate the counts for *biochemical fuel cells* with approximately 35% of the applications, the next biggest inventor countries are Japan, Korea, Germany and China. In terms of *biodegradable packaging*, the top five inventor countries are the United States, Germany, Great Britain, Japan and China. The *aqueous solvent* area is

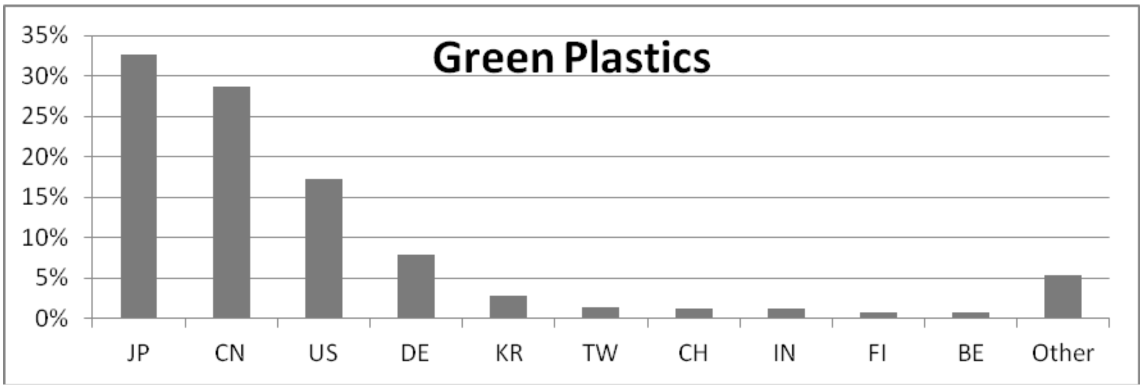
dominated by Japan, Germany and the United States. *Selected white biotech* is a large area with a number of inventor countries, the top five being the United States, Japan, Germany, China and the Netherlands. The main inventor in the *TCF* area is the United States, the next four largest are Sweden, Canada, Finland and Germany. For *Green plastics*, Japan and China account for over half of patents, the United States, Germany and Korea are the next largest. The result for the *Green plastics* area is likely to be biased due to the key word selection criterion.

Figure 29. Share of world wide patenting by inventor country – CPs+SINGs 1988-2007




Selected White Biotech
35%
30%
25%
20%
15%
10%
5%
0%
US
JP
DE
CN
NL
GB
KR
CH
DK
FR
CA
RU
SE
IN
Other

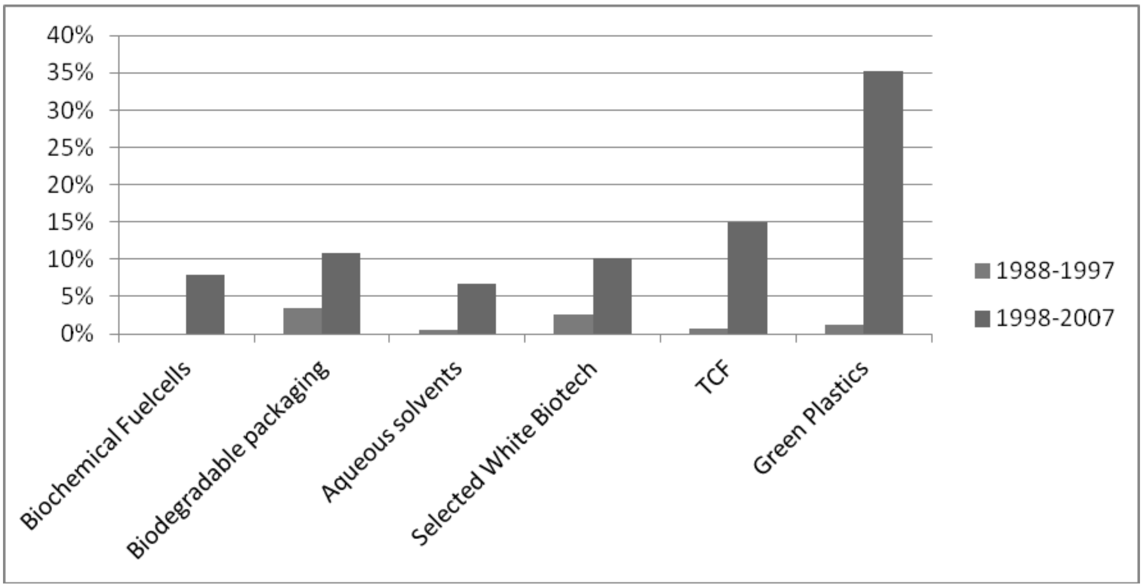

TCF
50%
40%
30%
20%
10%
0%
US
SE
CA
FI
DE
CN
FR
GB
BE
NL
Other


Green Plastics
35%
30%
25%
20%
15%
10%
5%
0%
JP
CN
US
DE
KR
TW
CH
IN
FI
BE
Other

Box 5. Increasing Share of Invention by China

Figure 9 shows the share of invention in China in the 1988-1997 and 1998-2007 periods. In the 1988-1997 period China had proportionately very few or no patents in these Sustainable Chemistry areas. However, in the 1998-2007 period, invention in China notably increased in all of these categories. For instance in the 1988-1997 period, China accounted for less than one percent of *TCF* patents, this increased to 15% in 1998-2007 period. The rate of increase for *Green Plastics* was even more dramatic, but needs to be treated with caution due to the key word selection criterion.

Figure 30. Share of invention by China 1988-2007



Intellectual Property Offices Where Protection is Sought

58. Protection of intellectual property must be obtained from the patent office of each country where protection is wanted. Looking at the data in term of the offices in which applications are deposited (CP, DUPL and SING) allows us to determine the markets where protection is sought, rather than the origin of the invention. This can be useful, for instance, when assessing the impacts of environmental regulations on local production practices.

59. However, care must be taken when interpreting such data. Patent offices have different procedures which can bias the results. For instance, the scope of claims may vary widely - a single patent application submitted to the European Patent Office may require coverage by two different applications in the Japanese Patent Office due to different practices relating to the scope of claims (See Johnstone and Hascic 2009.)

Table 9. Patent Application Offices for all patents 1988-2007

	Biochemical fuel cells	Biodegradable packaging	Selected White Biotech	TCF	Aqueous solvent	Green Plastics
Number of patent application offices	32	57	73	59	54	21
Top 10 patent application offices						
1	JP	JP	JP	JP	JP	CN
2	US	EP	US	CA	EP	US
3	EP	US	EP	EP	US	EP
4	CN	DE	CN	US	DE	JP
5	AU	AU	AU	AU	CA	CA
6	CA	CA	CA	FI	CN	KR
7	KR	CN	DE	DE	AU	MX
8	DE	AT	AT	BR	AT	DE
9	ES	ES	BR	SE	ES	NZ
10	GB	GB	KR	AT	BR	TW
% of patents in top 10 authorities	89%	78%	80%	74%	81%	95%

60. Table 3 shows three types of information for the different fields: i) the number of offices receiving at least one application; ii) the offices receiving the most applications; and, iii) the proportion of all patents that are found in the top 10 offices. Firstly, the number of offices receiving applications varies widely by type, but this is partly a function of the overall number of applications. For instance, *selected white biotech* applications have been deposited in the most patent offices (73) when compared to other areas. However, they also have the greatest number of patents.

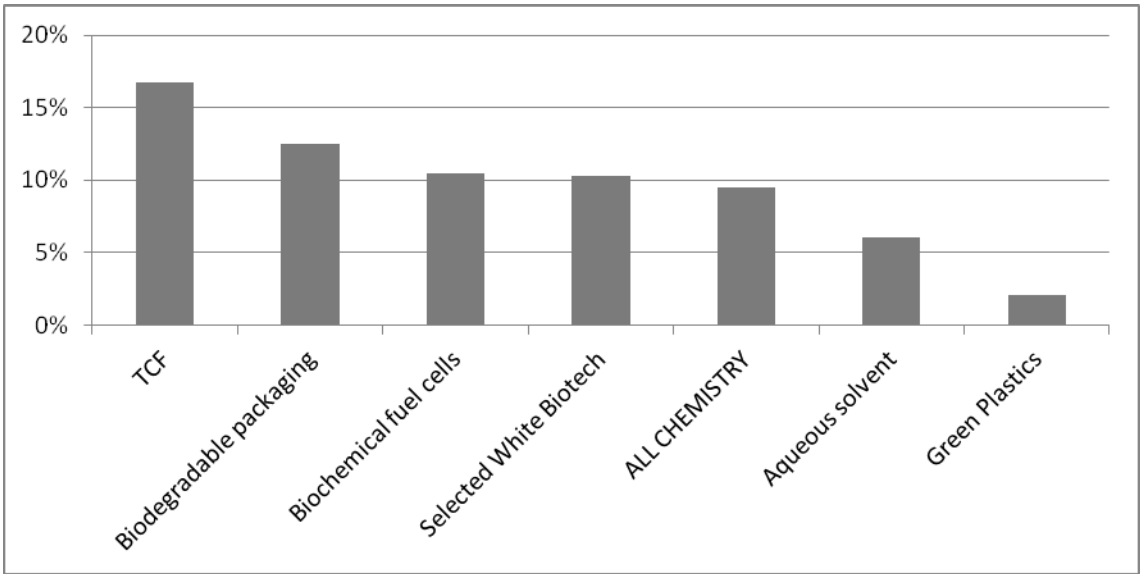
61. The Japanese, United States and European patent offices commonly have the most applications, with the exceptions of *TCF*, where Canada is prominent and *green plastics* where the Chinese Intellectual Property Office leads. Again, the *green plastics* area must be treated with caution as it is hard to determine the extent to which this is an artefact of the data. For instance, care has been taken to provide clear English titles for Chinese patents in the PATSTAT database, where as for countries such as Germany, the titles will be in German and so will not be picked up by the key word selection criterion.

International Research Cooperation

62. This section looks at the level of international research cooperation in the sustainable chemistry area. Figure 10 shows the proportion of patents that have been invented by researchers from more than one country. The overall rate of international cooperation found in *ALL*

CHEMISTRY applications is 9%. *Biochemical fuel cells* and *selected white biotech* have similar rates at 10%. *Totally Chlorine Free (TCF)* has the highest rate at 17% followed by biodegradable packaging at 12%. Aqueous solvents have a lower rate of cooperation at 6% than the *ALL CHEMISTRY* area. *Green Plastics* have the lowest rate of co-invention, but this may be due to the nature of the data extraction method.

Figure 31. Proportion of patent applications involving international cooperation 1988-2007



63. Table 4 shows the top five countries involved in international invention cooperation. The United States has cooperated most often in the five sustainable chemistry areas. Note however, that they are also a prominent inventor, being top in all these areas with the exception of *aqueous solvents*. Although Japan is also a significant inventor in many of these areas, they have low involvement in international invention cooperation. Looking at *ALL CHEMISTRY* patents, the United States co-invents the most, followed by Germany, Great Britain, France and Switzerland.

Table 10. Top 5 co-invention countries 1988-2007

	Biochemical fuel cells	Biodegradable packaging	Selected White Biotech	TCF	Aqueous solvent	ALL CHEMISTRY
1	US	US	US	US	US	US
2	KR	GB	DE	CA	DE	DE
3	DE	DE	CH	SE	JP	GB
4	ES	FR	NL	FI	SE	FR
5	CA/AU	BE	GB	FR	FR	CH

64. Table 5 shows the proportion of top inventor countries cooperating internationally by area. Asian countries such as Japan, China and Korea tend to cooperate less often than European countries and the United States. In the *ALL CHEMISTRY* area, Germany co-invents for 29% of their inventions compared to

15% for the United States, 6% for Japan and Korea and 5% for China. In the selected Sustainable Chemistry areas, Japan co-operates the least often, while Korea and China have high co-invention rates for some areas such as *Biochemical fuel cells* for Korea at 48% and *Aqueous solvents* for China at 16%.

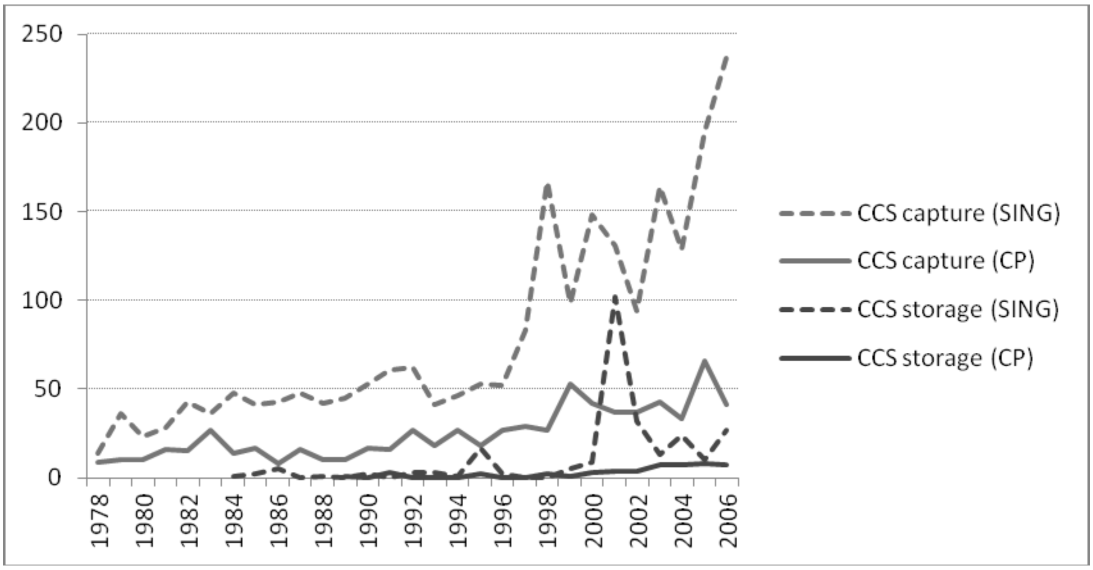
Table 11. Proportion of selected top inventor countries cooperating internationally

TCF		Biodegradable packaging		Biochemical Fuel cells		Selected White Biotech		Aqueous solvents		ALL CHEMISTRY	
US	29%	US	23%	US	14%	US	16%	JP	3%	US	15%
SE	25%	DE	23%	JP	0%	JP	6%	DE	10%	JP	6%
CA	56%	GB	49%	KR	48%	DE	43%	US	14%	DE	29%
FI	39%	JP	1%	DE	34%	CN	4%	CH	9%	CN	5%
DE	21%	CN	7%	CN	11%	NL	40%	CN	16%	KR	6%
CN	9%	KR	2%			GB	50%				
						KR	10%				
						CH	63%				
						DK	46%				
						FR	48%				

Box 6. Carbon Capture and Storage

Identification of patent applications related to carbon capture and storage (CCS) is complicated because no IPC code corresponds precisely to this technology.[18] Data on CCS reported here are based on a search algorithm that was developed separately from those concerning other technologies discussed in this paper. Therefore a separate subsection is dedicated to it. Patent applications were identified that relate to CO_2 capture using absorption, adsorption, biological, chemical, membrane diffusion, and rectification and condensation processes, and those that relate to CO_2 storage (see Hascic et al. 2010). In total, 2981 and 309 priority documents (CP+SING) filed between 1978 and 2006 were identified for CCS capture and storage, respectively. Approximately 20% of them are CPs. The data clearly suggest an increasing trend for both capture and storage innovations, however the volume of patenting activity in CCS storage remains low.

Figure 32. Patenting activity in CCS
(Count of singulars and claimed priorities worldwide)



In terms of all priority docs (CP+SING), the US, Japan, Germany but also Canada and the Netherlands were the top inventor countries in CCS capture during this period (together they account for 77% of CP+SINGs worldwide). Other significant inventors include France, the UK, and Norway, followed by China, Australia and Italy (15% of CP+SINGs worldwide). The Soviet Union was an important innovator in the 1980s. Since the late 1990s, Korea, South Africa, Denmark, Switzerland and Russia started to chip in. For CCS storage, the US, followed by the Netherlands and Japan were the major inventor countries (74% of CP+SINGs). Since early 2000s, a wide range of countries such as Canada, France, Australia, Russia, the UK, Germany and Norway emerged as significant sources of invention.

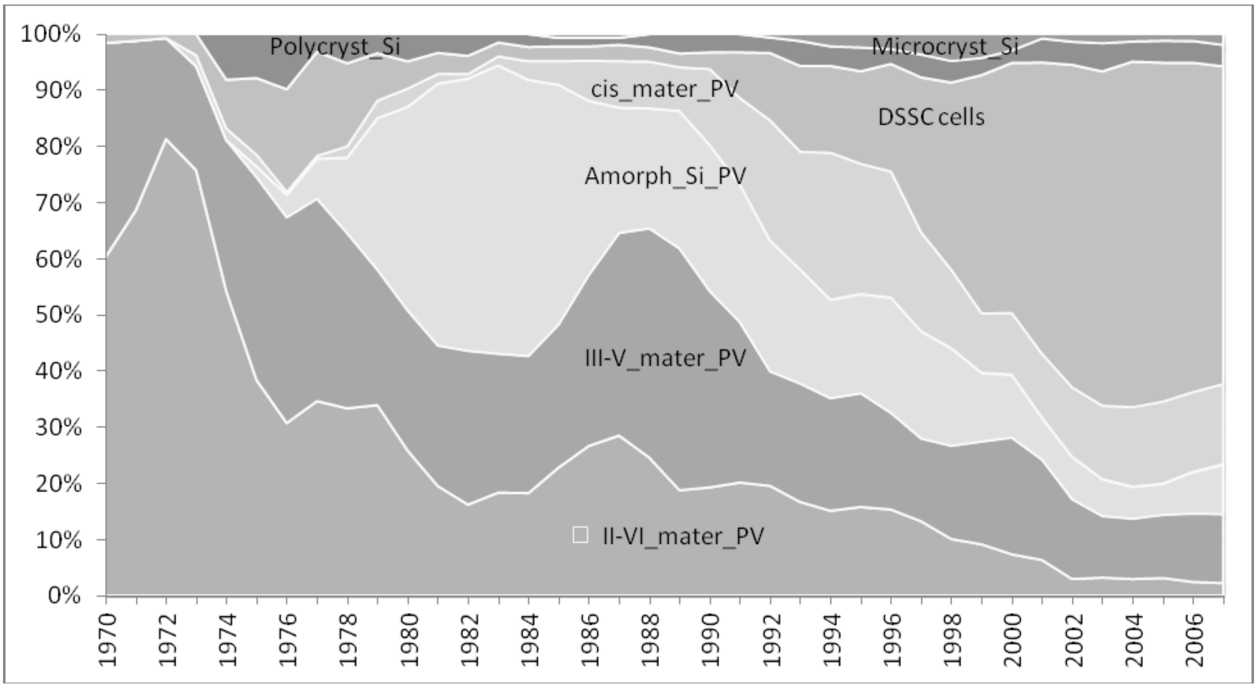
In terms of CPs only, the US, Japan, Germany, France and the UK were the top inventor countries in CCS capture during this period (together they account for 82% of CPs worldwide). Other significant inventors include Norway, Canada, the Netherlands and Italy (10% of CPs worldwide). Since late 1990s, countries such as France, Norway, and Korea show the most important growth rates. For CCS storage, the US, France and Japan were the major inventor countries (65% of CPs). However, Japan completely dropped out since the late 1990s, and instead Germany, Canada and Norway started to chip in. Finally, our data suggest that CCS differs from other mitigation technologies in several respects. First, inventive activity in CO_2 storage and, to a lesser extent, in CO_2 capture is concentrated in hands of a small number of patent applicants (assignees) relative to renewable energy fields. Second, the 'propensity to patent abroad' is significantly higher in CCS than in other renewable energy fields.

[18] The B01D53/62 class concerns separation of carbon oxides and as such contains some of the relevant inventions (but also many irrelevant).

Box 7. Trends of Photovoltaic cells

Invention in Solar Photovoltaic cells has grown rapidly in the last decades and is an important innovation area amongst climate mitigating technologies. The Figure below shows the relative share of various PV technologies. Since 1990, DSSC cells (Dye Sensitised Solar Cells) have become prominent in patent applications.

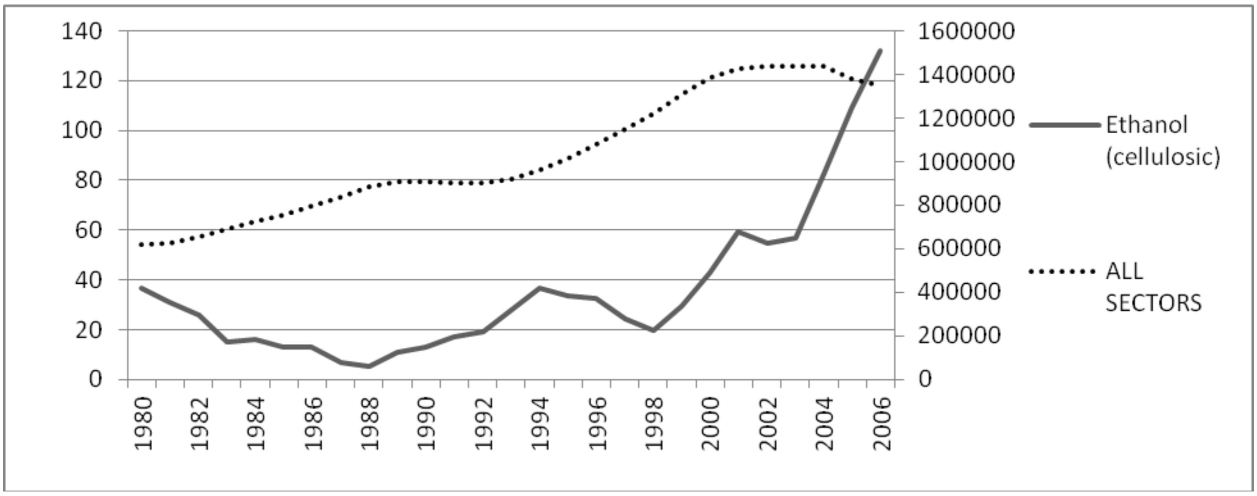
Figure 33. Inventive activity in solar PV technologies 1970-2007, Relative share of selected PV technologies, 3-year moving average)



Box 8. Trends in Cellulosic Ethanol

Cellulosic ethanol is produced from low value plant matter such as wood, grass and non-edible parts of crops, The main advantage of cellulosic ethanol over traditional biofuels made from crops such as corn or starch, is that it can be made from a wide range of inputs including wastes from crops. Furthermore it has lower Green House Gas emissions than traditional biofuels. However cellulosic ethanol does require more processing. The Figure below shows that the patent application rate for *Ethanol (cellulosic)* has grown much faster than *ALL SECTORS*, furthermore, it has risen sharply since 1998.

Figure 34. Patent applications (CP,SING+DUPL) for cellulosic ethanol 1980-2006

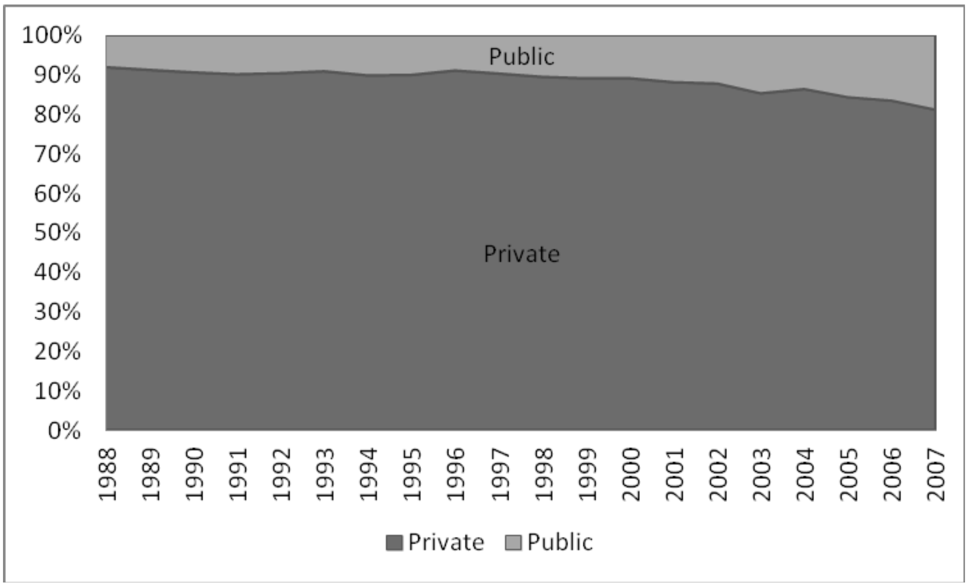


The Institutional Characteristics of Assignees

65. Patent databases include information on assignees who apply for patent protection and, if successful, are the owners of patents. The assignee can be an individual, but typically it is the company, university or research centre where the invention took place. By looking at assignees we can look at which companies are involved in invention.

66. The proportion of inventors from 'public' bodies has increased over time for chemical patents. This increase has been largely driven by universities, in 1988 there was approximately an even split between government, universities and private-non-profit, by 2007 university inventors accounted for over 11% of patents, private-non-profit at 5% and government at 3%.

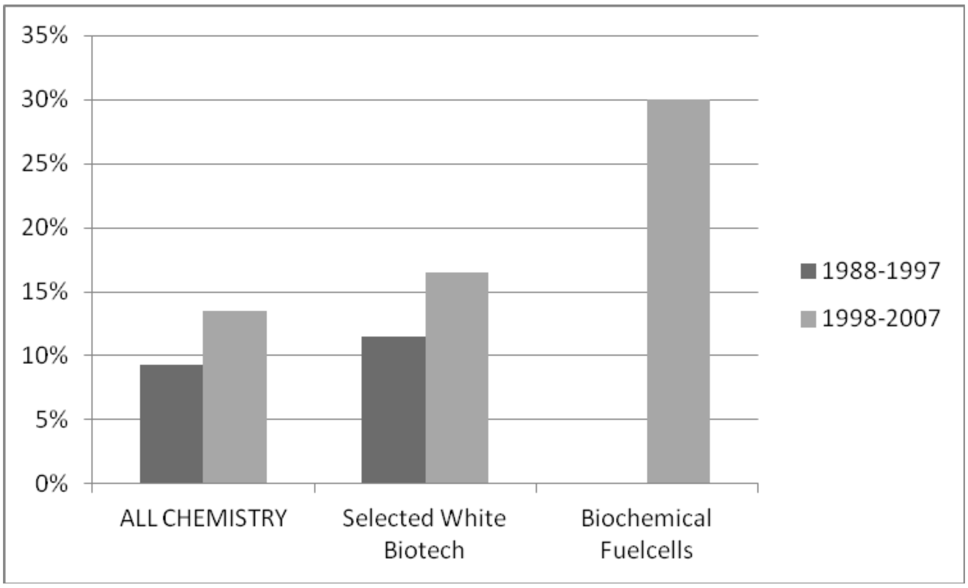
Figure 35. Proportion of patents by public or private inventor (CP + SING) for ALL CHEMISTRY



Note: Private includes individuals and companies while public inventors are made up of government, universities, private non profit and hospitals.

67. Green technologies have a higher proportion of public inventors when compared to all chemical patents and new technologies more so than mature ones (see Figure 15.)

Figure 36. Proportion of patents with public inventors 1988-2007 by selected technologies



Note: the proportion for biochemical fuelcells for the 1988-1997 is removed due to the small number of patents.

68. For *selected white biotech* large broad-based chemical companies such as Du Pont, BASF and DSM are the top assignees. However, more specialised biotech companies such as Novozymes, a producer of industrial enzymes, also have a strong presence. In the *aqueous solvents* area, large

chemical companies again predominate: Nippon Shokubai, BASF, Dow and Mitsubishi Chemicals. Pulp and paper companies, major chemical companies and other large companies are major assignees in the *totally chlorine free* area: Mitsubishi, OJI Paper, Weyerhaeuser and Cargill Incorporated, a large privately held multinational company. Consumer goods companies such as Proctor and Gamble and Reckitt Benckiser feature in the *biodegradable packaging* area along with companies including Mitsubishi. In the *biochemical Fuel cell* area large corporations such as Sony, Ebara and Canon feature along with a number of Universities including St Louis, Michigan State, Western Ontario and Konkuk. In the *green plastics* area, predominant assignees include Toray Industries from Japan, Samyang for Korea and Donghua University.

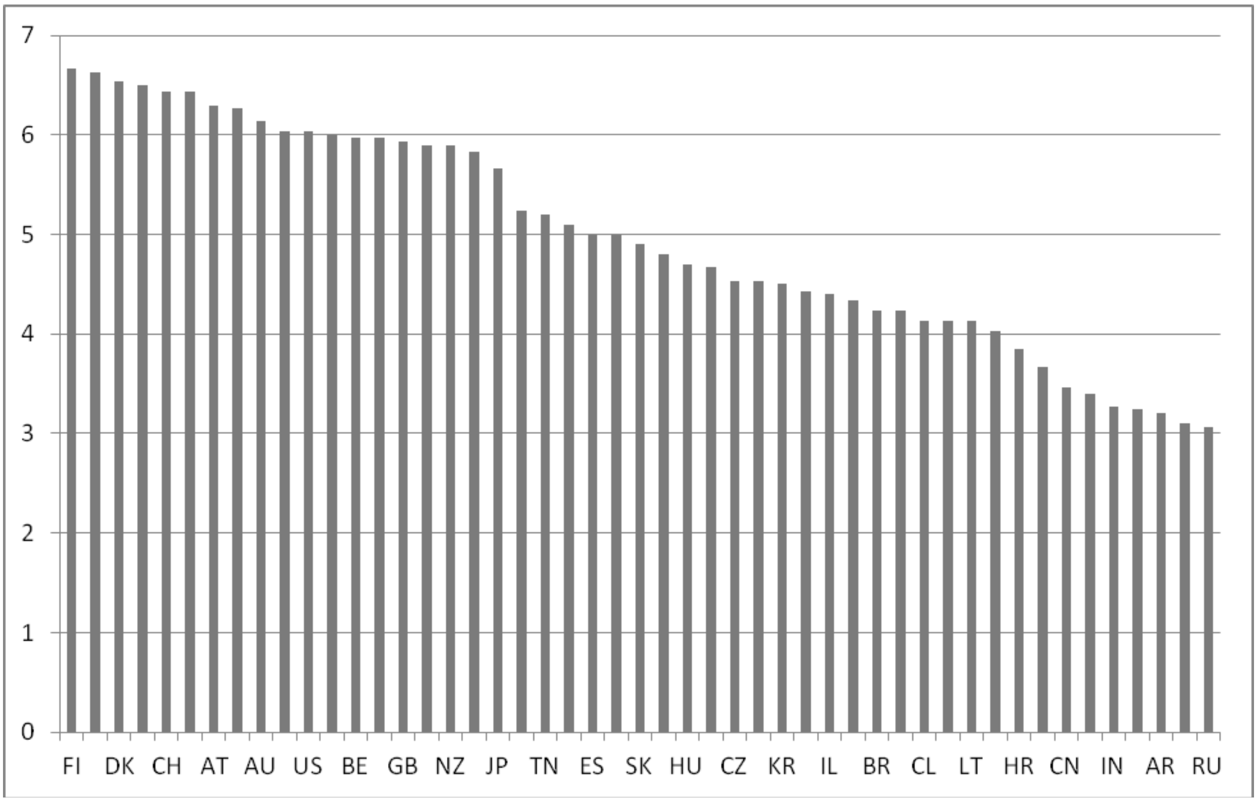
THE EFFECT OF PUBLIC POLICY ON GREEN CHEMISTRY INNOVATION?

69. Previous work undertaken at the OECD has shown that public policy can be an important inducement to innovation. In particular it is found that policy stringency, predictability, and flexibily have a significant impact on the number of 'high-value' patents for environmental technologies deposited. (See http://www.olis.oecd.org/olis/2009doc.nsf/linkto/ENV-EPOC-WPNEP(2009)2-final).

70. Given the breadth of 'sustainable chemistry' it is particularly difficult to come up with commensurable measures of the policy frameworks in place in different countries. In the aforementioned study, data from the *World Economic Forum*'s "Executive Opinion Survey" is used to measure policy stringency. The survey was implemented by the WEF's partner institutes in over 100 countries, which include departments of economics at leading universities and research departments of business associations. The means of survey implementation varied by country and included postal, telephone, internet and face-to-face survey. In most years, there were responses from between 8,000 and 10,000 firms (see WEF 2008 for a description of the sampling strategy.)

71. Respondents are asked a number of questions related to environmental policy design. Unfortunately, none of them relate directly to 'green chemistry'. However, the degree of perceived stringency of a country's chemical waste policy was assessed on a Likert scale, with 1 = lax compared with that of most other countries, and 7 = among the world's most stringent. Mean responses for selected countries are provided in Figure 16.

Figure 37. Stringency of Chemical Waste Waste Policies (Mean WEF Value 2001-2004)



Examples of Instruments

72. While it is true that some of the countries with the most stringent chemicals waste policy are also the countries with the highest rates of innovation, such a measure only covers a small sub-set of the areas in which the benefits of green chemistry are likely to arise. As such, in this section we consider more specific examples of public policies, and how they may have had an influence on green chemistry. Relevant policy instruments can be broadly classified as:

- Negative instruments – provide incentives for innovation in 'green' technologies by concentrating on identifying, assessing and then controlling polluting and dangerous chemicals. By reducing negative environmental and health impacts these instruments can broadly encourage sustainable chemistry innovations. These instruments include: risk assessments, regulations (i.e. limits, and bans) and taxes (including the purchasing of pollution permits).

- Positive policies – aim to stimulate sustainable chemistry by concentrating on encouraging the good technologies: adoption and training of industry, procurement, labelling and awards.

Negative instruments

73. Risk assessment plays a central role in basic chemical legislation in many OECD countries, and can be considered as a precondition for the implementation all other instrument types. The recent EU REACH legislation and the US Toxic Substance Control Act 1976 (TSCA) are both policies where assessment of risk plays a large part. See box A and box B for details. Both policies aim to address the problem that in the past chemicals were introduced to the market without comprehensive safety testing and consequently there are many substances on the market that may or may not be safe.

74. The US treats existing and new chemicals differently under the TSCA (Toxic Substances Control Act) of 1976. Existing chemicals are defined as those prior to December 1979 (approximately 62,000 chemicals). In order to impose limits on existing chemicals the EPA (Environmental Protection Agency) must prove that they pose an unreasonable risk and that the benefits of regulation outweigh the costs to industry. For new chemicals, the TSCA registration process requires chemical manufacturers to provide any available test data, but in practice only 15% of pre-manufacturing notices submitted to the EPA contain any health or safety test data; this data gap has been attributed to cost and time disincentives faced by chemical companies (US GAO 09) [ref: US GAO report 09-428T, Toxic Substances Control Reforms].

75. Consequently only five chemicals out of more than 83,000 now used in commerce have faced restrictions since the inception of TSCA. As part of assessment procedures for new chemicals, the EPA has developed a number of tools to help tackle the problems associated with knowledge gaps – specifically whether chemicals safe or not. The EPA also operates a program called "Design for the Environment" that aims to identify chemicals that are best in class according to health and safety metrics for a variety of industrial and consumer applications, but does not have clear authority to establish safety standards based on the findings. In 2009 the EPA announced "Essential Principles for Reform of Chemicals Management Legislation", calling for data and testing burdens to be shifted to industry, consistent funding for safety assessments, and greater transparency and public access to chemical information. The principles also specifically state that green chemistry should be encouraged to lower risk and improve energy efficiency and sustainability. [http://www.epa.gov/opptintr/existingchemicals/pubs/principles.html]

76. The European Union introduced the REACH[19] Regulation in June 2007 to be phased in over 11 years. REACH stands for Registration, Evaluation and Authorisation of Chemicals. REACH legislation pushes the burden of proof onto industry to prove that products are safe, whereas under past legislation the burden was on the government to prove the chemical was not safe. Prior to REACH, the EU had different safety testing for 'new' and 'existing' chemicals. Existing chemicals, those in the market before 1981 were not automatically required to meet the testing requirements of new chemicals. As existing chemicals are the majority of those used, this resulted in a knowledge gap where the health and environmental effects of these chemicals is unknown.

[19] See http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm
http://ec.europa.eu/environment/chemicals/reach/pdf/2007_02_reach_in_brief.pdf

77. REACH was designed to solve this anomaly by requiring all chemicals to be assessed. Furthermore, the burden of testing has been shifted from the state to industry. Other aspects of REACH include the phasing out and substitution of the most dangerous chemicals. The safety data on chemicals will be publically available on a database managed by the European Chemical Agency. Other important EU legislation includes the Regulation for Classification, Labelling and Packaging of Substances and Mixtures (CLP Regulation, January 2009). This requires internally agreed classification and labelling so that hazards are transparent to the entire supply chain that may use or distribute the chemical, including consumers, and is based on the UN GHS Globally Harmonised System of Classification and Labelling of Chemicals. The UN GHS system aims to provide a clear, worldwide standard for classifying chemicals according to various hazards such as acute toxicity or flammability. By focusing on the intrinsic properties of the chemical and communicating the resulting hazards, the CLP regulation is line with the green chemistry approach to risk, which focuses on inherent hazard instead of the circumstances of chemical exposures.

78. In Japan, the "Law Concerning the Examination and Regulation of Manufacture of Chemical Substances" was passed in 1973, and subsequently revised in 1986. This was primarily concerned with identifying (and regulating) the adverse effects from chemical substances. In 1999 the "Law Concerning Reporting and Release to the Environment of Specific Chemical Substances and Promoting Improvements in Their Management" was passed. This stressed the disclosure of information on the use and impacts of chemical substances.

79. Canada announced the Chemicals Management Plan in 2006 which proposes to assess all chemicals by 2020.[20] More recently, the Californian "Green Chemistry Initiative" is working towards a comprehensive system specifically aimed at encouraging green chemistry. To date, legislation passed in 2008 has initiated a web-based database 'Toxics Information Clearinghouse' with information on toxicity and hazards of chemicals.[21]

80. As noted above, risk assessments are a necessary precursor to regulation. For instance, the California Department of Toxic Substances Control (DTSC) has been given authority to develop processes to identify chemicals of concern and subsequently to impose restrictions or bans. In September 2010 DTSC released a Proposed Regulation for Safer Consumer Products. Under these rules, the DTSC will prioritize chemicals and products according to both hazard and exposure traits, considering volumes and effects on sensitive sub-populations. Manufacturers will be required to submit alternatives assessments, which will be reviewed by DTSC. DTSC will have a range of regulatory options including labelling requirements, usage restrictions, and outright bans.[22]

[20] http://www.chemicalsubstanceschimiques.gc.ca/plan/index-eng.php

[21] http://californiagreenchemistry.squarespace.com/

[22] .http://www.dtsc.ca.gov/PollutionPrevention/GreenChemistryInitiative/Proposed-Regulation.cfm

Positive instruments

81. Significant gains can be made by providing positive support to help industry adopt greener technologies. A number of governments provide financial support (grants and tax preferences) for R&D expenditures which related to green chemistry. While, in the United States proposed "Green Chemistry Research and Development Act" was never passed, grants are provided under the EPA/NSF program on "Technology for Sustainable Development". [23]

82. In Japan, the National Institute of Advanced Industrial Science and Technology (AIST) undertakes a considerable amount of research on green and sustainable chemistry, particularly in the areas of catalysis, membranes, supercritical fluids and renewable resources. In addition, the Ministry of Economy, Trade and Industry provides support for research in the following areas:[24]

- Chemicals Risk Reduction Technology
- Technology for Supercritical Fluid Utilization
- Development of Transgenic Plants for Production of Industrial Materials
- Development of Technological Infrastructure for Industrial Bioprocesses
- Biocatalysis

83. Incentives for the adoption of green chemistry products is an important driver for innovation. This is particularly relevant for small-to-medium enterprises which typically spend fewer resources process improvements and product development than large companies. The Massachusetts Toxics Use Reduction Act (TURA) 1989 is of particular interest as it requires firms to look at ways to use alternatives and reduce waste of some 900 industrial chemicals. TURA created a state Office of Technical Assistance and Technology (OTA) that consults with users of toxic substances to implement pollution prevention and reduction strategies and promote innovative, less toxic technologies. The legislation also created a Toxics Use Reduction Institute (TURI) that sponsors programs in research, education, and information dissemination related to cleaner, safer products. Over 1,000 firms have participated since 1990, but almost have since dropped out of the programme since they have reduced or eliminated the use of any of the toxic chemicals listed.

84. This encourages chemical substitutions and process changes that are less toxic. This program has resulted in major reduction of toxic and hazardous waste. (Tickner J, et al 2005, Koch et al. 2006) It has been estimated that "TURA filers have decreased their toxic chemical use by 14% from the 2000 base year to 2007. Using the same method of adjustment, TURA filers are generating 34% less by-products or waste per unit of product and have reduced releases of TRI reported on-site chemicals by 44%. Quantities of chemicals shipped in product have varied over

[23] http://www.epa.gov/greenchemistry/pubs/grants.html#TSE

[24] See http://www.chugoku.meti.go.jp/mailing/ouen/59-2.pdf

the past years, yielding a production adjusted reduction of 14% since 2000." [25] "Since 1990, over 1000 Massachusetts firms have participated in the Toxics Use Reduction Program.

85. Many OECD countries have introduced green public purchasing policies to reduce the environmentally damaging effects of their procurement of goods and services. The government is a significant purchaser of goods and services and therefore such procurement preferences can act as incentive to industry to develop more environmentally friendly products. Also, if there is sufficient government demand this can serve as a signal ("demonstration") to private purchasers, giving the greener technology the competitive advantage thus encouraging innovation. Furthermore, the government demand may allow economies of scale thus reducing the cost and encouraging wider use of these technologies.

86. One prominent example of the use of environmental criteria for purchasing decisions which may have encouraged 'green chemistry' would be the requirement that paper meets chlorine-free standards. Austria's "Check It!" green purchasing criteria expresses a preference for TCF (totally chlorine-free) over ECF (environmentally chlorine-free) paper because of reduced pollution. Support for alternative-fuelled vehicles, and purchase of alternative-fuelled vehicles is seen for example in the United States, where the Energy Policy Act of 1992 mandated that certain federal and state government fleets acquire AFVs [http://www1.eere.energy.gov/vehiclesandfuels/epact/].

87. Awards have proven to be a successful means of inducing innovation in a number of areas, including health and energy technologies.[26] They have raised the profile of Green Chemistry and encouraged research. The US presidential Green Chemistry Challenge Awards have been granted in the following areas:[27]

- Biotechnology - General
- Biotechnology - Genetic Engineering
- Biotechnology - Use of Isolated Enzymes
- Polymers – Chemical Polymers
- Polymers - Biopolymers
- Renewable Resources
- Safer Chemical Products
- Solvents – CO2
- Solvents- Solvent-Free Processes
- Solvents - Water
- Solvents - Other
- Synthetic Processes
- Chemical Catalysts

88. There are many other countries which have instituted awards including the European Sustainable Chemistry Award and the Royal Australian Chemical Institute Green Chemistry

[25] See http://turadata.turi.org/Success/ResultsToDate.html .

[26] See, for example, Newell and Wilson (2005).

[27] For a list of past award winners see http://www.epa.gov/opptintr/greenchemistry/pubs/pgcc/technology.html

Challenge awards.[28] In Japan the the "Green and Sustainable Chemistry Network Awards" were established in 2002.

The Evidence of Innovation Impacts

89. Matching policy data with innovation impacts is complicated by the heterogeneous nature of both 'green chemistry' policies and the innovations themselves. As such, in this final sub-section a limited number of technologies and policy measures are examined. It is important to emphasise that the data is presented descriptively and it is not possible to draw firm conclusions from the effects of different policies on innovation. For instance, more general trends in the market may be driving much of the innovation.[29]

Aqueous Solvents

90. Figure 17 charts the trend in patent counts for aqueous solvents in the EU-27, Japan and the United States. Arguably the 1999 Directive affected the trend rate in growth in patents, at least for the EU-27. However, there was an earlier peak for both Europe and Japan. This may have been a consequence of the 1979 Geneva Convention on Long-range Transboundary Air Pollution (http://www.unece.org/env/lrtap/lrtap_h1.htm). As part of the Convention a Protocol was signed by 23 European countries on VOC emissions. (http://www.unece.org/env/lrtap/vola_h1.htm)

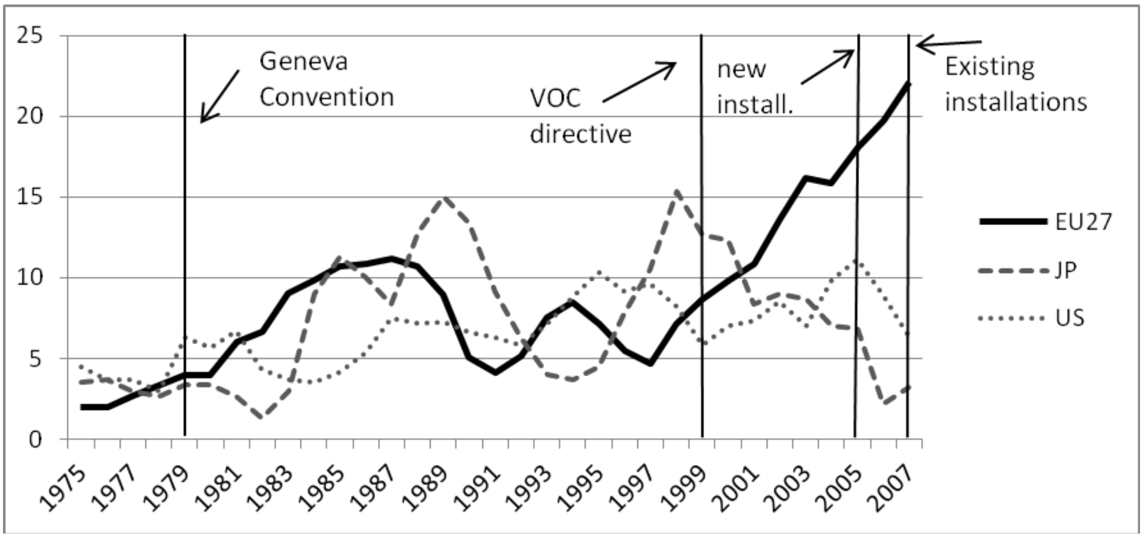
91. The European Commission's VOC Solvent Emissions Directive (SED) is another example. Passed in 1999, the Directive covers emissions from printing, surface cleaning, painting and coating activities, dry cleaning and manufacture of footwear, and pharmaceutical products. The SED establishes emission limit values for VOCs in waste gases and maximum levels for fugitive emissions for solvents (http://eur-lex.europa.eu/LexUriServ/site/en/consleg/1999/L/01999L0013-20040430-en.pdf). The Directive takes the quantity of solvents input and then sets maximum allowances depending on the type of activity and the toxicity of the solvent.[30] New installations had to comply by 2002, while existing installations had until 2007 to do so.

[28] http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_TRANSITIONMAIN&node_id=1316&use_sec=false&sec_url_var=region1&__uuid=ff85c816-f628-407c-aa2e-cc040f58c64b; http://www.gscn.net/awardsE/index.html; http://www.euchems.org/ESCA/; and, http://www.raci.org.au/national/awards/greenchemistry.html

[29] See Johnstone, Haščič and Popp (2010) for a discussion in the context of renewable energy technologies.

[30] See Belis-Bergouigan et al. 2004

Figure 38. EU legislation on VOC and Patent Counts



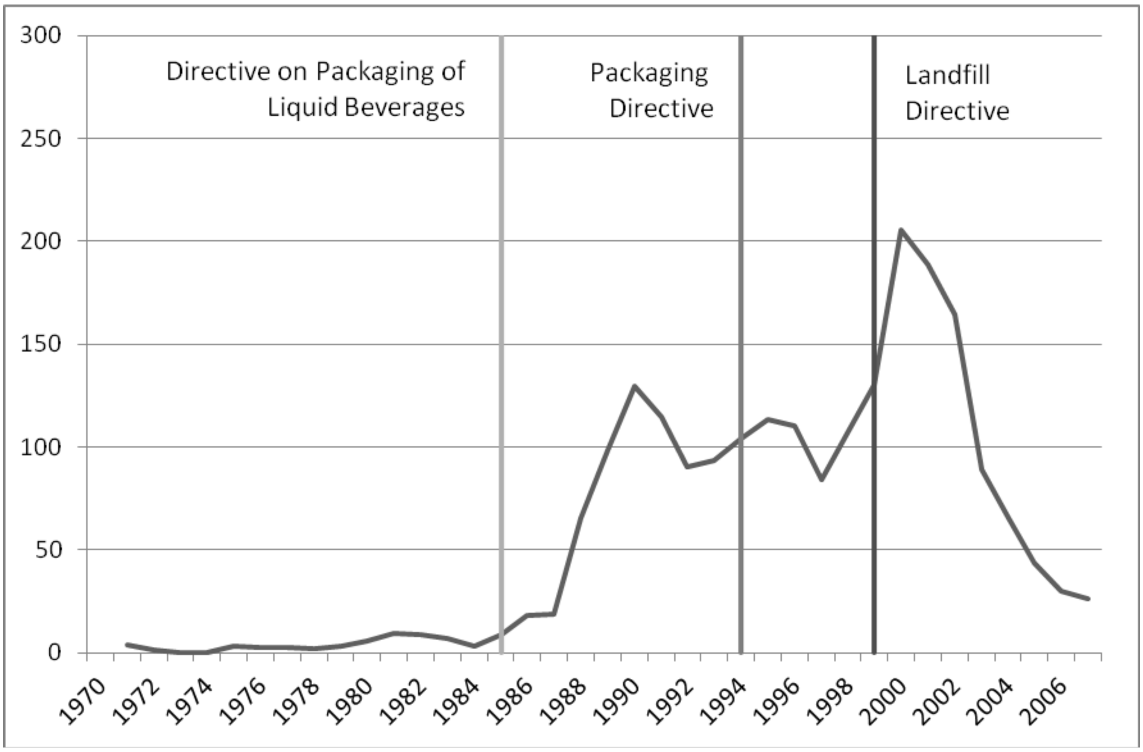
Packaging

92. Waste has also been subject to stringent regulations which may have given a spur to 'green chemistry' innovation. For instance, in Europe the Directive on Packaging of Liquid Beverage Containers (1985), the Packaging Directive (1994), and the Landfill Directive (1999)[31] may have lead to innovation in the area of biodegradable packaging and 'green' plastics. While there was clearly a sudden increase in the late 1980s and late 1990s in European countries, the link with specific policy initiatives is less clear.

[31] http://europa.eu/legislation_summaries/environment/waste_management/l21207_en.htm

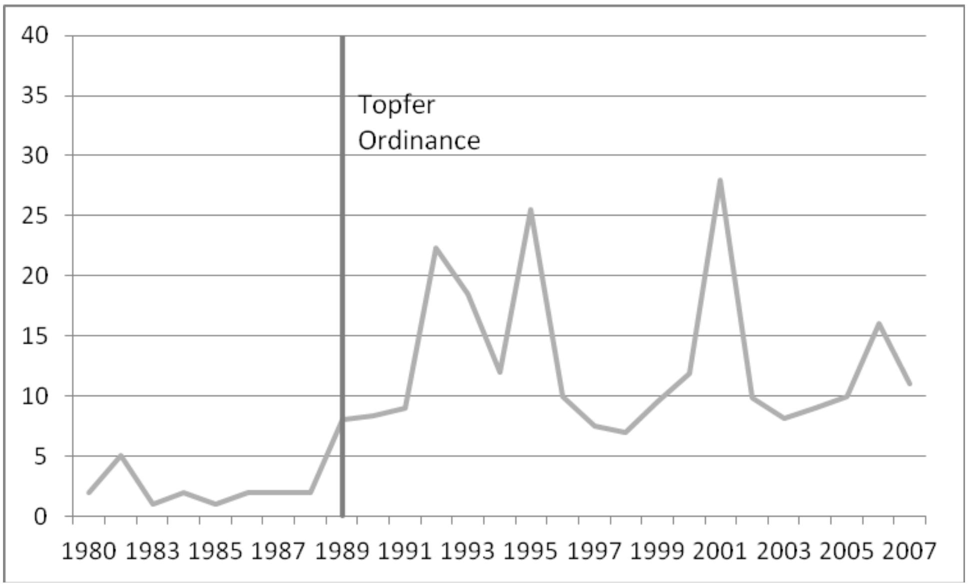
Figure 39. EU Packaging Directives and European Inventor Country Patents for Biodegradable Packaging

(CP's and SINGULARS – 3 yr Moving Average)



93. However, if we look at the case of Germany, the effect of the Töpfer Ordinance is more revealing. There was a discernible impact on innovation in biodegradable packaging patent counts in the years following the introduction of the law.

Figure 40. The "Topfer" Law and German Inventor Country Patents for Biodegradable Packaging

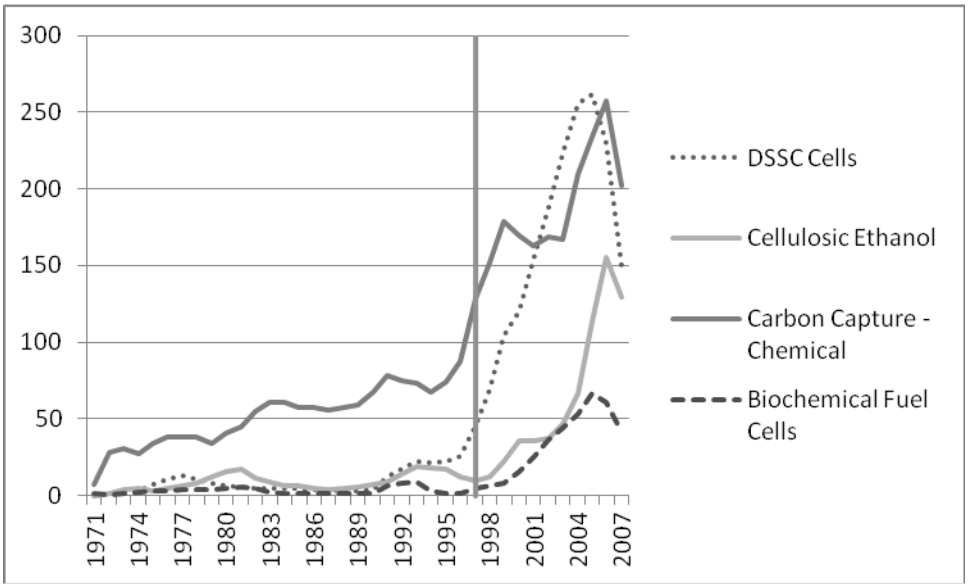


CCM Technologies

94. Dechezlepretre et al. (2010) have looked at the effect of the Kyoto Protocol on climate change mitigation technologies. Using a more refined search strategy developed by patent examiners from the European Patent Office it is possible to identify specific 'green chemistry' innovations which serve to mitigate climate change. As can be seen in Figure 20, the rate of innovation for many of these – particularly dye-sensitised silicon crystal cells – increased markedly in the period following the signing of the Protocol.

Figure 41. Kyoto Protocol and Selected CCM Green Chemistry Technologies

(Global CPs and Singulars – 3-yr Moving Average)



Chlorine-Free Bleaching Technologies

95. The main regulations related to emissions of AOX in the bleaching of pulp are summarised in Table 6.[32] It is important to note that some of these regulations could be met through the use of elemental chlorine-free bleaching rather than totally-chlorine free bleaching. However, the standards passed in Sweden and later Finland and some Canadian provinces would have been a spur to the use of TCF.

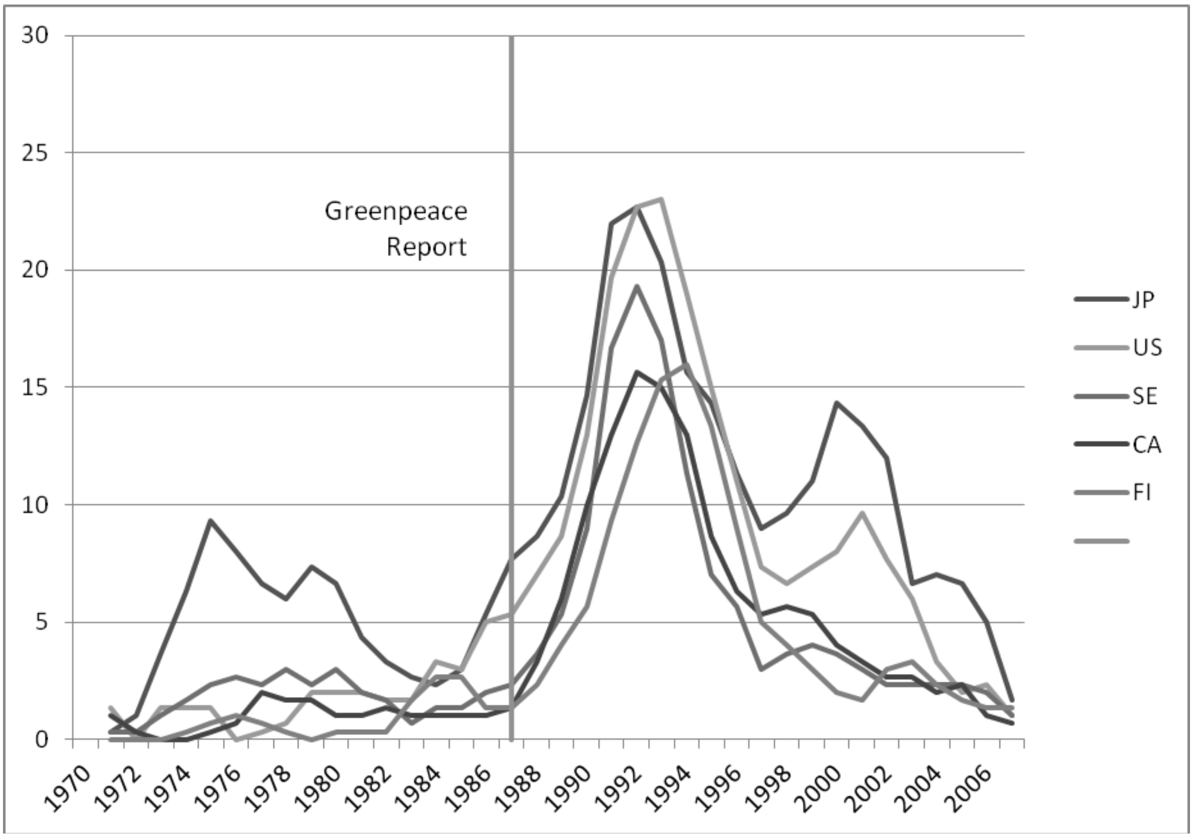
[32] See OECD (2008).

Table 12. Summary of Key Regulations for the Pulp and Paper Sector

Sweden	
1991:	Environmental legislation establishes strict guidelines for AOX (**0.1-0.2 kg/t**). Enforcement is through plant-by-plant permitting.
Finland	
1987:	Issues first guidelines for AOX (**1.4 kg/ADT**), to be met by 1994. Enforcement is through plant-by-plant permitting.
1993:	Accepts Nordic Working Group performance standards for AOX (**0.2 – 0.4 kg/t**). Enforcement is through plant-by-plant permitting.
Canada	
1990:	British Columbia sets AOX limits of **1.5 kg/ADt**, to be met by 1995. Since lowered to **0.6 kg/ADt**.
1992:	Quebec passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000. New mills limited to **0.25 kg/ADt**.
1993:	Ontario passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000.
United States	
1993:	Proposed Cluster Rule suggests TCF as best available technology. Never took effect.
1997:	Revised Cluster Rule limits monthly average AOX releases to **0.62 kg/t** pulp for existing sources, and **0.27 kg/t** pulp for new sources. Mills have until 2001 to comply.
Japan	
1991:	Pulp and paper industry proposes voluntary AOX limit of **1.5 kg/metric ton** by end of 1993.
2000:	First law limiting dioxins in wastewater (1 pg/l). No specific limit for AOX or for the pulp and paper industry.

96. However, as can be seen in Figure 22 innovation in TCF technologies in the main pulp-producing countries preceded the introduction of these regulations. Popp et al. (2008) argue that this was a consequence of consumer pressure, with regulatory measures following afterward as a response. In particular, the release of a Greenpeace report, highlighting the environmental and health implications of bleaching technologies seemed to have played a role. This is quite different from the other cases discussed, and may be related to the fact that there were direct health concerns associated with the use of bleached paper. Indeed, it has been argued that the discharge limits adopted by the Nordic States became redundant because green market demand had surpassed those limits for more stringent measures (Smith and Rajotte, 2001).

Figure 42. TCF Patents (CPs and Singulars) in the Main Pulp-Producing Countries



CONCLUSIONS

97. This paper has provided a review of the development of sustainable chemistry. While there is significant evidence of institutional activity, it is important to determine whether this has been translated into concrete innovations. Descriptive analysis of trends in sustainable chemistry innovation was undertaken using patent data. Unfortunately, due to the nature of the patent classification system it was impossible to identify all green chemistry patents, however we looked at a number of important green chemistry areas.

98. Of the green chemistry technologies surveyed, biochemical fuel cells and green plastics were the two areas that have shown the most growth. Other areas were past their peak: notably totally chlorine free pulp and paper technology and biodegradable packaging. For TCF technology the peak was in the early 1990s while the trend for biodegradable packaging has been less obvious, with a peak at 1992 and in 2002. The trends in selected white biotechnology are interesting in that this is a key area for green chemistry and it is hoped that many future green technologies will emerge from this area. Although this area has increased, it has not increased more than the general chemistry or all-sector indicator.

99. Some tentative conclusions have been drawn on the role of public policy in inducing innovation in selected areas. In some cases, like TCF pulping, it appears that public pressures on the market led to changes in technology before regulations took effect. In other cases, for example biodegradable packaging in Germany, the effect of policy on innovation is less ambiguous. There are, however, some more 'qualitative' conclusions that can be drawn from the review of country experience.

How to support efficient partnerships between industry, government and academia

100. It has been noted, that there is an increasing role of public inventors, particularly universities, in green technologies. The other major trend in assignees is an increasing proportion of inventors from China. Policymakers who seek to support innovation in green chemistry should be aware of this change in the patenting landscape.

101. For instance, there are a number of models that policy-makers can look to in developing programs that support efficient partnerships between industry, academia and government. One example is the Design for the Environment (DfE) program at the US EPA. This program brings together industry, academia and government to assess alternatives to particular chemicals, has instituted a labelling program, and has defined and disseminated best practices for chemical use in particular sectors. Work at DfE has included flame retardants, cleaning products, car-care, de-icers and odour removal. DfE is popular with industry, which is able to take advantage of the program's expertise with LCA, alternatives analysis, and other evaluation tools. They benefit

from both the label, as well as from the development of best practices that protect their own employees as well as their customers.

102. Another partnership model can be found in Oregon, at the Oregon Nanoscience and Microtechnologies Institute (ONAMI). ONAMI is a network of academic, industrial, and government research institutes, working to develop and commercialize key nano and micro technologies[33]. Members of ONAMI have access to shared technical resources, and work together on interdisciplinary projects that would be difficult for any individual member to complete on their own.

103. In China, governments at the provincial and municipal level are providing incentives for green chemistry R&D Centres by providing matching funds to academic institutions that are able to secure funding from an industrial partner. Government at these levels is also acting as a matchmaker, disseminating requests for proposals (RFP's) to academic researchers around the country. These RFP's are usually focused on key green chemistry challenges faced by local industry, and are considered of strategic economic importance for a local area. By working with academics throughout the country, the government and industry have access to a broader range of expertise than might be available locally.

104. These are all just examples of different successful partnership models. What they all have in common is that they are focused more on key technology platforms or areas that are attractive to a number of firms and academics. In these partnerships, there are benefits for all of the parties. The combination of partners has several advantages- it helps industry coordinate with academia on areas of research that are important, but whose pre-competitive nature makes it difficult and inefficient to perform within a single firm. It also provides a route for academic R&D to become commercialized. And effectiveness is also aided by the ability of government to act as a convenor or matchmaker to bring together more interdisciplinary groups.

How to avoid "moral hazard"

105. From a policy standpoint, it would be desirable to avoid funding projects industry would undertake, even in the absence of government support (the problem of "moral hazard"). However, government support, if provided intelligently, can either speed along existing R&D efforts, or make new initiatives more attractive. One strategy is to fund areas in which companies tend to under-invest. There are many developments in green chemistry that are considered to be pre-competitive research, but which would benefit many firms. In the case of the pharmaceutical industry, the members of the ACS- GCI Pharmaceutical Roundtable have contributed to a series of yearly grants on particular green chemistry challenges that are common to all of the members. This has included specific transformations or reactions, but could also be powerful in areas such as solvent systems, catalysis, and alternative reaction conditions which have a broad impact- and thus very little incentive for any one firm to develop on their own.

[33] http://www.onami.us/about/

106. Another strategy is to develop a more detailed picture of where green chemistry technologies have the greatest barriers in moving from laboratory to full commercialization. There are certain steps in the process that can be particularly risky- such as moving into pilot scale, or building (or changing over) large production facilities based on a new, largely unproven technology. In biotech and pharmaceuticals, these problem areas have been addressed in some cases by partnerships between smaller innovators, who conduct novel research, with larger pharmaceutical companies who have the financial capital and other resources required for clinical trials, production and marketing.

107. Policies could be used to help remove some risks/uncertainties in order to encourage firms to invest themselves. For small and medium sized companies, that could involve providing expertise and assistance, or helping to create partnership with larger firms at key stages in the commercialization process. Some examples of incentives include access to less expensive capital, in the form of rotating capital funds or low-interest loans linked to specific projects that require applications, business plans, and demonstration of how government investment would make otherwise unfeasible projects possible. Other potentially useful policies include beneficial regulatory timelines and more tax credits for particular R&D on green chemistry in order to stimulate firms to invest. It is probably impossible to prevent some firms who would have invested in the absence of policy from benefiting. However, even these firms are providing some level of public benefit through their actions, so some government support for their actions is not completely unjustified.

How to “pick winners” (or avoid picking losers)

108. Governments are not always best qualified to “pick winners” when it comes to the development of new technologies. Rather than just focusing on one or two particular “hot” areas, policy-makers can take different approaches. One is to come from the problem-centred perspective. Policy-makers can identify key chemicals of concern for which alternatives do not exist. This is the approach being considered in the latest draft of the Safer Chemicals Act of 2010 in the US, and is also to some extent the method employed by the California Green Chemistry Initiative. In this case, the advantage is that the problem is already identified, and there is less uncertainty about a market for green chemistry products. If the government funds a variety of projects in a particular area, at least some of them will be successes, although some funding will inevitably go to less successful innovations.

109. Another approach is to fund key pre-competitive areas of basic research (see above), such as important transformations or solvent systems. Once again, for any given project, it is hard to anticipate success. But certain areas are of a high level of industrial importance, and government funding can help direct academic efforts into these areas. Furthermore, it encourages the development of more basic scientific knowledge and understanding, which is important in the long-run when new and difficult challenges requiring alternatives arise.

110. In terms of the individual projects which are supported, the best strategy is most likely to be one in which the government adopts a portfolio approach. The government usually funds a number of projects in any particular area, with the expectation that the combination of markets

and the science will render some successful and others not. The goal for policy-makers should be that overall their investment is yielding progress in key areas.

How to give innovators long (and clear) enough policy horizon to make the necessary risky investments

111. Innovators do not like regulatory uncertainty. It makes what are already technically challenging and uncertain projects subject to yet another kind of risk. Several things can be done to give innovators a long and clear enough policy horizon to make risky, but important investments. The first is to have a comprehensive chemicals policy. Situations in the United States, where different states are legislating regulations on a chemical-by-chemical basis increase the level of risk and uncertainty, and make it hard to anticipate what markets will be in the longer term for particular green chemistry technologies. While the US' Toxic Substances Control Act (TSCA) has been criticized on many aspects, firms appreciated its predictability, and the ability to interact with regulators relatively early in the regulatory process for new chemicals. The expectations were generally clear. While REACH and proposed TSCA reform will mean large changes in the chemical regulation process, once they have been fully implemented, firms will know what to expect, and will better be able to invest in the long-term.

112. The other policy that helps firm invest is to have incentives that are also stable. Small Business Innovation Research (SBIR) grants in the US frequently do this by having smaller, initial grants. These can be followed, if firms are able to demonstrate success in the first round, by larger grants in the second round. The sum total is a long enough time frame for firms to make investment decisions, while still allowing the government an "out" for projects that are not performing. Additionally, wherever possible, incentive programs, such as tax credits, should be available for multiple year periods, to prevent some of the problems in the US with wind energy subsidies, whose tenuousness hurt the willingness of investors to put their funds into wind projects.

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