



Holding a Candle to Innovation in Concentrating Solar Power Technologies

A Study Drawing on Patent Data

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JEL Classification codes: O31; Q42; Q54; Q55

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Abstract —

Improved understanding of the innovative pathways of renewable energy technologies is vital if we are to make the transition to a low carbon economy. This study presents new evidence on innovation and industry dynamics in concentrating solar power (CSP) technologies. Though CSP is undergoing a renaissance, innovation studies so far have explored innovative activity in solar technologies in general, ignoring the major differences between solar photovoltaic and CSP technologies. This study, based on patent data, examines the level and dynamics of innovative activity in CSP between 1978 to 2004. Our unique contribution, based on engineering expertise and detailed datawork, is a classification system mapping CSP technologies to the International Patent Classification (IPC) system. The innovation performance of CSP is found to be surprisingly weak compared to the patent boom in other green technologies. Performance was strong around 1980 before falling dramatically, and has only recently begun to show signs of increased activity. Innovation and R&D are concentrated in high-tech countries; the US, Germany and Japan, which do not necessarily have high domestic CSP potential. Large CSP potential is therefore not a sufficient condition for innovation, and only developed countries such as Australia with both CSP potential and adequate economic and scientific capabilities are found to be among the group of relevant innovators.

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1 Introduction

Concentrating solar power (CSP) technologies are undergoing a renaissance. In the 1980s many successful projects proved CSP to be a set of clean, reliable and economically promising technologies for power generation, but they have subsequently been outshone by other renewable energy (RE) technologies. However, it is increasingly apparent that CSP is again regarded as a technology set that can make a major contribution to a low-carbon and secure power system. Its potential is huge – scenarios predict a share between 12% (IEA, 2009b) and 25% of global electricity needs by 2050 (Greenpeace, 2009). Estimates of the size of the project pipeline vary, but one suggests that 980 MW are under construction and projects of a total of 7,500 MW have been announced (Greenpeace, 2009). One project, the DESERTEC Industrial Initiative is particularly prominent and attracting high level support: initiated in 2009 by industry stakeholders, it envisions a sustainable electricity supply for the EU and the Middle East and North African (MENA) region based largely on harnessing solar power through the installation of CSP technologies in desert areas (DESERTEC Foundation, 2009).⁵ The sheer volume of industry activity around CSP in these and other projects is striking, but academic research on technological progress in CSP technologies has failed to keep pace. The primary objective of this study is to fill this research gap by assessing for the first time the dynamics and geographic distribution of innovative activity in CSP. A secondary objective is to examine the actual outcome of the innovative behaviour that we describe (CSP installations) and the firms that populate the industry that supplies the technology.

Empirical research can provide important insights on the characteristics of innovation in RE technologies and on how to enhance technological progress; this is the first empirical study to focus on innovative activity in CSP technologies. Accurate evaluation of individual technologies requires a precise technological definition, particularly if such evaluation is to inform the design of technology specific policy instruments. Unfortunately existing research on solar energy technologies fails to differentiate between technologies such as solar photovoltaics (PV), heating or CSP (Glachant et al., 2009; Johnstone et al., 2010; OECD, 2009a), which means that it “blurs” the innovation trends of any of these technologies. The unique contribution of this study which is based on engineering expertise and detailed data work, is the development of a classification system that enabled us to precisely define CSP and map it to the International Patent Classification (IPC) system.

⁵The DESERTEC Foundation originally launched this vision which was later complemented by the DESERTEC Industrial Initiative. For recent work related to these projects see Komendantova et al. (2010) or Williges et al. (2010).

Filtering out non-CSP innovation in this way allowed us to overcome the shortcomings of prior work in the field, and to generate a more accurate picture of the temporal and geographical dimensions of innovation in CSP.

Patent data are a well established metric of innovative activity in the general innovation literature, and are increasingly used as a measure of innovation in “green” technologies (Braun et al., 2010; Johnstone et al., 2010) since they exhibit distinct advantages over alternative measures such as R&D personnel (Griliches, 1990; OECD, 2009a).⁶ A patent legally defines an invention as truly novel, a status which is assured by the responsible patent office. Patent documentation is rich with detail such as technical classification and documentation which can be exploited for techno-economic analysis such as this study.

For a precise technology definition, we draw on engineering expertise and a careful assessment of the features of CSP technologies, and develop two schemes which map the technologies to the patent classification: one based on a narrow definition of CSP focusing on solar heat, and the other on a broader definition which encompasses the development of components that are crucial to CSP (e.g. high-temperature heat exchange, boilers). Classifying patents in this way allowed us to construct a unique dataset on CSP which contains the number of annual patent applications filed at both the European patent office (EPO) and the United States (US) patent office (USPTO) over the years 1978 to 2004.⁷

Our paper relates to recent work on the empirical foundations of technological change in energy technologies (for an overview, see Popp et al., 2010). Some of these contributions have also considered CSP, but few make an explicit distinction between the latter and PV technologies. One strand of research studies the link between environmental policy and the direction and level of technological change, often using patent data. Lanjouw and Mody (1996) were the first to apply patent data to the issue, identifying environmentally benign technology patents and finding a positive link between environmental regulation and innovative activity. Recently, Johnstone et al. (2010) investigate the influence of policies promoting renewable energy such as green certificates schemes on patent activity. Feed-in tariffs were found to be particularly strong drivers of innovation in solar technologies, but the approach adopted does not distinguish between solar PV and solar thermal technologies. Experience curves are another analytical tool used to infer the influence of R&D and particularly capacity expansion, on the costs of a technology (CSP is covered by e.g., Neij, 2008; Jamasb, 2007). A third focus is the diffusion of new technologies

⁶Patent data are a strong indicator for innovation, but they are not exhaustive. We will return to this issue in Section 3.1.

⁷We will briefly elaborate on the patenting activity at the Japanese Patent Office (JPO) in the Appendix.

over time and across regions or countries (for an application with patent data refer to Dechezleprêtre et al., 2009).

We begin with an overview of the evolution of the technology in Section 2. Section 3 describes the dataset and derivation of classification scheme for CSP technologies. Subsequently we discuss the public R&D support background against which these innovations have occurred (Section 4). Based on the methodological work of Section 3 and the R&D background laid out before in Section 4, Section 5 will discuss our findings on patenting activity. Section 6 will discuss dynamics and characteristics of the CSP industry. In the final Section we draw together these strands and conclude.

2 Technology overview

Solar thermal systems are based on the physical principle of energy conversion from short-wave solar radiation into heat, also described as photo-thermal conversion. Although solar thermal systems work on a common principle, the technical designs and materials required vary significantly depending on the required process parameters for different applications, i.e. the temperature and pressure of the working medium. Room and water heating in residential solar thermal systems is a common application for low-temperature solar heat utilization. These systems are in most cases based on non-concentrating solar thermal technologies, i.e. they do not amplify the direct solar irradiation by collecting and focusing the solar radiation in a focal point or line, and show a solar concentration ratio $CR=1$, which describes the ratio of the optically active collector to the absorber area exposed to solar radiation. In recent years the production of process heat, water desalination, and power generation have become important applications, or at least show a high potential for solar thermal energy conversion. These processes require high temperatures and therefore technologies must incorporate devices which concentrate the sunlight's direct normal irradiance (DNI) in a focal point or line ($CR>1$). Apart from water desalination, the highest potential for the future of CSP technologies lies in electric power generation. Estimated global cumulative installed CSP capacity is shown in Figure 1.

CSP systems exhibit a wide range of technical designs which differ with respect to a range of characteristics; the underlying thermodynamic cycle (e.g. Clausius-Rankine-, Stirling-, Brayton-cycle), applied heat transfer media (oil, steam, air, other gases), its working temperatures and working pressures, heat storage technologies (e.g. molten salt, phase change materials, concrete, ceramic, pressurized gases) among others. The

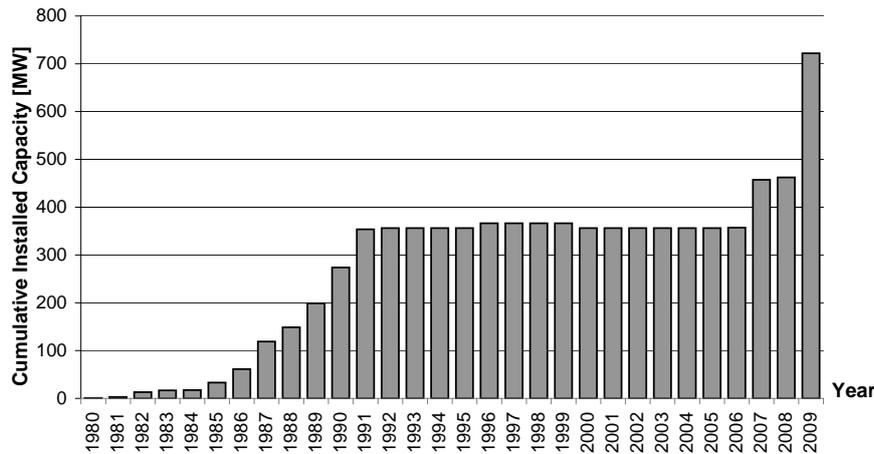


Figure 1: Global cumulative installed capacity, CSP. *Sources:* Earth Policy Institute EPI (2008) EPI (2008), Greenpeace (2009), company reports

major CSP technologies are studied in this paper; (1) Parabolic Trough Systems, (2) Linear Fresnel Reflectors, (3) Solar Towers with a central receiver, and (4) Parabolic Dish/Engine Systems. Figure 2 gives a diagrammatic representation of the technologies, which are described in turn:

- Parabolic trough systems: shaped as semicircular mirrors which reflect the sunlight along a focal line on a tube. The receiver tube contains a heat transfer fluid (normally thermal oil) that absorbs the 70-100 times concentrated sunlight. The heat transfer fluid produces steam in a heat exchanger at a temperature of almost 400° Celsius which drives a turbine-generator unit for electricity generation. The underlying thermodynamic cycle is a Rankine cycle, which is similar to conventional thermal power plants. Parabolic trough systems dominate the global market for CSP plants with more than 95% share in the estimated 560 MW of operating CSP plants in mid-2009 (Greenpeace, 2009).
- Linear Fresnel reflectors: similar to trough systems being a line-focus technology that reflects the solar radiation from fixed ground mounted mirrors onto a receiver pipeline carrying a heat transfer medium. Current designs use water directly in the receiver tubes at pressures up to 50 bar and temperatures of 280°Celsius or molten salt fluids (DOE, 2008). Its relatively lower optical and thermal performance compared to parabolic trough systems is compensated for by reduced investment, and operational and maintenance costs. This technology promises further cost savings through the use of less expensive reflector materials and absorber components

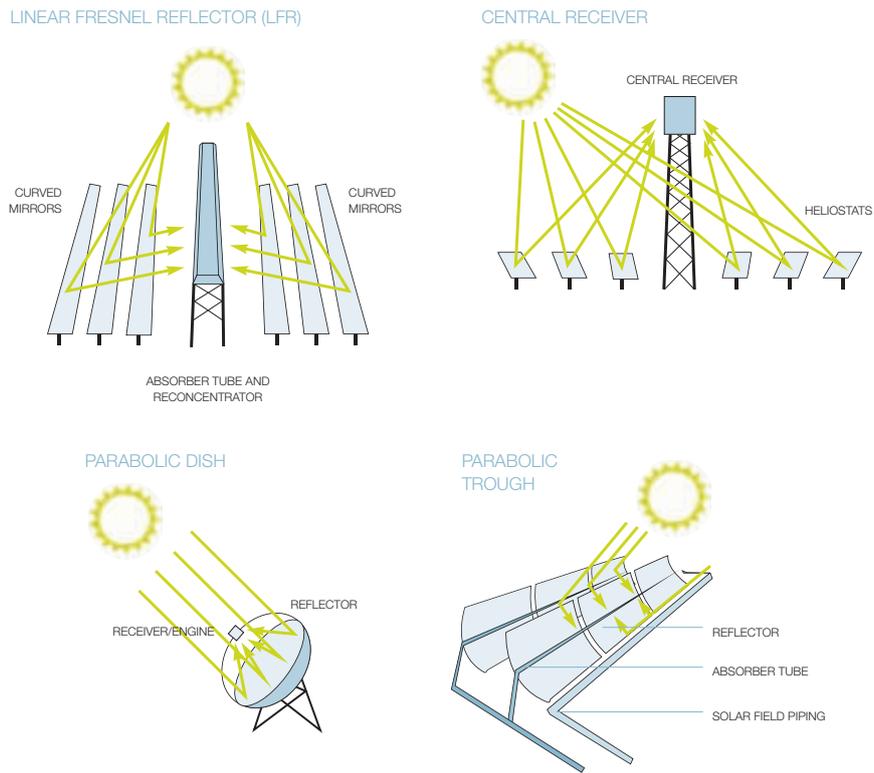


Figure 2: Diagram of CSP technologies

than parabolic mirror systems. Linear Fresnel collectors are still in the demonstration phase, with two operating plants and a total capacity of 6.4 MW in mid-2009 (Greenpeace, 2009) though there are several proposed commercial projects.

- Solar power towers work at the highest process temperatures among CSP technologies (700° Celsius and higher temperatures are possible). A field of biaxial tracking mirrors (heliostats) reflects sunlight at $CR= 600\dots1000$ onto a receiver at the top of a centrally located tower. Common receiver materials consist of porous ceramics, which are streamed by air (as a heat transfer medium) to produce steam and run a turbine-generator unit for electricity generation. For large plant sizes this technology has potentially lower generation costs than line-focus collectors due to its higher steam parameters (pressure, temperature) and thus greater thermodynamic efficiency.⁸ This becomes particularly important for dry cooling applications which operate under high ambient temperatures and water scarcity in arid regions. By comparison with parabolic trough or linear Fresnel systems, the higher working

⁸The maximum efficiency of a thermodynamic cycle is determined by the Carnot efficiency factor. It depends on the temperature difference between the heat source and heat sink in a thermodynamic cycle.

temperature of tower systems means that their performance will be less diminished by the increased condenser temperatures associated with dry cooling. Solar tower concepts offer good heat storage characteristics for dispatchable power generation. In mid-2009, 32.5 MW of solar tower capacity was in operation.⁹ At the same time, ca. 3 GW of capacity were proposed or under construction (Greenpeace, 2009).

- Parabolic dish concepts use individual dishes on two axes that track the sun, each dish focusing the sunlight onto a gas turbine or external combustion engine (Stirling engine) at between CR= 1,500...4000 (Kaltschmitt et al., 2007). The turbine or engine generates electricity via a generator. In contrast to the systems considered above, parabolic dish technologies do not require steam as the turbine/engine is driven by heated air. Because of the high sunlight concentration and the associated high working temperatures they compare favorably in terms of efficiency, converting more than 30% of the solar energy into electricity. A single dish-engine unit's capacity ranges from 1 to 25 kW, and its modularity allows for scaling up capacity. Being determined by demonstration projects the operating capacity was less than 1 MW in mid-2009. In addition, further 1.7 GW of capacity has been proposed (Greenpeace, 2009).

In addition to CSP technologies further designs for (non-concentrating) solar thermal electricity generation exist. The solar updraft tower or solar chimney, passively heats air in a greenhouse which then passes through a chimney where it drives turbines which are again connected to an electric generator. We have briefly discussed solar towers for the sake of completeness, but since they are a non-concentrating solar thermal technology (Viebahn et al., 2008) they fall outside the scope of this study.

Since all solar thermal technologies rely on sunlight which is inherently variable as a resource, they are unavailable if the sun is not shining. This dependence on the sun and the variability of irradiation combined with the impossibility of storing electricity on a large scale and at economically viable cost, means that the so-called intermittency problem affects CSP technologies. However a strength of CSP technologies over other RE technologies that rely on intermittent resources is that this drawback can be overcome by heat storage. Heat storage systems are one of the major research fields in CSP and an important driver that is expected to reduce electricity generation costs. Parabolic trough, solar tower, and linear Fresnel systems can be equipped with heat storage, either

⁹Previously two projects in the Mojave Desert (Solar One and Solar Two Power Tower demonstration projects) were in operation, but were dismantled after the demonstration period.

directly (water/steam) or indirectly (e.g. by molten salt, phase-changing media, solid heat storage materials). Among the CSP technologies, parabolic dish/engine-systems face difficulties with cost-effective heat-storage systems for design reasons. However, current research areas comprise materials as well as engineering sciences for medium and high temperature heat storage systems (e.g., Salomoni et al., 2008; Gil et al., 2009; Felderhoff and Bogdanovic, 2009)

3 Patents as indicator of innovation in CSP

Innovation in so called green or climate change mitigating technologies is receiving increasing attention both in economic research (Glachant et al., 2009; Braun et al., 2010; Johnstone et al., 2010) and in the policy debate (European Patent Office (EPO), 2010), yet methodological issues and questions around the appropriate way to measure these innovations remain. The most frequently used measure of the outcome of innovative activity are patent data, which have the key strength that they allow the mapping of technology domains, which makes them particularly suited for our technology-specific study. In the following subsection we introduce general issues related to the use of patent data and in the next, describe how the relevant CSP technologies can be mapped within the patent data.

3.1 Patent data

Patent documents are informationally rich: they convey information on inventors and owners, technical descriptions of the invention, its technological classification, the timing of the invention and protection coverage, all of which can be exploited for our research purposes. Patents are based on a common legal framework and are therefore comparable across countries and time. Patent-based data as statistical indicators of innovation have provoked strong interest by researchers (Schmookler, 1950), and have been used as a measure of the dynamics of technological change in countries, regions, institutions (such as universities), sectors and firms.

Patents are very closely linked to novelty and invention, i.e. a product or process that is new, involves an inventive step and can be used for industrial application (OECD, 2009b). A patent is a (temporary) legal title protecting an invention by granting its owner the exclusive rights over the use or sale of the underlying product or process. The patent system therefore enables the appropriation of the gains from the invention which

is itself the incentive to invest in research in the first place. In addition, patents require the disclosure of the underlying discovery, which spurs the dissemination of knowledge.

Patent documents are published eighteen months after application no matter when the patent for the underlying invention is granted. In the present analysis, we use data on patent applications (not patents granted) to infer recent innovative activity. The duration of the granting procedure itself may vary remarkably within and between patent offices and may therefore bias the analysis, hence studies on innovation dynamics usually focus on patent applications.

Besides the numerous advantages (e.g. novelty, availability), patent data also suffer from a number of drawbacks and raise issues that should be kept in mind when interpreting results (Griliches, 1990). First, the distribution of the value of patents is highly skewed to the right since only a few inventions have a significant economic value. Second, not all inventions are patented and some firms might prefer a secrecy strategy to prevent imitation. These features of patent data render them an imperfect but nevertheless very useful and widely applied measure of innovative activity.

Data on patent applications in solar thermal technologies was sourced from the European Patent Office’s Worldwide Patent Statistical dataset (PATSTAT), which contains all applications made at national (e.g. United States Patent and Trademark Office (USPTO)) and transnational patent authorities (e.g. European Patent Office (EPO)). Our principal focus is on applications to the EPO, since an application to a transnational authority can be taken as a signal that the patentee believes the invention to be of sufficiently high value to justify the additional expense of an international application, by contrast to one made to a national authority such as the German patent office.¹⁰ Since it is interesting to investigate whether innovation dynamics at the national level mirror worldwide trends, we augment our analysis of patenting in the transnational domain by turning to the national level, more specifically the largest domestic market covered by our sample: the US. This helps to put our EPO European focused results into context. Furthermore, as Section 5 reveals, the US is one of the most important players in CSP, so it is enlightening to assess their contribution to worldwide innovation dynamics.

All patent applications filed with the EPO and the USPTO and having a priority date between 1978 and 2004 were included in the dataset. The priority date is the date at

¹⁰A problem potentially arising in this context is home bias which can emerge for non-European countries: inventors in the United States or Asia may tend to seek initial patent protection in their home market and then second internationally. However, inventions that are valuable from an economic point of view and for which the market is thought to be international, will usually also be protected in the transnational domain.

which the underlying invention was covered by a patent for the first time. It could be the case that an invention was first applied for at a national authority not covered in our dataset, but afterwards international protection was sought, e.g. by filing at the EPO; this would be known as a second stage filing. Patent applications were dated from the date of the initial application to the national patent office, which represents the date closest to the date of the actual invention, and which is the only meaningful option from an economic point of view (de Rassenfosse and van Pottelsberghe de la Potterie, 2007). Our analysis of patenting activity was conducted in two steps: first, we compared innovation dynamics in CSP with the overall trend in patenting behavior by simply comparing the number of applications made in each year. Second, we proceeded to the country level by assigning applications to the inventor’s home country. We identified countries that were global players in this field, and whether their relative importance changed over time.¹¹

3.2 Patent search strategy and classification

Patents related to CSP technologies were extracted from the technical classification provided by the initial patent document, which is expressed in terms of symbols of the IPC. In contrast to commodity classifications or sector definitions used in official statistics, the IPC is inherently technological; more than 70,000 separate classification codes exist which allows for a very precise identification of technologies. The IPC is a hierarchical system which codifies the subject of a patent. An example is given in Table 1: for example the IPC F24J 2/07 refers to: (F) mechanical engineering, lighting etc.; (F24) heating, ranges, ventilating; (F24J) production or use of heat not otherwise provided for; (F24J2) use of solar heat, e.g., solar heat collectors; (F24J 2/07) Solar heat collectors having receivers working at high temperature, e.g., for solar power plants.

A step-wise search strategy was adopted, in accordance with OECD (2009a) who use a detailed patent identification procedure for environmentally sound technology innovations. First, the technological options were correctly identified through a review of the standard literature and publications from internationally recognized research institutions, associations and CSP equipment manufacturers (World Resources Institute (2009); Viebahn et al. (2008); EC (2007); DLR, 2005). As a result of this exercise, we identified CSP components for each technology. For example, the parabolic trough systems include

¹¹As patent applications usually contain more than one inventor with possibly also different home countries, we calculate our country-level patent counts in such a way that an application counts for every home country listed in the initial patent document.

Table 1: Example of an IPC code associated with CSP

Level	Symbol	Description
Section	F	Mechanical engineering, lighting, heating, weapons, blasting
Class	F24	Heating, ranges, ventilating
Subclass	F24J	Production or use of heat not otherwise provided for
Main group	F24J 2	Use of solar heat, e.g. solar heat collectors
Sub group	F24J 2/06	Solar heat collectors having concentrating elements
	F24J 2/07	Solar heat collectors having receivers working at high temperature, e.g. for solar power plants

optical devices (collectors), receivers (heat absorbing components), enclosure technologies for receivers, mounting systems, heat transfer fluids, and heat storage devices. A similar analysis was conducted for each of the CSP technologies discussed in Section 2. In addition to this systematic view, we analyzed process technologies and materials used in solar thermal component production to define the scope of the patent data. In a second step we comprehensively reviewed the IPC scheme and identified the relevant patent classes for CSP.¹² Third, cross-checking this initial set of IPCs with the components identified in step one, results in a refined patent classification. To validate this IPC set in a fourth step, we used the EPO’s world patent search engine¹³ as an additional tool to determine relevant IPCs by keyword search in patent names and abstracts, using logical operators. Figure 3 shows this multi-step selection process.

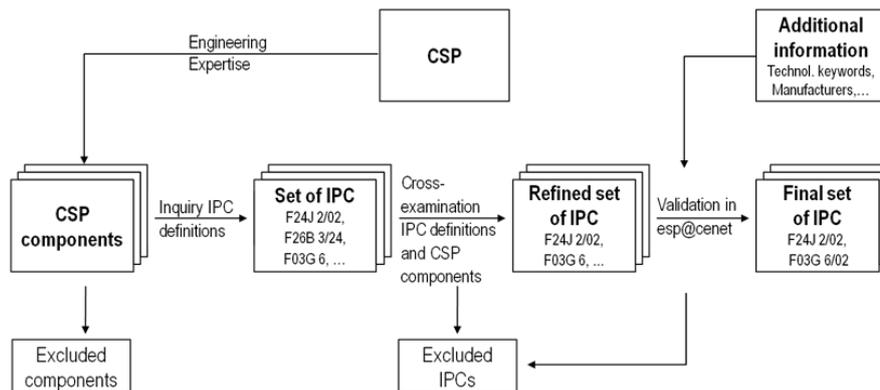


Figure 3: Scheme to identify international patent classes (IPC) associated with CSP

Such a search strategy might suffer from two potential types of error: on the one hand, irrelevant patents might be included, or on the other hand, relevant patents might

¹²www.wipo.int/classifications/ipc/ipc8/?lang=en

¹³esp@cenet.com/index.en.htm

be left unidentified. Either error would bias our results. While leaving out relevant patent classes leads to lower total patent counts, this seems less dramatic than the inclusion of irrelevant classes, since it can be assumed that the identified patents represent the majority of innovation activities and therefore serve as a good proxy (OECD, 2009a). To avoid the first error (i.e. the inclusion of irrelevant patents), we use the esp@cenet dataset to cross-check the identified classes on their relevance for CSP by analyzing abstracts for a sample of patents and using logical conjunction of IPC classes and relevant keywords (logical AND operator for IPC class and keywords). If too few patents matched these combinations, these classes were left out (Lanjouw and Mody, 1996). To give an example, this procedure led us to exclude the IPC F26B 3/28 (“Drying solid materials or objects by processes involving the application of heat by radiation, e.g. from the sun”). The class was excluded because less than 10% of the abstracts or patent titles for this class contain relevant keywords (e.g. “solar”, “sun”, “visible light”). An additional analysis of a sample of patent abstracts in this class indicated that the majority was not related to CSP.

This multi-stage process resulted in a set of IPC classes for innovative components in CSP shown in Table 4 in the Appendix. The design of CSP thermal plants and fossil fuel thermal power plants often differs only marginally, the main difference being the primary heat source, and different designs can be found in combination, e.g. as “integrated solar combined cycle” (ISCC) concepts. Many of the recently installed CSP plants employ this concept, where CSP generation is backed-up by gas turbines. Thus, heat exchangers, boilers, pipes, turbines, cooling tower designs, pumps, and other components are to a great extent similar for both technologies. Innovations in CSP plants (e.g. cooling concepts for power production in arid regions) also affect fossil fuel power plant design, and “vice versa” overall efficiency increase in thermal power plant development will ultimately improve the efficiency of CSP. This issue is addressed by the development of two separate classification schemes: the narrow classification captures CSP-specific patents (bold print, see Table 4). These patent classes refer to applications in solar heat. A second enlarged set (comprising all IPC classes according to Table 4) additionally includes components which are crucial for CSP development (e.g. high-temperature heat exchangers, boilers), but also relates to other technologies as multi-purpose applications.

We have argued above that imprecision with respect to the definition of the specific technology has led to bias in existing analysis of patents. Our analysis is therefore restricted to CSP-relevant thermodynamic and mechanical components and unspecific (e.g. mechanic-electric converters) or irrelevant (e.g. flue gas filtration) technologies are excluded from our analysis. Sound reasoning suggests the necessity to discriminate

between technologies, and engineering expertise has allowed us to define both a narrow and a wide classification.

4 Public R&D support for CSP

Public support for research and development (R&D) has been crucial to the development of CSP, as it has been with other RE technologies such as wind and solar PV. The rationale for public support is that the externalities, in particular environmental and climate change repercussions, associated with energy supply are significant and the public benefit from reducing them is greater than the private benefit from doing so. At the same time the creation of any new knowledge is also characterized by externalities. As emphasized in the innovation literature, new ideas and technologies have public good characteristics and are therefore under-provided by the market (the so called appropriability problem (e.g., Arrow, 1962)). Innovation in environmentally benign energy technologies is therefore afflicted simultaneously by these two issues, and government action such as R&D support or strategic deployment may therefore be warranted as means of “correcting” for these research and environmental externalities.

Historically, energy research has been conducted by the private sector, with the exceptions of nuclear power and basic research. Rising fuel prices and concerns about security of supply and import dependence in the 1970s transformed energy R&D, particularly on alternative energy, into a matter of public interest. Public R&D on RE technologies in International Energy Agency (IEA) countries rose rapidly from a share of less than 3% of total energy R&D spending in 1975 to over 9% by 1978. For the period 1974 to 2008, it reached a peak of 14% in 1981 (IEA, 2009a).

The evidence suggests a strong similarity in the patterns of public R&D funding for CSP across countries. For the countries leading in terms of their absolute volume devoted to CSP, we find that CSP R&D was the highest in both absolute and relative terms in the early 1980s and that the support has been quite volatile over time (Figures 4 and 5). The US were in a striking lead position up to 1980, with a maximum support of 344 million US dollars allocated to CSP or 23% of all funds for renewable R&D in the US in 1980. Support declined sharply after 1980 due to the lower priority given to federal (alternative) energy research by the Reagan administration in the face of lower energy prices and a requirement for fiscal consolidation. The decline of CSP support after the early 1980s was

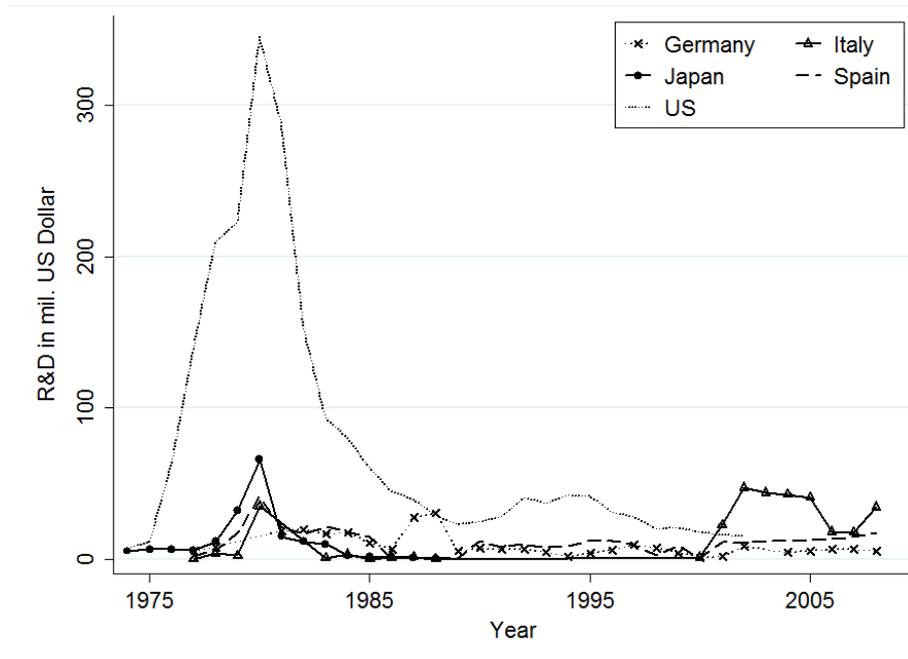


Figure 4: Annual public R&D expenditure for CSP by country, 1974-2008. *Note:* All values in 2008 PPP US \$. Data from IEA (2009a).

mirrored across countries and technologies¹⁴: Japan and Germany, the other major high tech countries, also followed this pattern, but granted support much more moderately in any case. Japan phased out CSP funding in 1988 and concentrated its ambitions on PV technology (DOE, 2005)¹⁵. Interestingly, Italy and Spain are strongly committed to CSP, particularly after 1997, the year of the Kyoto protocol; neither are typically among the group of highly innovative OECD countries.

A second measure of the commitment to developing CSP is the ratio of public R&D support for CSP to support for the other solar technologies, PV and solar heating and cooling. Figure 5 shows that the relative importance of CSP versus other solar public research funding fluctuates remarkably, but overall describes a downward trend for most countries. Since 2000 however, interest has revived; this may be attributed to the increased focus on stabilizing greenhouse gas (GHG) emissions after the Kyoto protocol. Storage systems like those operating with molten salt, and materials research are also still in an early phase and require further research efforts.

In 1980 CSP and solar PV received approximately the same level of R&D support in

¹⁴Lanjouw and Mody (1996) also describe this phenomenon and suggest spillovers from the US phase-out of public RE R&D funding to other OECD countries as an explanation.

¹⁵A second Asian country, South Korea, started only at the year 2000.

the US (about 300 million dollars each) but subsequently a wide gap opened up. Japan initiated R&D support for several alternative technologies with its Sunshine Project (1974), and originally gave CSP priority over solar PV, but as the figure shows, around 1980 the priorities were reversed, and by the mid 1980s CSP support ceased. The European countries most active in supporting CSP in terms of volume of (public) R&D are Germany, Italy and Spain. Germany gives CSP a much lower priority than the others, but its support efforts are characterized by greater stability, which may be important given the sensitivity of investments in R&D to uncertainty (e.g., Neuhoff et al., 2007). Italy and Spain show larger variation over time, with a strong upward movement around the time that the Kyoto protocol was signed. Spain and particularly Italy's R&D funding display a large variance over time but exhibit nonetheless remarkably high commitment to developing CSP technologies.

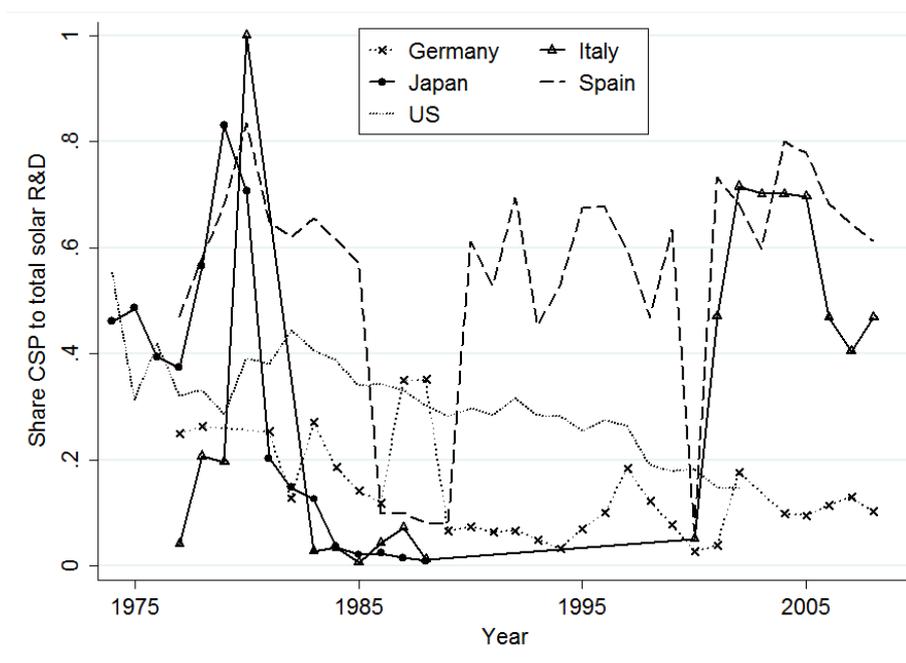


Figure 5: Share of public CSP R&D to public R&D expenditure for all solar technologies by country, 1974-2008. *Note:* All values in 2008 PPP US \$. Data from IEA (2009a).

5 Innovation activity in CSP technologies

We consider three aspects of innovative activity in CSP technologies. First, worldwide innovation dynamics are inferred by investigating the evolution of patent application

counts in CSP compared to the trends in overall patenting behavior.¹⁶ Second, we examine patent application counts at the country level, a common approach in the literature (e.g., Glachant et al., 2009; Johnstone et al., 2010), to refine our analysis with a view on the leading-inventor countries in this specific technology. The analysis first relies on data on the international patenting activity at the EPO (Section 5.1). The focus then turns to the US as a large (CSP) home market and uses USPTO patent applications to this end (Section 5.2).

5.1 Innovation activity at the EPO – an international perspective

5.1.1 Global trends at the EPO

It is well established that the number of patents in general has been growing strongly over time. The trend can be attributed to various factors like ease of access to patent databases, globalization of business and research activities. Figure 6 shows the evolution of total patent applications in all technologies as a benchmark to compare total CSP patent application according to the narrow and broad definition over time. To account for the substantial difference in volume of patents we normalized each time series to unity in 1978, the first year where data are available.

The total innovation activity in *all* technologies, i.e. the benchmark, clearly shows an upward trend over time. In the early years the CSP technologies displayed a dynamic similar to that of this benchmark. At the beginning of the 1980s, however, CSP patent applications (narrow definition) experienced a striking downward trend, followed by a trough lasting until 2000 and a subsequent slight increase in patenting activity. The CSP technologies have underperformed compared to the overall patenting activity at the EPO: in 1978 they accounted for 0.54% of all patents and in 2004 for just 0.06%.¹⁷ Different from what we find for CSP, innovation in other RE technologies such as wind or PV follows a dynamic growth path and has even accelerated its growth since the end of the 1990s (see e.g., Braun et al., 2010; European Patent Office (EPO), 2010; Johnstone et al., 2010; Glachant et al., 2009). A different picture emerges when considering the CSP technologies defined broadly, i.e. technologies which are important elements of CSP, but

¹⁶The countries covered are abbreviated as follows: AU Australia, AT Austria, CH Switzerland, DE Germany, FR France, GB United Kingdom, IL Israel, IT Italy, JP Japan, KR South Korea, NL Netherlands, SE Sweden, TW Taiwan, US United States.

¹⁷To put this into perspective, note that green technologies account for roughly 2.5% of all patents (Lanjouw and Mody, 1996).

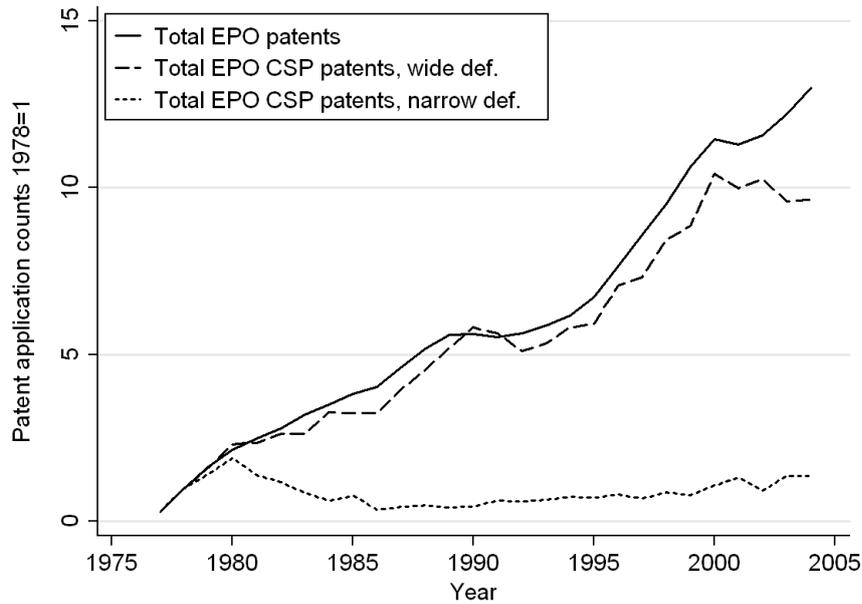


Figure 6: Comparison total to CSP patent applications at the EPO, 1978–2004

are not exclusive to CSP. Hence there is still active knowledge creation and technological advances that are critical to CSP (though it has trended slightly downwards since 2000). Here, patenting activity tracks the path of the benchmark, but falls slightly since 2000.

These technologies may in some cases not apply uniquely to CSP, however, as described in Section 3.2 they are easily adapted for CSP and are therefore constituent elements of CSP technologies. Such CSP technologies which are captured by the broad definition can be also thought also serve as a strongly related knowledge pool and the basis for CSP development. The role of such strongly related technology fields in inducing innovation is non-negligible as Braun et al. (2010) show. These findings not only moderate the “pessimistic” picture found for the narrow definition and give a somewhat more optimistic outlook for the innovation performance of CSP, but also point to the importance of defining technologies appropriately when using patent data. Existing studies (e.g., Johnstone et al. (2010)) have neglected to motivate their choice of technologies and identification of IPC in an explicit manner and moreover failed to provide a range of possible patent classes for sensitivity analysis.

5.1.2 Innovation activity according to the narrow definition of CSP

The innovation pattern of the narrowly defined CSP technologies is striking, particularly when considering the sizable capacity expansions that are planned (for details refer to Section 6.1). Technological progress as depicted by patent applications is very weak. However, this reflects the evolution of public R&D support as shown in Figure 4. Research activity was highest prior to the 1980s and was apparently effective in inducing CSP innovation output. Similarly as R&D deteriorated after 1980 patenting activity declined. One might hypothesise the reason for the low level of innovation activity in CSP technologies to be due to the fact that it is rather a mature technology. The technology components are in some but not all cases, scientifically well understood. The application of well-established components for a new purpose i.e. using solar radiation to generate power is novel and constitutes an innovation in an emerging technology. However, a mature technology is generally regarded as one with a record of widespread use over a long period. The installed capacity of CSP is still rather low (around 700 MW, see Table 2) so the maturity argument might therefore be insufficiently strong to explain the strikingly low patenting activity.

Next we consider how trends have evolved at the country level (Figures 7 to 10). Geographic dispersion of technology development as depicted here by patent counts, can illuminate the role of different energy policy regimes, market demand or natural potential in promoting innovation. Germany is the leading innovator in CSP technologies (narrow definition, Figure 7) – the mean number of patents filed with the EPO is around 18. Particularly active patenting was concentrated into two time periods; around 1980 and then again from 1995 onwards. Though Germany supports CSP research and has set up demonstration plants, it is not a relevant market for applying CSP technology due to unfavorable resource potential. The second highest number of patents was recorded by the US, but with a mean of around 8, activity is at a different order of magnitude. Note that these are US patents filed abroad i.e. at the EPO; apparently the US considers Europe to be a promising market for their newly developed technologies. Evidenced by volumes of public R&D funding, the US was very supportive of CSP at the beginning of the 1980s and we found evidence of intensive patenting. However R&D support was cut dramatically in 1981, after which we observe a decline in patenting. Hence the US appear not to have built up a sufficiently large knowledge base in CSP during the years of intensive R&D support to allow them to exploit their position in later years (the so called “Standing on shoulders of giants effect”).

In third place, closely behind the US, is Japan, and only France and Switzerland among the European countries show significant CSP innovation output. Japan’s innovation performance is nonetheless interesting as, in contrast to the US, Japan phased out its public CSP R&D and only few solar power plants have ever been built (for instance 1 MW plant in Nio). All these leading innovators show high innovation activity at the early 1980s and a moderate innovative activity afterwards, except Germany and France where patenting activity gained momentum after 2000.

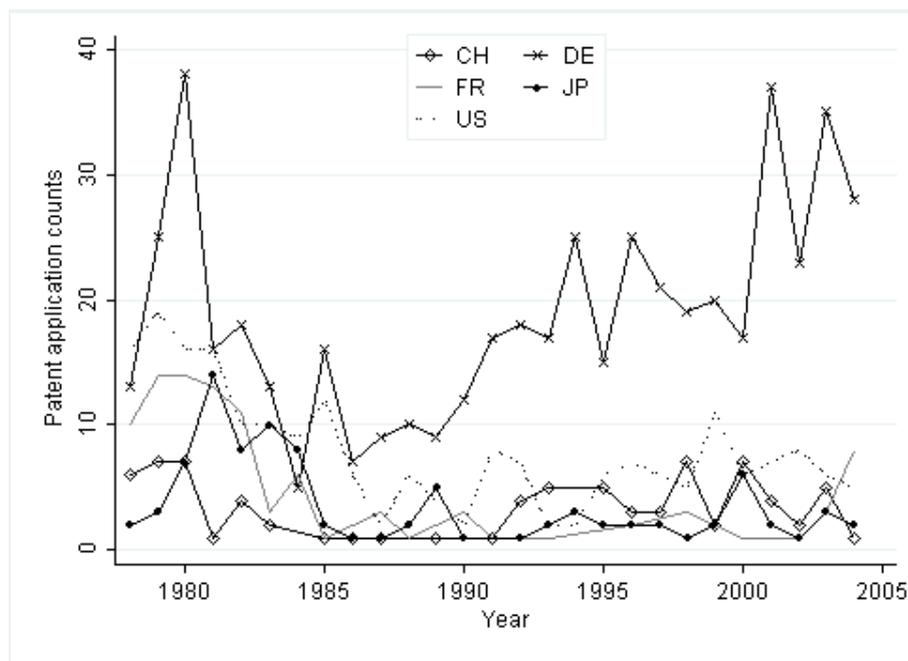


Figure 7: EPO patent applications by major countries, 1978–2004. CSP technologies, narrow definition

Additional country level details are presented in Figure 8. Patent filings in general tend to be concentrated in a few countries; the US, Japan and Germany accounted for 60% of the total patent filings in *all* technologies for 2004. CSP technology development is also concentrated in traditional high-tech countries. The five leading countries by patent application counts, Germany, US, Japan, France and Switzerland, account for a substantial share of the total innovation activity which has, however, declined over time (1978: 74.6%, 2004: 45.8%). Except for the US, these leading countries have rather limited potential for the deployment of solar power plants. Japan and the US have a particularly impressive performance, considering that they obviously seek active protection at the EPO i.e. outside their home countries. Their patents are often secondary filings. As patent applications are costly, investors would only seek protection if they are interested

in entering these markets. Over time the composition of innovators has become more heterogeneous: Great Britain, Australia, Israel and Italy join the group of important innovators, whereas Japan and Switzerland loose share towards the end of the sample period.

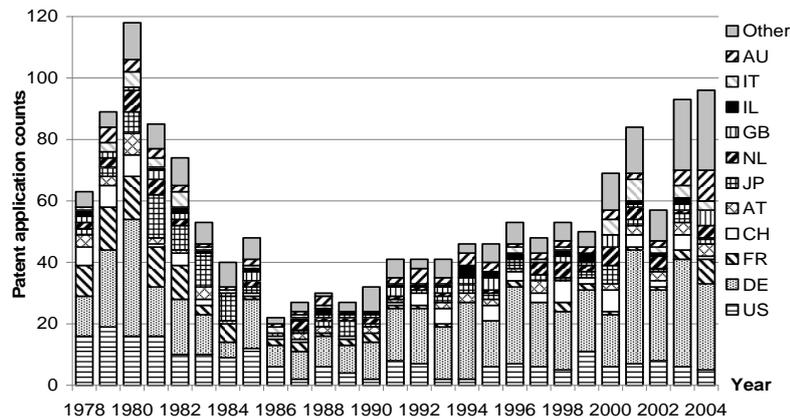


Figure 8: Total CSP EPO patent applications by countries of origin, 1978–2004. Narrow definition of CSP

Australia, Israel and Italy are potentially large markets for CSP applications and already have capacity installed. Their strong innovative activity provides some evidence for a demand side impetus on innovation – having natural potential may be conducive to stimulate innovation. Comparing Spain and Italy is interesting in this regard – both are potentially large markets for CSP and indeed Spain in particular has been referred to as the “epicentre of CSP development” (Emerging Energy Research, 2009). Within Europe, Spain currently offers the most generous CSP subsidies. Starting with the Royal Decree 841 from 2002, Spain has increased the feed-in tariff granted to solar thermal power generation from 0.12 Euros per kWh to 0.269 Euros in 2007 (Royal Decree 661).¹⁸ Spain and Italy are usually considered to be among the less innovative Western European countries. In spite of these common characteristics, and Spain’s higher installed capacity and project pipeline, Italy has a far higher level of patenting activity than Spain. In fact Spain’s patent filings at the EPO were too low to be adequately shown in the graphs. As presented in Section 4, Italy has devoted substantial funds on CSP technol-

¹⁸Importantly an explicit CSP target was set at 500MW in Spain by 2010. However, a review of the support programme is currently underway, and substantial downward revision of the level of support could be expected to pose a significant threat to the 1 GW of planned capacity in the project pipeline (Emerging Energy Research, 2009).

ogy development which appears to have been successful in inducing innovation, although variability in funding over time has resulted in a relatively unstable innovation path with high levels of activity in the early and very late phase. Natural potential alone may not be sufficient to “generate” CSP innovation, as also the absence of activity by the MENA countries shows, but in addition adequate technological, scientific and research capability are critical to high levels of innovation performance.¹⁹

5.1.3 Innovation activity according to the broad definition of CSP

Patenting activity in the broadly defined CSP technologies (Figure 9) is substantially higher than for the narrow definition, which is not surprising since it covers a wider set of IPC classes. The US were in the leading position over most time periods in contrast to what we found for CSP narrowly defined. Particularly strong were the 1980s and the 1990s, though at the end of the 1990s we observe a decline in US patenting. Patent filings from Japan decreased from the end of the 1990s as in the US case. In contrast to Japan or the US, as with the narrow case, Germany managed to accelerate its innovative activity, and indeed by 2002 the number of filings from Germany exceeded the number filed by inventors from the US.

A pronounced increase in patenting activity since 2000 was also found by Glachant et al. (2009) who argue that the 1997 Kyoto Protocol has been vital for spurring the innovation performance in climate change mitigating technologies of the main inventor countries, except for the U.S and Australia.²⁰

The time path of innovative activity for CSP according to the broad definition is different from the case of narrowly defined CSP technologies; it is characterized by more or less steady growth from the 1980s with particularly active times in the early 1990s and 2000s. Within the field of broadly defined CSP technologies, the US, Germany and Japan are again among the leading innovators, collectively accounting for 64% of CSP patent applications in 1978 and even 71% in 2004 (Figure 10).

The middle field with European countries such as France, Great Britain and Switzer-

¹⁹More recently, emerging economies are beginning to implement subsidy schemes, for example South Africa announced a feed-in tariff scheme offering about 0.175 Euros per kWh for concentrating solar power, and MENA countries such as Algeria and Israel are following their lead.

²⁰This finding covers all climate change mitigating technologies, but in the case of solar innovations the study rather finds a decline. Note however, that it relies on a much broader categorization of solar technologies – including power generation (solar PV, solar thermal power) and heating applications (solar heating and cooling, and drying) – and comprises over 44 patent offices. This underpins the importance of being precise about which technologies is being referred to in discussion of technological change dynamics in climate mitigating technologies.

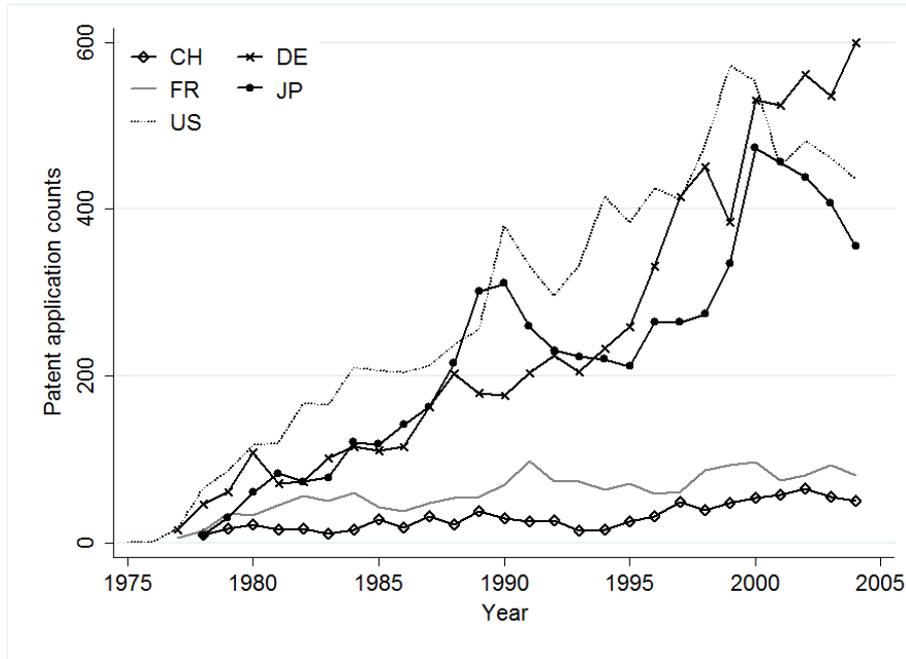


Figure 9: EPO patent applications by major countries, 1978–2004. CSP technologies, broad definition

land is remarkably stable, but considering their smaller size, not surprisingly at a much lower level. Residual patenting activity is dispersed over more than 40 countries.²¹ As shown by Figures 8 and 10, the leading innovative countries are typically highly innovative OECD countries often with limited natural potential for the use of CSP technologies themselves. These countries must take leadership in fostering technology diffusion and dispersion of CSP technologies which is vital for the regions with the best resource potential (Africa, west coast of Southern America, India), but which lack knowledge and expertise. Facilitating technology transfer and knowledge exchange between the technology developing and the adopting countries is therefore a priority, and it has also been addressed by transnational initiatives such as SolarPACES.

²¹South Korea is one of few emerging countries showing some innovation recently, but the overall role of emerging economies is still small in contrast to Glachant et al. (2009) who find China, South Korea and Russia to be strong new entrants accounting for up to 15% of patent filings in climate mitigating technologies.

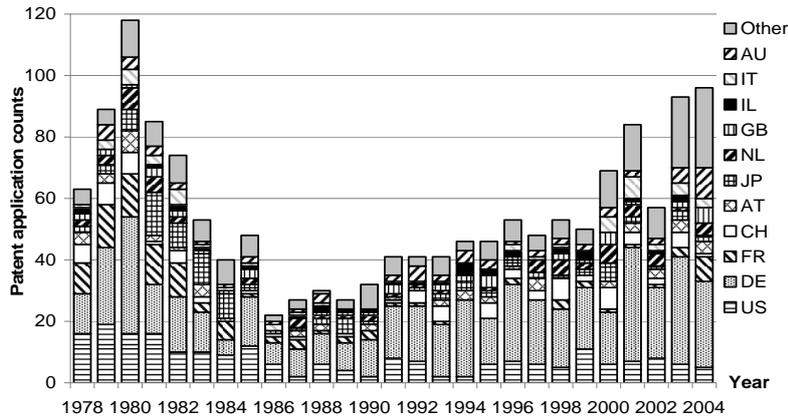


Figure 10: Total CSP EPO patent applications by countries of origin, 1978–2004. Broad definition of CSP.

5.2 Innovation Activity at the USPTO – a glance at a dynamic home market

5.2.1 Global trends at the USPTO

The US has a substantial solar resource and thus a large domestic market. We now proceed to the country level analysis of the USPTO data as a complement to the earlier analysis on international patenting trends based on the EPO data. Patent application activity at the USPTO in *all* technologies follows a highly dynamic path (Figure 11). Total patenting increased strongly from 1978 until 2002, then experienced a decline in 2003 and 2004. Trends in patenting in CSP as defined by the narrow definition, first decline, then remain approximately stable before increasing slightly around 2000 – similar to the EPO case (Section 5.1). Since the early 1980s, the narrowly defined CSP technologies did not recapture their former momentum and such low levels of knowledge creation make it hard to maintain a knowledge base.

This lack of momentum was reflected in the degree to which the capacity diffused within the US – the most intensive capacity expansion occurred prior to 2000. Public policy had an important role to play – the cornerstone of the Federal support scheme was the investment incentives scheme. The cornerstone of the Federal support scheme was the investment incentives scheme. The 1978 Energy Tax Act introduced residential tax credits and importantly for CSP, business tax credits of 10% for investments in RE sources

(Moore, 1996).²² In addition to Federal action, many states launched their own initiatives and California was an early leader in this context by granting tax credits of up to 55%. The tax credits gave the adoption of CSP and solar power plants real impetus; indeed most CPS and early solar plants were installed in California. However, the instrument was poorly designed since it was renewed on an annual basis so failed to address the need for policy certainty that underlies investment in RE technologies. In 1992, the Californian government delayed the decision over the extension of its credit tax. The major actor in the CSP business, LUZ, went bankrupt (Martinot et al., 2005) and installation of new CSP systems across the US ground to a halt. The prevailing attitude towards RE technologies in the US then remained low until the 1990s and it was again the states that launched several initiatives, among them Renewable Portfolio Standards (RPS), tax cuts and other financial incentives. These policy instruments have stimulated new installations of solar power plants in Nevada and California and have thus contributed to a renaissance of CSP.

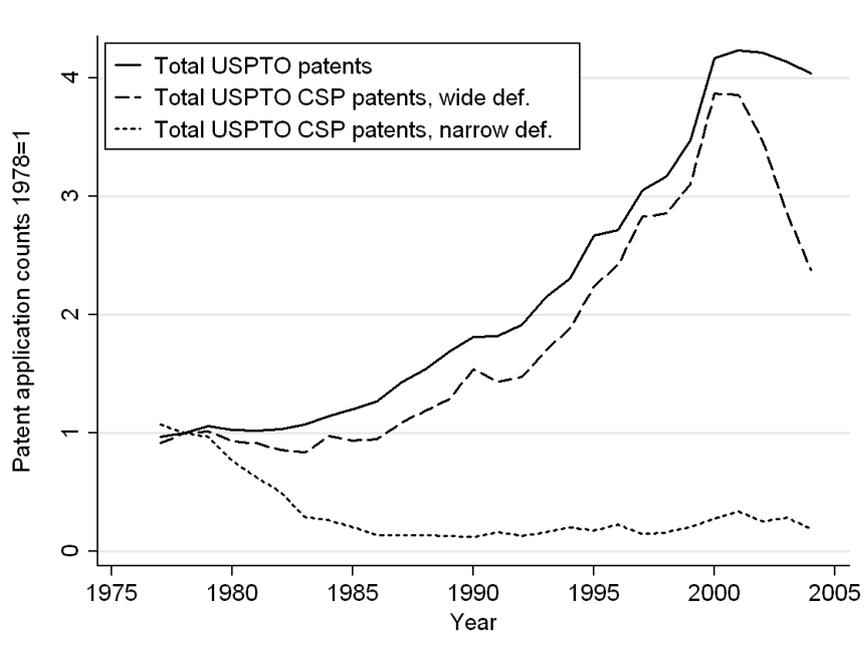


Figure 11: Comparison total to CSP patent applications at the USPTO, 1978–2004

Innovation in CSP technologies in the broad sense displayed similar tendencies to trends in overall patenting activity up to 2000. Subsequently, there was a sharp decline in patent filings at the USPTO which was much more pronounced than the more moderate

²²The Electricity Production Tax Credit (PTC) introduced in 1994 and amended several times since grants RE technologies such as wind, a tax credit of 1.2 cent per kWh or the option of a Business Energy Investment Tax Credit (ITC). However, solar electricity projects such as CSP are eligible only for ITC. The credit equals 30% of expenditures and no maximum applies (DSIRE, 2010).

decline observed at the EPO. Possible explanations for the differences between the US and Europe might be the increased interest and particularly R&D support schemes or feed-in tariffs eligible to CSP in Europe after 2000. This might partly explain the moderated effect observed with the EPO.

5.2.2 Innovation activity according to the narrow definition of CSP

We now proceed to the country level analysis of the USPTO data. CSP patent counts at the USPTO are considerably higher than those of the EPO (Figures 12 and 13). Performance was very strong before 1985 before falling dramatically, and has only recently begun to show signs of increased activity.

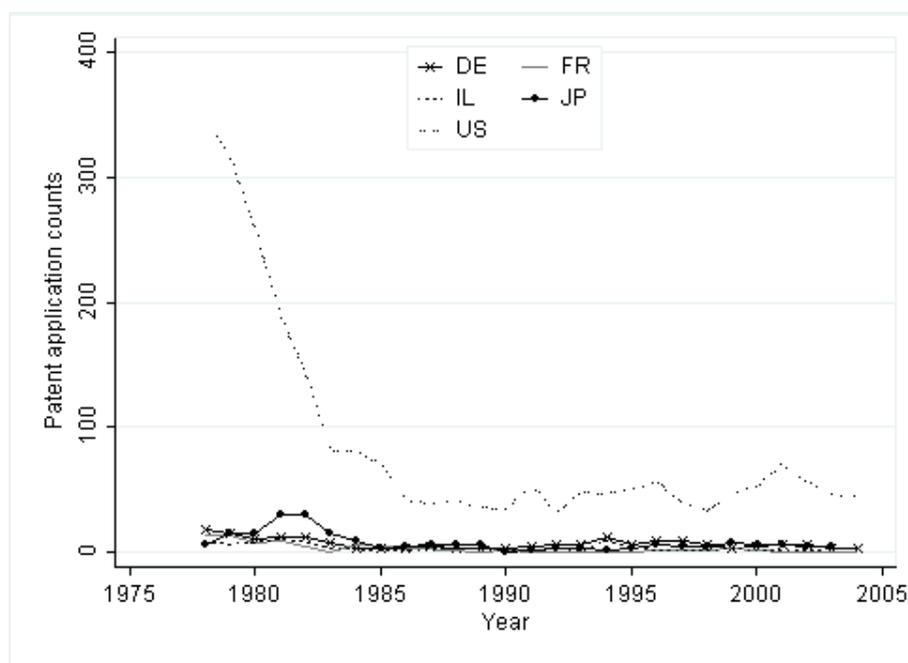


Figure 12: USPTO patent applications by major countries, 1978–2004. CSP technologies, narrow definition

The US, Germany and Japan are again the leading actors in this technological domain (Figure 13, narrow definition). The US, not surprisingly, are dominant with their home patent office (“home bias”) and account for the majority of all CSP patent applications in all years (1978; 80% and 2004; 70%). In the early years Germany ranked second and France third, but France lost significance over time. Japan on the other hand is gaining influence and has overtaken France. We observe Israel to be among the leading innovators and to even have a stronger performance than with the EPO.

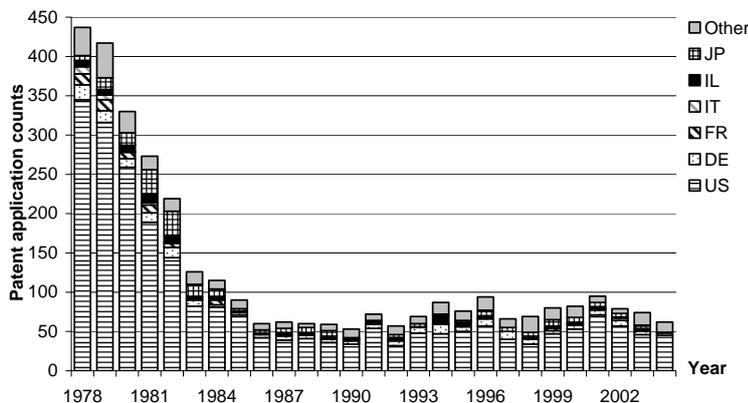


Figure 13: Total CSP patent applications by country of origin at the USPTO, 1978–2004. CSP technologies, narrow definition

5.2.3 Innovation activity according to the broad definition of CSP

The set of main inventor countries resembles the EPO case and is again highly concentrated among OECD countries. As expected, the US is the main inventor at their home patent office with a share of 60% of the CSP patents according to the broad definition in 2004 (see Figure 15). The second most important inventor was Japan (2004: 18%) and Germany (2004: 5%) followed some distance behind. Great Britain and France again rank in the middle tier of inventor countries at the USPTO. This ranking of innovative countries is quite stable in both the USPTO and EPO data. In recent times a few emerging countries have entered as innovators, for instance South Korea and Taiwan. Their performance measured at the USPTO is more remarkable than observed at the EPO. The share of Korea at the USPTO is 5% compared to 2% at the EPO in 2004, while Taiwan accounts for roughly half as many patents as Korea.

Though in absolute terms the USPTO display higher innovative activity in CSP technologies (narrow and broad definition), the innovation activity or dynamics in CSP technologies itself is only moderate. Compared to the EPO, the innovation dynamics at the USPTO were high in the early 1980s when CSP demonstration plants raised hopes for a significant US CSP market, but afterwards activity plummeted. Though there were some signs of recovery after 1997 (also seen at the EPO) it was of a temporary nature and the surge lost its drive again in the last two years of our sample. The latter phenomenon was not found at the EPO. Both the US (at least on state level) and Europe implemented

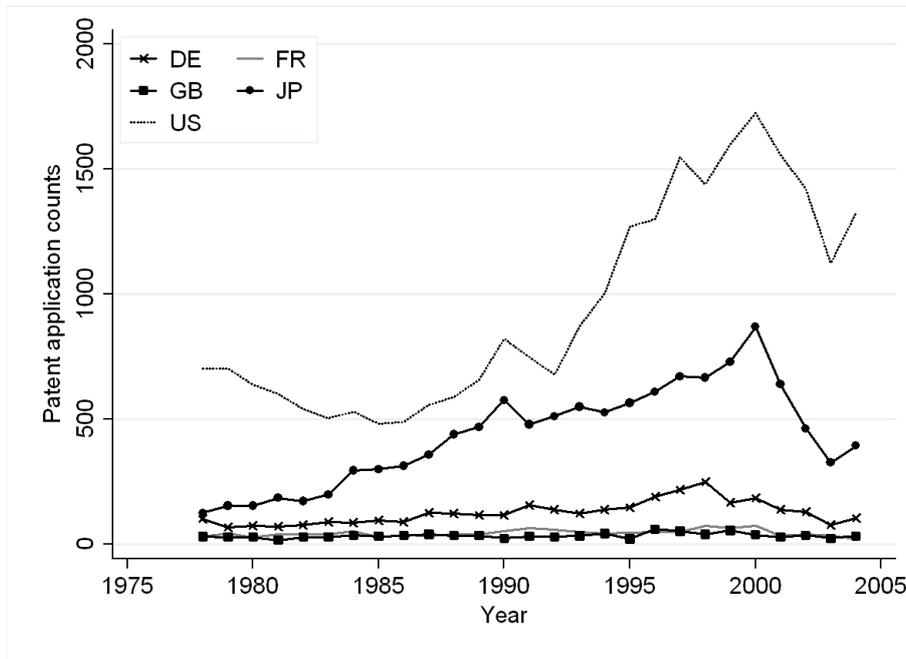


Figure 14: USPTO patent applications by major countries, 1978–2004. CSP technologies, broad definition

new support schemes to foster capacity expansion in CSP and many new CSP projects are being planned.²³ Yet patenting at the EPO conveys a more dynamic and optimistic picture in recent years than the USPTO case. One explanation for this difference might be R&D support – some European countries like Italy have increased funding for CSP research, unfortunately quantitative information on US R&D support is not reported.

This and previous chapters have taken a technology-driven and methodological perspective on innovation in CSP, introducing the technologies of interest, explaining how patent data can be used to map CSP into precise technology classifications, and finally to track the dynamics and composition of CSP innovation. Innovation processes and performance are influenced by a diverse set of interdependent factors.

²³At the time of writing, more than 20 US states have implemented a version of the RPS which differ in terms of eligible technologies, targets etc., but almost all include CSP applications (EPA, 2009; DSIRE, 2010). Several southern European countries including France, Portugal and Greece, eventually introduced feed-in tariffs for CSP (for details see Solar PACES, 2009).

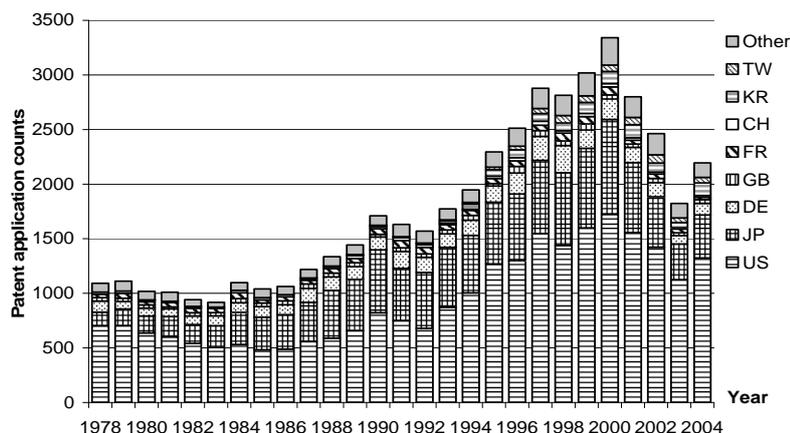


Figure 15: Total CSP patent applications by country of origin at the USPTO, 1978–2004. CSP technologies, broad definition

6 The dimensions of the supplying industry

In this section the unit of analysis shifts from the region or country, to the firm. The technology portfolio realised tomorrow is a direct consequence of decisions to invest in both innovation and capacity taken in previous periods. Despite the role for public policy and support discussed above, it is firms that *both* develop new technologies and adopt new technologies. We briefly rehearse the principal arguments regarding incentives to innovate in order to provide some context for our findings, then set the scene by means of a discussion of patterns of installed capacity, before going on to consider the industrial structure in which firms that conduct CSP R&D operate.

The incentive to innovate can be broadly defined as the ratio of the profit a firm would make if it invests in innovative activity (usually R&D) to the profit that it would make if it did not (Gilbert, 2006). That industrial structure has important impacts on the incentive to innovate is not in dispute, however, consensus on which type of market structure provides the greater incentive to innovate remains elusive in spite of considerable volume of academic research. Initiated by Schumpeter (1934) who took the view that large firms offer a more stable environment that is conducive to innovation, the debate was enjoined by Arrow (1962) who considered resource allocation under the uncertainty implied by Schumpeter’s position and showed that the incentive to innovate is always greater under competition than under monopoly except in the case where appropriability is greater under monopoly than competition. The volume of the theoretical literature is vast, yet no

commonly accepted general theory of innovation and competition has emerged. However some empirical regularities are becoming apparent; there is some evidence that above an industry specific threshold, R&D is generally proportionate to the size of the business unit, though there is little empirical support for Schumpeter's notion that the stability of monopoly promotes innovation. Similarly, the notion that competition and innovation are invariably positively correlated is not supported either, which somewhat diminishes the validity of Arrow's argument.²⁴

However, one prediction following Arrow's work that has attracted empirical support (e.g., Jamasb, 2007) is the idea that expanding the market leads to learning and cost reductions and improvements in the product, which in turn underlie the notion of strategic deployment. That is to say, the use of policy instruments for example subsidies, to expand the size of the market and hence reduce costs and improve product performance through learning by doing. However the role of uncertainty remains critical to the level of investment in innovation. In the context of green technologies, Neuhoff et al. (2007) show that anticipated (but not unanticipated) growth in the size of the market accelerated innovation in solar PV.

The CSP industry supplies clean technology solutions to a sector (power generation) in which aggregate investment decisions (which technology to install) have the potential to materially alter the global emissions profile. So given the interdependencies that exist between industry structure, competitive pressure and innovation, tracking changes in the structure of the industry relative to the initial condition may be instructive with respect to policy formation, particularly since our understanding of innovation in clean technologies is so poor.

6.1 Installed CSP capacity

Two key facts can be drawn from Table 2 which details current installed capacity of CSP. First it shows that 51% of the 722 MW of operational capacity (mid 2010) was installed in the USA, with the bulk of the remainder in Spain. Both countries have a high solar resource, but as we discussed above, Spain has very low levels of innovation in CSP combined with a policy regime that is strongly supportive of CSP technologies, while the US has a high but variable level of innovative activity and historically a patchy record on support policies. Second, it is clear that the parabolic trough is the clear winner in terms of capacity installed so far. It will be interesting to observe whether or not they maintain

²⁴For an excellent survey, see Gilbert (2006).

this lead, as might be expected (Aghion et al., 2009).

In terms of the size of the CSP project pipeline, in Spain alone there around 5 GW planned and around 8 GW in in the USA (Emerging Energy Research, 2009), almost 5 GW of which are scheduled to be installed in California (California Energy Commission, 2010). This active pipeline is very likely to be strongly associated with resource availability; it is rational for firms to invest in technologies that maximize their expected profit. But if resource availability is the primary driver, we would expect to observe significant pipelines in other resource rich countries, such as Italy and the MENA countries. The link with policy certainty seems crucial. As discussed above, both the level and duration of support under the Spanish regime deliver a level of certainty to investors that gives the confidence in expected revenue or projects that outweigh the expected risks. A review of the level of support delivered under the mechanism is underway, and it will be interesting to observe the impact of any reduction in subsidy on realised projects. With respect to the US, CSP plants are operational in those states with both high resource, and with Renewable Portfolio Standards (RPS) and other policies regarded as successful (Wiser et al., 2005).

Table 2: Operational CSP plants in 2009

Project name	Location	Capacity (MW)	Technology
USA			
Maricopa Solar	Peoria, AZ	1.5	Dish Sterling
APS Saguaro	Saguaro, AZ	1	Parabolic Trough
Kimberlina	Bakersfield, CA	5	Fresnel Reflector
SEGS I & II	Daggett, CA	44	Parabolic Trough
SEGS III & IV	Kramer Junction, CA	310	Parabolic Trough
Sierra Sun Tower	Lancaster, CA	5	Solar Power Tower
Keahole Solar Power	Hawaii	1	Parabolic Trough
Total USA:		367.5	
Rest of the World			
Liddell Power Station	New South Wales, Australia	2	Fresnel Reflector
Themis Solar Tower	Pyrénées-Orientales, France	1.5	Solar Power Tower
Jülich Solar Tower	Jülich, Germany	1.5	Solar Power Tower
Shiraz Solar Power	Shiraz, Iran	0.25	Parabolic Trough
Yazd ISCC	Yardz, Iran	17	Parabolic Trough
Alvarado 1	Badajoz, Spain	50	Parabolic Trough
Andasol	Grenada, Spain	100	Parabolic Trough
Extresol 1	Badajoz, Spain	50	Parabolic Trough
Puertollano	Puertollano Ciudad Real, Spain	50	Parabolic Trough
PS10 Solar Tower	Seville, Spain	11	Solar Power Tower
PS20 Solar Tower	Seville, Spain	20	Solar Power Tower
Puerto Errado 1	Murcia, Spain	1.4	Fresnel Reflector
Solnova	Seville, Spain	50	Parabolic Trough
Total ROW:		354.65	
Total operational capacity		722.15	

Sources:

Emerging Energy Research (2009), Gereffi et al. (2008), company annual reports, own calculations.

In order to gain some insight into the characteristics of the players, we first characterize

firms according to their main competencies and look at the number of stages in the value chain in which they are active. We then consider the extent to which firms concentrate only on solar thermal power, or whether their interests are more widely dispersed.

We studied the annual reports and websites of 32 firms known to be active in the sector and based on the data gathered, characterize a simplified value chain consisting of six stages (based on but not the same as the version due to Gereffi et al. (2008))²⁵. The first stage in the value chain is component manufacture, when the collector systems, steam generators etc. are developed. Next comes site selection, planning and permit issues and real estate procurement - that is, project development. Project finance is the next consideration and finally the facility is constructed. After commissioning comes operations and maintenance (O&M). An additional stage in the value chain that was identified from our research, captures firms that are active in one or more stages earlier in the value chain, but who chose to retain a share in the completed project.²⁶

Having explained the value chain, we next establish the degree of vertical integration along the value chain as represented in Table 3. In contrast to Gereffi et al. (2008) we do not include final users in our value chain on the basis that total installed capacity is still very small, and is dominated by demonstration plants, there seems to be little to say on this aspect at present. We find that one firm, Solar Millenium is active in five of the six stages in the chain and four are active in four stages, whereas 19 firms focus on only one stage, for example the production of components. So while the majority of firms are active in one stage, approximately 40% of firms are vertically integrated to some extent, and 15% of firms are active in 4 or more stages.

Table 3: Number of stages in the value chain in which firm is active

	One	Two	Three	Four	Five	Six	Total
Number of Firms	19	5	3	4	1	0	32

Sources: Company websites and reports, own calculations in late 2009

Next we consider the importance of solar thermal power technologies in the value chain of each firm. Ideally this would be measured by the proportion of total revenue (or profit) accounted for by CSP activity, however such data is not publicly available. Instead

²⁵Though we fully acknowledge that the boundaries between them are somewhat blurred.

²⁶While an argument can be made for including upstream firms that supply materials to the component suppliers, the complexity of accurately identifying firms that manufacture products falling into this category is enormous and would require the construction of a classification system along the lines of that developed for evaluating patents that was outlined above. Unfortunately the resources required to undertake this task are not at hand.

we have identified the focus of firms from examining their annual reports. For example, if the firm reports activity in solar PV, or perhaps turbines, then they were regarded as not being focussed on CSP. We found that of the 32 firms examined, 14 were indeed focused on this technology alone. This is perhaps unsurprising given the immaturity of the industry, but it will be interesting to monitor whether there is significant vertical integration such that firms that currently specialise only in solar thermal are bought by larger more generalist firms.

A third perspective is gained by looking at the number of competitors active in each stage. 22, or 68% of firms studied supply components; some are novel but others are more mature technologies, such as steam turbines and pipes. Perhaps unsurprisingly, the area in which there are fewest firms is finance. The volume of funds available for investment in RE projects by for example, specialist venture capital firms is growing rapidly, so there is probably little that can be deduced from the sample data at the time of writing. The category is included to illustrate the overlaps and in particular, we note that one of the global giants in generation technologies, GE, appears to be present only in this stage of the value chain.

6.2 Implications of the industry structure

The industry structure that emerges from this necessarily brief analysis is one in which there are many small firms which focus solely on CSP technologies, 40% of which are active in more than one stage in the value chain. The distribution of firms sizes is vast – giant global equipment suppliers Siemens and GE are active in the market but there are numerous small specialist firms too. A trend for consolidation has been observed in recent years: in 2009 Siemens bought the Israeli parabolic trough producer Solel and also a 28% stake in Archimede Solar Energy, manufacturers of receiver tubes.²⁷ Interestingly, at the time of the takeover of Solel Siemens declared their intention to become the global market leader in solar thermal. Another example of consolidation is that by 2009 MAN Ferrostaal, the global plant building firm based in Germany, had built up a 45% share in Solar Power Group which produces Fresnel collectors, and in that year also formed a joint venture with Solar Millenium in the United States.

The mergers literature suggests that the number of mergers will be higher in industries that have been subject to an exogenous technological or regulatory shock (Mitchell and Mulherin, 1996), so consolidation is perhaps to be expected. However, expected or not, it

²⁷Prior to 2009 Siemens had supplied only mature technologies (steam turbines) to this sector.

is well known that vertical integration can lead to the downstream foreclosure of rivals (Rey and Tirole, 2007). Furthermore, vertical integration has been shown to change information flows and incentives to invest in R&D (Milliou, 2004), so what this brief overview suggests is a need for vigilance and monitoring. However, it is not really clear who should be doing the monitoring, since many of the mergers will not fall under the jurisdiction of the EC but rather be dealt with on an ad-hoc basis by national competition authorities.

7 Conclusions

The development and adoption of low carbon technologies is critical if the future carbon intensity of the economy and environmental degradation are to be minimized. Climate change is simultaneously a serious threat to human welfare and, if we can kick start green growth, a real opportunity. If today's investment decisions are to result in a future technology portfolio consistent with a sustainable economy, "the green innovation machine needs to be turned on" (Aghion et al., 2009). Private sector investment and urgent direct public support must be incentivized through a mixture of sufficiently strong price signals and direct subsidies to R&D. However public endorsement of state support is contingent on the adoption of targeted, effective policies based on sound research and understanding of the innovation paths of green technologies.

The objectives of this study were two fold. First, to build up a detailed picture of patterns of innovative activity and innovation dynamics in CSP through an analysis based on patent data. Second, given the fact that decisions referred to by Aghion as the "green innovation machine" are made by firms, to provide a brief overview of the characteristics of the firms that supply CSP generation technologies and thus of the structure of the industry.

Four key results emerge from our analysis. First, measured by our narrow definition, innovation performance in CSP technologies is strikingly less dynamic than the growth path observed for other RE technologies like wind or solar PV (e.g., Braun et al. (2010); Glachant et al. (2009); Johnstone et al. (2010)). It is remarkable that the project pipeline for CSP is so healthy, in stark contrast to the low level of knowledge creation suggested by this measure of patenting activity. The early 1980s to mid 1990s appear to be a "lost decade", though there are some signs of a recent recovery with stronger innovative output since 2000 particularly at the EPO. The broad definition of innovative performance was somewhat more optimistic, and followed the average patenting trend of the econ-

omy. However the fact remains that it underperforms other RE technologies by some considerable margin.

Second, innovation leadership was found to be highly concentrated in high-tech countries; the US, Germany and Japan, despite the fact that only the US has a large market potential for CSP applications. We also observed the emergence of countries that are newly innovative in CSP; Israel became active at both the USPTO and EPO, and Australia and Italy at the EPO. These countries have active R&D support measures or abundant natural resources i.e. solar radiation, but they have clear advantages over other countries, e.g. MENA, with respect to research capacity and human capital.

What this analysis shows is that nations regarded as being innovative in general can apply this strength in the field of green technologies, though they often have limited natural potential for the use of CSP themselves. These highly innovative OECD countries must take leadership in fostering technology diffusion and dispersion of CSP technologies which is vital for the regions with the best resource potential (Africa, west coast of South America, India), but which lack knowledge and expertise. Initiatives facilitating technology transfer and knowledge exchange between countries developing the technology and adopting it is therefore a priority.

The third contribution of this study is methodological. Accurate depiction of the true state of technological advance for a given technology is crucially dependent on a precise definition of that technology. We constructed two schemes based on engineering expertise that allowed us to map CSP technologies to the IPC patent classification scheme: our narrow definition focused on solar heat, and our broad definition encompassed components also very closely related to CSP. The provision of two classification schemes highlights the need for precision when talking about innovation in green technologies, particularly given the potentially costly public funding required. This classification may stimulate further research in this field by enabling researchers to clearly identify innovation in CSP and aiding comparison with previous work.

Finally, we considered the structure of the industry supply of CSP technologies, many of whom can be expected to be conducting R&D. The overall impression is of an industry in which over 40% of firms are already active in more than one stage in the value chain and that is undergoing consolidation through merger. It was also noted that the size distribution of firms is vast, ranging from very small firms to the giants such as Siemens and GE.

Given the novelty of this study, promising issues for further research are many and var-

ied. First, we wish to extend our understanding of the dynamics in this technology field by focusing on the research behavior of equipment manufactures of CSP, ideally using patent data. Second, the picture on innovation dynamics could be clarified further by elaborating on the value of patents and thereby the value of the underlying invention. Third, policy instruments are clearly important, but the extent to which they drive innovative activity could be explored in more detail in a cross-country setting, using econometric techniques.

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9 Appendix

9.1 A1 – CSP and corresponding IPC patent classification

Table 4: CSP and corresponding IPC patent classification: broad and narrow definition

IPC section	IPC classes included in broad definition	IPC classes included in narrow definition
B Performing Operations, Transporting	B32B1/08	–
C Chemistry and Metallurgy	C09K5/00, C09K5/02, C09K5/04, C09K5/06, C09K5/10, C09K5/12, C09K5/14, C09K5/16, C23C	–
E Fixed Constructions	E04D13/18	–
F Mechanical Engineering, Lighting, Heating, Weapons, Blasting	F03G6/00, F03G6/02, F03G6/04, F03G6/06, F24J2/00–54 , F02G1/043, F15B11/00, F15B15/01, F16L9/00, F16L27/12, F24H1/00, F24H9/02, F24H9/06, F24H9/12, F24H9/14, F28D20/00, F28F9/04, F28F9/013, F28F9/06, F28F9/08, F28F9/12, F28F9/14, F28F9/16, F28F9/18, F28F9/20, F28F9/26, F28F13/18, F28F21/04, F28F21/08, F28F23/00	F03G6/00, F03G6/02, F03G6/04, F03G6/06, F24J2/00–54
G Physics	G02B27/14, G05B19/418, G05D3/20	–

Notes: IPC classes that are included both in the narrow and broad definition are set in bold face.

9.2 A2 – Innovation activity at the JPO

Normalized total patent applications at the JPO also reveal a clear upward trend, even though the increase is less drastic compared to the USPTO or the EPO. Patenting activity doubled between 1978 and 1987 and increased in total by a factor of 2.5 until 2004. Since beginning of the nineties, the total number of applications remains rather stable, a stylized fact which is in sharp contrast to the development at the EPO or USPTO.

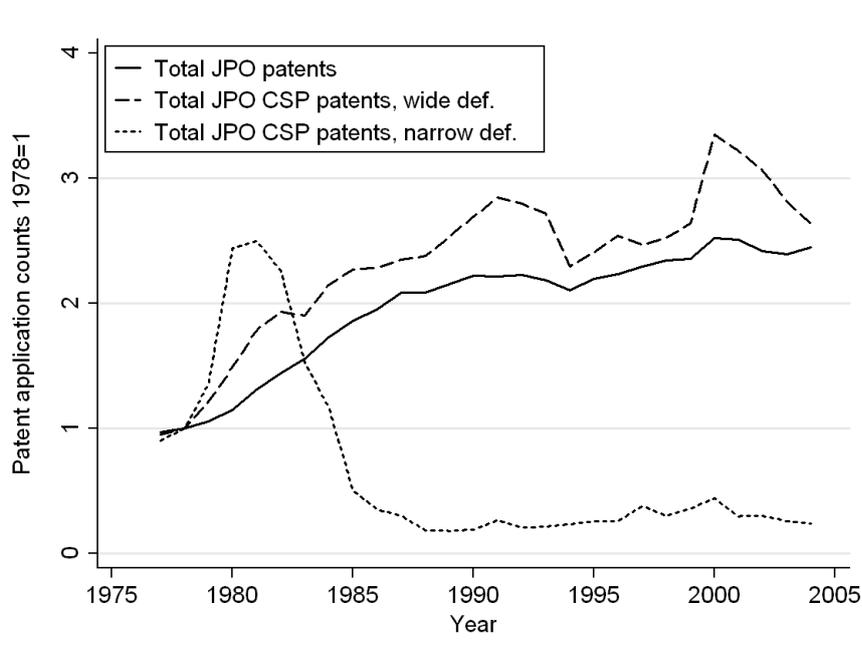


Figure 16: Comparison total to CSP patent applications at the JPO, 1978–2004

Patenting in CSP, according to our broad definition, evolves slightly more dynamic in relation to total applications, especially until the early nineties. Another peak followed rather recently in 2001. The upward trend in CSP in Japan is in line with picture drawn for the USPTO; in contrast the magnitude of growth at the EPO is substantially larger which is also caused by the fact that the beginning of our observation period is close to the founding year of the EPO. Overall, from 1978 to 2004, applications in CSP related technologies more than doubled at the JPO. In case of patenting activity measured according to our narrow definition, the dynamics mirrors the development that has taken place at the USPTO, however smaller in magnitude. We observe an early peak in CSP patents until 1982, followed by a sharp decline. From 1985 onwards, innovative activity in specific CSP technologies remains on a surprisingly negligible level. Only between 1996 and 2000, we notice a minor increase. This is an interesting finding considering that Japan decided to phase out its public R&D funding at the end of the 1990s and different from the US case.²⁸

²⁸Japan's support for RE technologies was very research (and PV) oriented (see Section 4 with few efforts devoted to the deployment of technologies until 1997, when it launched the New Energy Law

A note of caution is necessary when interpreting JPO applications: The information on inventor's country of origin is unfortunately missing in a considerable number of cases, roughly fifty percent. We are therefore forced to deviate from our initial approach and cannot proceed to the country-level analysis. Reliable information on inventor's location is only available for Japanese inventors. Only Germany and the United States are also found to patent substantially at the JPO but in a negligible share compared to their domestic activities. This might lead to the conclusion that the Japanese domestic market is of less importance for other countries but we are far from being able concluding this due to the aforementioned data problems. It will definitely be a line for future research to update and extrapolate data from the JPO to clarify the picture and to deepen our understanding.

requesting, but not formally obliging, retailers to buy renewable power. Electricity suppliers, however, voluntarily committed to fulfill this request. In 2003 a scheme came into effect that now legally mandates electricity retailers to provide a specified share of their electricity from renewable sources. Retailers can also fulfill their obligation by purchasing green certificates from other market actors. The scheme applied to all solar based generation technologies.