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Innovation in Concentrating Solar Power Technologies: A Study drawing on Patent Data

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Abstract —

Better understanding the innovative process of renewable energy technologies is important for tackling climate change. Though concentrating solar power is receiving growing interest, innovation studies so far have explored innovative activity in solar technologies in general, ignoring the major differences between solar photovoltaic and solar thermal technologies. This study relies on patent data to examine international innovative activity in concentrating solar power technologies.

Our unique contribution, based on engineering expertise and detailed datawork, is a classification system matching solar thermal technologies to the International Patent Classification (IPC) system. To this end we suggest a narrowly defined set of IPC classes and a broader one of technologies relevant to CSP, but not exclusively so. We moreover exploit information from three international patent offices, the European, the United States and the Japanese patent office.

Innovative activity in narrowly defined CSP technologies has experienced an early boom before 1980 and only recently showed some signs of more activity – a pattern closely resembling the R&D support path. R&D and innovation are concentrated in few high-tech countries - such as the U.S. or Germany. Large CSP potential is not a sufficient condition for innovation, 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.

Keywords: Innovation; Patent data; Solar technologies; Climate change

JEL: O31; Q42; Q54; Q55

1 Introduction

Tackling climate change will require significant reductions in the carbon intensity of the economy. The development of low carbon technologies and their global adoption is therefore an immediate priority. As called for recently by Aghion et al. (2009), "the green innovation machine needs to be turned on" to generate a future technology portfolio that helps mitigating climate change. Some low carbon technologies such as wind or those reyling on solar radiation have been deployed for some decades by now, but their market penetration is still hampered by high costs relative to conventional fossil fuel burning technologies. The innovation challenge spans the discovery of new energy supply technologies as well as - and possibly even more pressing - improving the performance, efficiency, and particularly lowering the costs of existing low carbon technologies.

The technology has huge potential - scenarios expect a contribution between 12% (IEA, 2009b) and up to 25% of global electricity by 2050 (Greenpeace International et al., 2009). Solar thermal power generation is perceived as a particularly promising low carbon technology - costs per kWh electricity are projected to decrease and to become competitive with conventional (mid load) power stations (e.g., IEA, 2008; DLR, 2006). It is, however, somewhat outshone by photovoltaic (PV) in public perception and (economic) research (see Section 2). This is stunning given its compelling benefits relative to those of PV. First, it has a high efficiency in solar to electric conversion and, second, large-scale application can deliver power throughout the day when used as a hybrid installation with other fuels or with storage capacity for thermal heat.

Understanding the evolution of a technology is important for the design of government policies to support technology development and adoption. It is likewise crucial for the advancement of environmental and innovation economics and serves as an input for energy-economy models and projections of future greenhouse gas emissions. This empirical study sheds light on innovative activity in solar thermal power technologies. Solar thermal technologies generate high temperature thermal energy by concentrating solar power. This heat can run a Stirling engine or produce steam to drive a turbine for electricity generation. This article is the first to focus on innovation dynamics in concentrating solar power (CSP) technologies. As a first step, it therefore contributes to the literature by developing a classification scheme to identify innovative activity by means of patent data. Using a unique worldwide patent database, it shows how technology development has evolved (from 1978 to 2004) and which countries have accelerated it. It further distinguishes between technologies being crucial to CSP and and those that correspond to a narrow definition of the field including solar heat and CSP-specific inventions. For a thorough assessment, the influence of R&D ("technology push"), government policies and capacity development ("market pull") are discussed.

In this study innovative activity is measured by counts of patents. Knowledge creation is usually perceived as a continuous process where R&D expenditures serve as an inputs while patents or scientific publications approximate innovative output (Crepon and Mairesse, 1998; Pakes and Griliches, 1984). Especially patent data are a well established indicator of innovative output in the literature on the economics of innovation and technological change. They exhibit a number of distinct advantages over alternative measures such as R&D personnel (Griliches, 1990). First, inventions protected by a patent are truly novel by legal definition which is assured by the responsible patent office and can therefore be interpreted as innovative. Second, they have become widely available and comparable across countries. Third, patent applications contain rich information and technological detail which can be exploited for economic analysis. Besides the notification of home countries of applicants and inventors and exact dating, technical documentation and classification are provided which is of particular interest for the purpose of our study.[5] A crucial and complex step in the analysis of innovation dynamics in CSP technologies is the identification and retrieval of patents in this field. All inventions protected by a patent are classified according to the International Patent Classification Scheme (IPC). This classification system is technology based but does not readily provide a CSP or solar thermal technology class. Hence, identifying the relevant IPC classes corresponding to the technology is a crucial and non-trivial step in the analysis and one of the central scientific contributions of this paper since it serves as starting point for further research in this area. Relying on engineering expertise and careful assessment of the technological features, we developed two schemes mapping solar thermal technologies to the patent classification: one using a narrow definition of CSP focusing on solar heat and a broad one which encompasses the development of components being crucial to CSP (e.g. high-temperature heat exchange, boilers). These classifications allow us to subsequently construct a unique dataset containing the number of annual patent applications from 12 OECD countries at the European, the American and the Japanese patent office over the years 1978 to 2004 in CSP and its related fields.

Recently, the interest in the empirical foundations of technological change in energy technologies is growing (Popp et al., 2010). One strand of research studies the link be-

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[5] Patent data are a strong indicator for innovation, but they are not exhaustive. We will return to this issue in Section 5.1

tween environmental policy and the direction and level of technological change, often applying patent data. Lanjouw and Mody (1996) are the first to use 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. (2009) investigate the influence of policies promoting renewable energy such as green certificates schemes on patent activity. They find that feed-in tariffs have particularly driven innovation in solar technologies, however, their approach fails to distinguish between solar PV and solar thermal technologies. Experience curves are another analytical tool which is used to infer the influence of R&D and particularly capacity expansion on the costs of a technology (e.g., Neij, 2008; Jamasb, 2007). A third focus is the diffusion of new technologies – the time lag between an invention and its market penetration – and across regions, for instance between developed and developing countries - or over time (Dechezleprêtre et al., 2009b).

Some of these contributions have also considered CPS, but few of them make an explicit distinction between the latter and PV technologies. This article is the first providing an in-depth analysis of CSP and to this end introduces a classification system that allows to identify patent classes for CSP. Key issues are technology developments in storage, efficiency and cost reduction. Their importance in the context of climate change is universally acknowledged, but empirical evidence is still limited. After providing a short literature review in Section 2, we give an overview of the evolution of technology and industry Section 3. We will proceed in Section 4 with the support of solar thermal technologies through public policy and R&D expenditures. The following Section 5 describes the database and derivation of classification scheme for solarthermal power technologies. Based on this work, Section 6 will discuss our findings on patenting activity. The last Section concludes

2 Literature review

In the economic literature many attempts to conceptualize technological change can be found and a coherent acknowledged concept has not evolved yet. A common perception is that technological change is a process involving several stages, each characterized by its own input factors and distinct risks. Schumpeter's invention - innovation - diffusion paradigm is the most well-known . Its simple linear framework has been strongly debated and given rise to diverse alternative frameworks such es evolutionary or systems of innovation. There is also a wide literature, drawing on the different concepts and empirical foundations of technological change. It examines how technological change, first, affects the growth of countries or performances of firms or institutions and second, which factors determine innovative activity in countries of firms themselves. Most of these studies are not technology-specific, but rather consider broad aggregates as for instance manufacturing. The perspective of the following literature review is rather narrow in the sense that it deals with the literature on innovation in environmentally benign technologies.

2.1 Innovation in Environmental Goods

Though the role of technological change for a sustainable and low carbon energy future is well-established, the literature on innovation in these technologies is only evolving. One of the first empirical applications using patents to measure environmental innovations is by Lanjouw and Mody (1996). An important contribution of their work is matching environmental technologies to their corresponding patent classes. Results point out that Japan has the highest share of environmental patents, roughly 2% in the 1970s to 1980s – compared to 1% for the U.S. One explanation is the strong environmental regulation in Japan. Generally results confirm a positive association between innovation and environmental regulation - with a particularly strong positive correlation for the renewable energy technologies. The authors however refrain from empirically quantifying or testing this association.
A more thorough empirical analysis for U.S. manufacturing firms stems from Jaffe and Palmer (1997), in which they ask whether regulatory stringency, measured by abatement expenditures, influences innovation activity. Innovation is measured in two ways - firstly by private R&D expenditures and secondly by the number of successful patent applications. The responsiveness of innovation to regulation is not clear cut and depends on which innovation proxy is applied. For the case of R&D a positive inducement from regulation is found; yet in the other specification, regulation has shown no significant impact on the number of patents. It is important to note that their study does not distinguish patents in environmental technologies from others, but includes all patents.

Brunnermeier and Cohen (2003) go beyond this by focusing only on environmental patents. They aim to explore how abatement pressures and government monitoring scrutiny affect environmental innovation in U.S. manufacturing from 1983 to 1992. To this end they employ several panel models and further, introduce variables such as concentration indexes and export intensity to control for industry characteristics. Their results point to a positive, but small, influence of pollution abatement expenditures on innovation, but no support is found for the hypothesis that stringency of regulation stimulates innovation. One of the new articles specifically on innovation in renewables applying patent data is by Johnstone et al. (2009). The analysis is based on a multi-country panel over the time period 1978 to 2003. The paper explores the relative effectiveness of various deployment measures such as tradable certificates, investment incentives or voluntary schemes in inducing innovation in renewable technologies. Additionally, public R&D expenditures, electricity price, total electricity consumption and the overall number of patents are included in the set of explanatory factors. The results show that investment incentives are the only significant influence on innovations in solar energy, whereas obligations and tradable certificate are conducive to other technologies such as wind. The study, however, does not distinguish the different solar technologies, but covers both solar PV and solar thermal technologies. A recent study by Braun et al. (2010) draws on the classification used by Johnstone et al. (2009) which is also similar to Dechezleprêtre et al. (2009a). It examines how knowledge spillover spur innovation in wind and solar technologies. They find that, apart from policy schemes like feed-in tariffs, both domestic and foreign spillovers have advanced technological change in these technologies.

These studies on renewable energy technologies have so far not distinguished between solar technologies used for power generation or space and warm water heating purposes.[6] In addition the distinction between solar PV and STT for power generation has not been drawn. These technologies are not only fundamentally different in terms of technology, application and market, but are also subject to other policies and regulations. The aim of our current study is to disentangle the group of solar technologies by introducing an explicit classification for STT. A precise and specific classification is not only an important methodological extension of the literature, but is also an essential prerequisite to analyze and understand innovation in these technologies.

2.2 Diffusion of Environmental Goods

It is clear that new technologies do not instantly fully replace existing ones, rather potential users adopt the new technology at different times, and use it with differing intensity. Assuming the new technology to be an improvement on existing knowledge, it follows that it is only when the diffusion process is complete that the social benefits of innovation are fully realized (Fudenberg and Tirole, 1985). Despite the obvious importance of diffusion in the process of technological change, it remains relatively neglected in the innovation

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[6] They in fact refer to very similar classifications, for details on how they were obtained Johnstone and Ivan Hascic (refer to 2009)

literature.

Early theoretical and empirical work was based on epidemic type models in which different rates of adoption resulted from the spreading of knowledge (Griliches, 1957). Subsequently second generation models were developed to explore factors that alter the benefits and costs, or the profitability, of adoption to explain differential rates of diffusion among firms. Firm heterogeneity (Davies, 1979) and effects resulting from the accumulated stock of the new technology and first mover advantages (Reinganum, 1981) are found to be important.

More recently Battisti et al. (2005) develop an encompassing model to explain the intensity of use within the firm, and show that the first adoption and intensity of use decisions are independent. Further, the lack of significance of variables representing epidemic effects suggests that epidemic type learning is not important in explaining differences in patterns of the intensity of use. This paper is an important step forward. It synthesizes theoretical advances made in inter firm modeling and tests the validity of applying such models in the intra firm context. While providing little support for the inclusion of epidemic effects specified in the Mansfield model, the results do not reject the hypothesis that differences in the intensity of use of a new technology are related to variation in user costs, and that characteristics such as firm size, in house R&D and other measures of firm flexibility are related to the intensification of use.

Learning curves are an analytical tool to estimate how the costs of a technology respond to its increasing installation. With the diffusion of a technology, learning-by-doing occurs which translates into cost reductions or incremental innovations. Sources for experience effects relate to the product itself such as standardization or product and quality improvements or to the production process by scale effects. Technological change is conceptualized by the reduction in (unit) costs as a function of accumulated installation or production. The learning rate is an estimate of the percentage change in costs when installed capacity (production) is doubled. They are used to project future cost paths and are an important input for energy-economy models. Estimations of experience curves have been conducted for various renewable technologies, but mostly for solar PV and wind. For solar thermal power technologies a learning rate of 10% is found by Neij (2008). The result - as also stated in the article - is subject to large uncertainties as solar thermal capacity expansion and accordingly data have been limited. Recent studies integrate learning-by-researching into experience curves. They extend the classic one factor experience curves to two factor experience curves by including the stock of R&D or in addition stock of patents (Jamasb, 2007). Only the latter has explicitly covered STT. He finds a 22.5%

learning rate for the simple one factor curve and a substantially lower one, 2.2%, when also resarch is inclued as an explanorty variable in the two factor curve. Dechezleprêtre et al. (2009a,b) are one of the few articles using patent data to infer the diffusion of knowledge in environmental technologies across countries. They focus on several climate change mitigating technologies, but their classification system does not distinguish solar PV from solar thermal applications (Dechezleprêtre et al., 2009a). In a second study drawing on this, they use an econometric panel model to disentangle the influence of intellectual property right protection, education or technology-specific capabilities on the technology diffusion. Dechezleprêtre et al. (2009b) show that absorptive capacity of the receiving country, measured by education level and the local stock of patents, is a crucial determinant of diffusion. Policy regimes such as trade barriers and weak intellectual property rights impede the flow of technology.

3 Technology and Industry Evolution

3.1 Technology overview

Solar thermal systems have been used for decentralized heating of rooms and water by means of non-concentrating solar technologies for a long time (residential solar thermal systems). These systems are based on the physical principle of heat transfer from radiation, where sunlight as an electromagnetic wave is absorbed and converted to heat. Although all STS are based on this physical principle, its designs can vary significantly. In recent years, the production of process heat, water desalination, and power generation have become important potential applications for solar thermal energy conversion. These processes often require high temperatures and therefore apply devices, which concentrate the sunlight's direct normal irradiance (DNI) in a focal point or line. Apart from water desalination, main expectations for the future are set in electric power generation. These systems are subsumed as concentrating solar power (CSP) technologies. The major CSP technology lines comprise:

- Parabolic trough systems, being shaped as semicircular mirrors, which reflect the sunlight along a focal line on a tube. This 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, being similar to conventional thermal power plants. Parabolic trough systems dominate the global market for CSP plants with more than 95% market share in the 560 MW of operating CSP plants in mid-2009 (Greenpeace International et al., 2009).

- Linear Fresnel reflectors are – similar to trough systems – 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 lower optical and thermal performance in comparison to parabolic trough systems is compensated by reduced investment, operation, and maintenance costs. This technology also promises further cost savings, using less expensive reflector materials and absorber components 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 International et al., 2009), but several proposed commercial projects.

- Solar power towers are working at the highest process temperatures among CSP technologies (700°Celsius and higher temperatures possible). A field of two-axes tracking mirrors (heliostats) reflects sunlight at concentrations of 600-1000 times 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 the potential of lower generation costs than line-focus collectors due to its higher steam parameters (pressure, temperature), which determines thermodynamic efficiency.[7] This becomes particularly important for dry cooling concepts under high ambient temperatures and water scarcity in arid regions. Because of their higher working temperature, tower systems' performance will be less diminished by increased condenser temperatures associated with dry cooling in comparison to parabolic trough or linear Fresnel systems. 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.[8] At the same time, ca. 3 GW of capacity were proposed or under construction (Greenpeace International et al., 2009).

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[7] The 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.

[8] Previously 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.

- Parabolic dish concepts use individual dishes that track the sun in two axes and each dish focuses the sunlight onto a gas turbine or external combustion engine (Stirling engine). The turbine or engine generates electricity via a generator. In contrast to the previous systems, these concepts 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, solar dishes are favorable 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. 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 were proposed (Greenpeace International et al., 2009).

In addition to CSP technologies further designs for solar thermal electricity generation exist. The solar updraft tower (this concept is also known as a solar chimney) passively heats air in a greenhouse, which then updrafts through a chimney where it drives turbines. Again these turbines are connected to an electric generator. In contrast to the previous technologies, this concept does not show concentrating characteristics of insolation (Viebahn et al., 2008).

All solar thermal technologies rely on sunlight as a variable resource. Therefore, they are unavailable at times of missing direct insolation. Particularly for CSP technologies irradiation variability leads to the so-called intermittency problem in electricity supply because electricity cannot be stored on a large scale so far. This downside may be overcome by heat storage. These storage systems are one of the major research fields for STT and an important driver to bring down electricity generation costs. Non-concentrating STT, parabolic trough, solar tower, and linear Fresnel systems can be equipped with heat storage, either directly (water/steam) or indirectly (e.g., by molten salt, phase-changing mediums, concrete heat storage). Among the CSP technologies, parabolic dish/engine-systems face difficulties of heat storage for a Stirling engine due to design reasons.

3.2 Industry

Given a current global installed capacity of solar thermal power plants of less than 500MW, it may appear to be somewhat premature to attempt to describe a "supplying industry". On the other hand, it is an innovation that may experience significant and perhaps fast growth in the coming years, so tracking changes in the structure of the industry relative to the initial condition may be instructive. Monitoring structural changes in this industry is particularly interesting given that it 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, and when our understanding of innovation in clean technologies is so poor.

In order to gain some insight into the shape of the "industry" supplying solar thermal power plants, 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 focus of the firm more generally - do they concentrate only on the solar thermal power or are their interests and expertise more widely spread? Finally we discuss the outlook.

Having studied the business models of 32 firms known to be active in the sector, we characterize the value chain as consisting of six stages (based on the simplified version due to Gereffi et al. (2009))[9] as shown in Figure 1. First we establish the degree of horizontal integration along the value chain, as represented in Table 3.2. In contrast to Gereffi et al. (2009) we do not include final users in our value chain on the basis that total installed capacity is still very small, and the existence of demonstration plants, there seems to be little to say on this aspect. 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 horizontally integrated to some extent, and 15% of firms is active in four or more stages.

Figure 1: CSP value chain

Table 1: 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

Source: Company websites and reports, own calculations.

Next we consider the importance of solar thermal techologies in the value chain of each

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[9] Though we acknowledge that the boundaries between them are somewhat blurred

firm. Ideally this would be measured by the proportion of total revenue (or profit) accounted for by solar thermal activity, however such data is not publicly available. Instead we have considered whether or not the firm is focussed purely on solar thermal power generation, and found that of the 32 firms examined, 14 were indeed focussed on this technology alone. This is unsurprising given the immaturity of the industry, but it will be interesting to monitor whether firms that currently focus on 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. Of the 32 firms studied, 22 supply components, some of which are novel but others of which are more mature technologies, such as steam turbines and pipes. As illustrated in Figure 15 perhaps unsurprisingly, the area in which there are fewest firms is finance, though the volume of funds available for investment in renewable energy projects by for example, specialist venture capital firms is growing, and is excluded from this study.

The industry structure that emerges from these features is one in which there are many small firms which focus solely on solar thermal technologies, some of which are active in several stages in the value chain. At the same time, giant global equipment suppliers Siemens and GE are present in the market, though GE only through financing at present. Interestingly, in 2009 Siemens, which previously had supplied only mature technologies (steam turbines) to this sector, bought the Israeli parabolic trough producer Solel, and also bought a 28% stake in Archimede Solar Energy, manufacturers of receiver tubes. At the time of the takeover of Solel, Siemens declared their intention to become the global market leader in solar thermal. We can expect consolidation to continue at a rapid pace. By 2009 MAN Ferrostaal, the global plant building firm based in Germany, owned 45% of the shares in Solar Power Group, which produces Fresnel collectors, and also formed a joint venture with Solar Millenium in the United States in the same year.

The expectation that this industry will experience rapid growth is supported by the emergence of the DESERTEC Foundation, devoted to turning the vision of a sustainable energy system for Europe, Middle East and North Africa, into a reality. Widespread use of CSP is central to the realisation of the DESERTEC vision. In addition to power generators such as E.ON and RWE, several of the firms active in the solar thermal value chain as discussed above are involved with the DESERTEC project, including Siemens and Man Ferrostaal.

4 Solar Thermal Public Policy and R&D expenditures

The evolution of CSP has been relying on public commitment to support research and development and policy incentives for CSP technology adoption by the market. Supply and use of energy is associated with externalities problems - an obvious example are environmental repercussions. At the same time the creation of any new knowledge is characterized by an externality as well. As emphasized in the innovation literature, new ideas and technologies have public good characteristics and are therefore underprovided by the market. As inventors can not fully appropriate the gains from their inventions, they invest too little in R&D compared to the social optimum. This is particularly severe for basic research that is characterized by high risks of failure and whose outcome is rarely of any commercial usage. Innovation in (environmentally benign) energy technologies is therefore afflicted by these two issues at the same time. Government action – for instance via R&D support or market penetration measures – may hence be warranted as means of "correcting" the outcome of the market.

4.1 Public R&D funding

Historically energy research has been conducted by the private sector - with the exceptions of nuclear power and basic research. The 1970s oil crises began to change this picture. Rising fuel prices and concerns about security of supply and import dependence turned energy R&D, particularly on alternative energy, into a matter of public interest. Since then, public R&D has become an important factor for energy research, but its relative contribution to total energy R&D is not easily assessed. Business R&D expenditures disaggregated by technologies are typically not provided and hence the depth and quality of information on public R&D exceeds that of the private sector.[10]

Public R&D expenditures for renewables accounted for only about 2.78% of public total energy R&D expenditures in all IEA countries in 1974. By 2007 this share has increased to 12.81% (information on public R&D for diverse energy technologies since 1978 are provided by IEA, 2009a). Across countries, the stability of public R&D funding is low (Figure 2). The US have been a strong supporter of research in this technology, Japan and

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[10] Nemet and Kammen (2007) found that the ratio of public to private energy R&D expenditures was about 0.5 at the beginning of the 1980s in the US, then about unity to mid 1990s and about 0.25 after. The figures contain all energy technologies, but it can be supposed that the importance of public R&D funding is even more prominent for emerging technologies such as solar power.

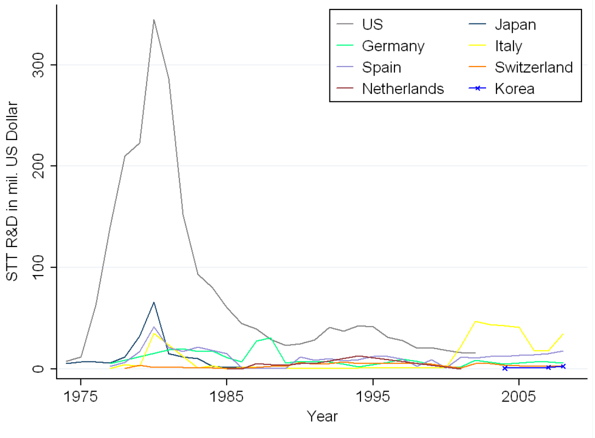

Figure 2: Annual public R&D expenditure on CSP by country, 1974-2008.
Note: All values in 2008 PPP U.S. $. Data from IEA (2009a).

Germany as the other major high tech countries granted support much more moderately. The US have been in a striking lead position up to 1980, with a maximum support of 300 million U.S. dollars. Afterwards the support declined sharply. It can be attributed to the lower priority given to federal (alternative) energy research by the Reagan administration in face of lower energy prices and need for fiscal consolidation. Expenditures by Spain, Japan and Italy, which are overall at a lower level, displayed this decline after beginning of the 1980s. Germany and the Netherlands started their funding a few years later. Japan on the other hand phased out its funding in 1988 and concentrated its ambitions on PV technology (DOE, 2005). A second Asian country, South Korea, started only after 2000. Interestingly, with Italy and Spain two countries show fairly high commitment to CSP, particularly after 1997, the year of the Kyoto protocol. Both are not typical high innovative countries, but their natural potential in terms of exposition to solar radiation may explain this focus.

A second measure of commitment to developing new CSP is the importance of CSP within the country's support portfolio (Figure 3). In the most recent year covered, 2007, Spain and Italy exhibit a high focus on CSP relative to all funds devoted to solar research (the latter including in addition solar heating and cooling and solar PV). Others like US or Germany give CSP a much lower priority. Portugal and France are two Mediterranean countries who, similarly to Italy or Spain, are potential users of CSP technologies, however R&D grants for CSP do not exits.

Figure 4 shows that the relative importance of CSP is varying remarkably over time. For most countries it displays a downward trend. Simple applications of CSP have reached maturity and are therefore less research intensive which may also explain the declining

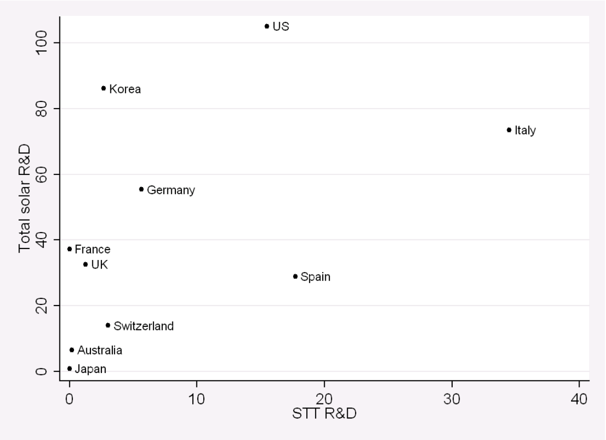

Figure 3: Public CSP R&D relative to public R&D expenditure for all solar technologies by country in 2008.
Note: Data from IEA (2009a). All values in 2008 PPP U.S. U.S. data refer to 2003, France 2007 and Australia to 2002, in each case the most recent year information on CSP was available.

trend. After 2000 the interest has however revived; it may be attributed to the awareness of altering the carbon intensity of the energy system after the Kyoto protocol. Storage systems like those operating with molten salt or materials research are also still in an early phase and require further research efforts. Spain and particularly Italy's R&D funding are varying over time but exhibit nonetheless remarkably high commitment to developing solar thermal technologies. The US support until 1980 was high in absolute terms, about 300 million dollar (Figure 2) and went down afterward. In relative terms, however, the support for CSP has been rather been rather on the low side until 1980 and high later on. Hence US policymakers may have granted less to solar R&D in total, but CSP has still been relatively less affected than the others, i.e. PV or solar heating and cooling. Japan's Sunshine Project (1974) comprised R&D support for several alternative technologies. It first has given CSP priority to solar PV, but - as seen in Figure 4, support switched to solar PV around 1980.

The information available provides quantitative indication, but little on the qualitative design of the R&D support. Relevant characteristics are if funds are allocated to national research laboratories, universities or industry partnerships and if they are granted in a competitive procedure. Evaluating the coherence, effectiveness or interrelatedness with other technology or support policies like feed-in tariffs is a much needed field for further research.

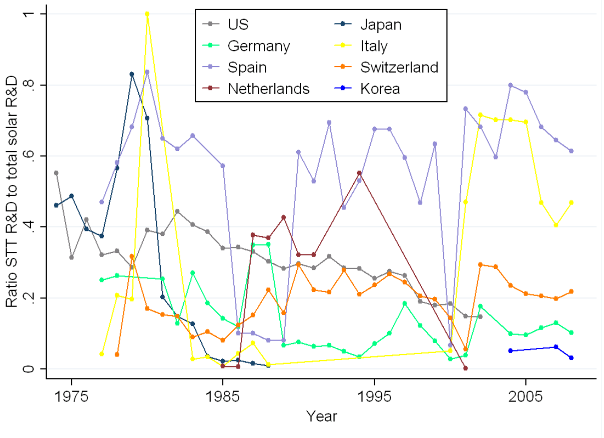

Figure 4: Share of public CSP R&D to public R&D expenditure for all solar technologies by country, 1974-2008.
Note: All values in 2008 PPP U.S. \$. Data from IEA (2009a).

4.2 Government policies - market creation incentives

Support of the market penetration of alternative energy technologies is crucial as long as they suffer from cost disadvantages compared to conventional technologies. A diverse set of incentives and policies have been implemented by several countries. Identifying those applying to CSP is not always easy as some documents make the distinction between CSP and solar PV or residential solar thermal warm water applications not explicit. At the same time not only national, but also international (such as the EU) or sub-national policies play a role. The literature on the issue of policy support in CSP is likewise sparse (one exception is Mills, 2004).

The US is the country with the most intensive capacity building before 2000. A decisive step in the federal policy for alternative energies has been the 1978 Public Utility Regulatory Policies Act (PURPA). It obliged public utilities to purchase power from third parties at so called avoided costs.[11] The 1978 Energy Tax Act introduced residential tax credits and, importantly for CSP, business tax credits of 10% for investments in alternative energy sources. By redistributing the tax revenue from the 1980 Crude Oil Windfall Profit Tax Act, the credits were increased (to 15%) and the spectrum of eligible technologies, particularly for CSP electricity technologies, was broadened (Moore, 1996). Many states launched their own initiatives. California has had a prominent role in this regard. It

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[11] Determining the avoided costs were left to the states. The main difference between PURPA and the feed-in tariff used in Europe is that the latter set a fixed rate or a rate defined relative to average electricity prices. Avoided costs are instead computed from projected wholesale costs of conventional power generation (Martinot et al., 2005).

granted tax credits of up to 55%. This measure significantly spurred the adoption of CSP; most of the early installation of solar power plants were errected in California. The design of this measure was in some respects, however, unfavorable as it expired after each year. In 1992 Californian government delayed the decision over the extension of its credit tax and the major actor in the CSP busines, LUZ, went bankrupt (Martinot et al., 2005). Installation of new CSP systems came to a halt in the US subsequently. Until the mid 1990s the US showed less commitment to fostering renewable energies. It were particularly the states that launched several initiatives - among them Renewable Portfolio Standards, tax cuts and other financial incentives. Renewable Portfolio Standards (RPS) oblige power suppliers to produce a specified share of their production from renewable sources. By now more than 20 states have implemented a RPS, but they differ strongly in terms of eligible technologies, targets and timing of implementation. However, almost all include solar thermal electric applications (EPA, 2009).[12] They stimulated new installations of solar power plants in Nevada and California and have thereby contributed to a renaissance of CSP. The federal level introduced the Electricity Production Tax Credit (PTC) in 1994. It has been amended several times, most recently in February 2009. Selected renewable technologies such as wind are eligible to a tax credit of 1.2 cent per kWh or can alternatively choose the Business Energy Investment Tax Credit (ITC). Solar projects generating electricity such as CSP are not eligible for the PTC, but only the ITC. The credit equals 30% of the expenditures, no maximum applies.

Japan's policy was very research (and PV) oriented with few efforts devoted to the deployment of technologies until 1997. In 1997 it launched the New Energy Law 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 applies to all solar based generation technologies. Other countries such as those from Scandinavia, Germany or the UK do not cover solar thermal electricity generation in their market deployment policies as due to their low solar radiation commercial operation is not an feasible option (Mills, 2004).

Spain managed to provide the necessary incentives for the deployment of solar thermal power generation. The Royal Decree 841 from 2002 grants 0.12 Euros per kWh (for systems form 100kW to 50MW). By 2004 levels increased to 0.18 Euros, thereby guaran-

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[12] The first state to introduce such a standard was Iowa in 1983, followed by Maine in 1994, Arizona in 1996 and Nevada plus others in 1997. The Californian RPS started only in 2002.

teeing the same rate as to PV. Support stretches over 25 years and hybrid systems with conventional fuels are eligible (Mills, 2004). The Royal Decree 661 increased support to 0.269 Euros in 2007. An explicit CSP target is set as 500MW in Spain by 2010.

Recently many other southern European countries have realized the potential of CSP and introduced feed-in tariffs for solar thermal power: France guarantees 0.30 Euros per kWh (up to 12MW capacity), but just for non-hybrid, solar only systems. Portugal followed in 2007 and grants 0.21 Euros per kWh for installations up to 10MW and between 0.16 to 0.20 for those with greater capacity. Greece offers 0.25 Euros per kWh for small systems up maximum 5MW (Solar PACES, 2009). Emerging economies follow this example – South Africa announced a feed-in tariff scheme offering about 0.175 Euros per kWh for concentrating solar power. Other MENA countries such as Algeria or Israel are following the lead.

Transnational initiatives have been launched to foster technology development and policy coordination. Many developing countries have a very good conditions for applying solar thermal technologies, but a good R&D environment is for many developing countries difficult to create and therefore technology transfer is an important opportunity. Already in 1977 Solar Paces was founded under the auspices of the IEA. Members are countries and industries . The focus is technology development and deployment. The Global Market Initiative includes several countries worldwide- among them Japan, the US, and many Middle East countries. Its efforts are devoted to facilitating exchange and removal of regulatory obstacles to its announced target of 5000 MW capacity worldwide. In 2007 the European Commission set up the European Solar Thermal Technology Platform. Members are countries and industry consortia which are committed to designing a strategic research agenda and accelerating technology development.

5 Patent Data and its Use for Solar Thermal Power Technologies

5.1 Patent data

The measurement of innovative activity by means of patent data is of critical importance. Patents have a very close link to novelty and invention as understood as a product or process that is new, involves an inventive step and can be used for industrial application (OECD, 2009). 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. A patent then allows appropriating the gains from the invention and can therefore serve as an incentive to conduct research. Patents, however, require the disclosure of the underlying discovery, which spurs the dissemination of knowledge. Patent data are published by the national patent offices, such as the European Patent Office (EPO) or the U.S. Patent Office (USPTO). In the present analysis, we use data on patent applications instead of patents granted to cover recent innovative activity. Patent documents are published eighteen month after the application, no matter when the underlying invention is granted by the patenting authority takes place. The time length of the granting procedure itself may vary remarkably within and between patenting offices, hence, studies on innovation dynamics usually focus on patent applications because otherwise the problem of right-censoring occurs which would bias or even falsify the results.

Patent documents confer rich information on inventors and owners, technical description of the invention, its technological classification, the timing of the invention and protection coverage that can be exploited for our research purposes. Patents are based on a common legal framework and therefore facilitate comparability across countries and time. Patent-based data have attracted large interest by researches as statistical indicators of innovation (Schmookler, 1950). They are applied to measure and analyze the dynamics of technological change of countries, regions, institutions (such as universities), sectors or firms. Besides their undisputable advantages, patent data, also reveal a number of drawbacks and raise issues that should be kept in mind for interpretation (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 (Harhoff et al., 2003). Second, the propensity to patent varies across sectors. Third, not all inventions are patented and some firms might prefer a secrecy strategy to prevent imitation. Fourth, patent applications are not directly linked to the commercialization of inventions. These features of patent data render them an imperfect but nevertheless very useful measure of innovative activity.

For our analyses, we use information on patent applications in solar thermal technologies to the European Patent Office's Worldwide Patent Statistical Database (PATSTAT). This database contains all applications made at national (e.g Japanese or American) and transnational patent authorities (e.g. European Patent Office (EPO)). In this study, we focus on EPO applications since an application to an international authority, in contrast to one made to a national authority such as the German patent office, can be taken as a signal that the patentee believes the invention to be of high enough value to justify the additional expenses of an international application. A problem arising in this context is the existence of a home bias which emerges for Non-European countries. Inventors in the United States or Asia will tend to seek patent protection first in their home market and then second in other national markets, but not necessarily in Europe. This could lead to a systematic underestimation of innovative activity in the United States, Japan or South Korea. We therefore amend our analysis by adding patent applications made at the United States Patent and Trademark Office (USPTO) and at the Japanese Patent Office (JPO). This approach complements our analysis by pointing to developments taking place outside of Europe. Applications at the American and Japanese authority are chosen even though they serve a domestic but considerably large and important market. Hence, the inventions patented there could contribute significantly to worldwide innovation dynamics.

We use all patent applications filed with the EPO, USPTO and JPO having a priority date between 1977 and 2005. The priority date is the date at 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 internationally, e.g. at the EPO, to expand patent protection; this would be called a second stage filing. To date patent applications using the date that is closest to the date of the actual invention which is what we are interested in, we date the applications back to the initial application, which would be the first national application (de Rassenfosse and van Pottelsberghe de la Potterie, 2007). Dating patent applications by the priority date is the only meaningful procedure from an economic point of view. Our analysis of patenting activity is conducted in two steps: first, we compare innovation dynamics in solar concentrating power with the overall trend in patenting behavior. Therefore, we simply compare the number of applications made in each year. Second, we proceed to the country level and assign applications to the inventor's home country to. We investigate which countries are the global players in his field and whether their relative importance changes over time. 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. Hence, a co-invention by a German and a Dutch inventor counts twice, once for Germany and once for the Netherlands and our measure of innovative activity may therefore be larger than the absolute number of applications made. This approach helps to approximate the value of innovative output since it is often argued that international co-inventions are of higher economic value because their generation imposes larger costs.

To extract the patents related to technologies for solar thermal purposes, we exploit the information on technical classification provided by the initial patent document which is expressed in terms of symbols of the International Patent Classification (IPC). The IPC is a hierarchical system which codifies the subject of a patent. An example is given by Table 2: for example F24J 2/07 refers to mechanical engineering, lighting etc. (F); heating, ranges, ventilating (24); Production or use of heat not otherwise provided for (J); use of solar heat, e.g., solar heat collectors (2); Receivers working at high temperature, e.g., for solar power plants (2/07). Our classification is a unique achievement and contribution covering the relevant fields of technology and builds therefore the basis of the analysis.

Table 2: Example of an IPC code associated with CSP

	Examples for 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	Receivers working at high temperature, e.g. for solar power plants

5.2 Technology Selection

This paper relates to patenting activities in CSP with a special focus on CSP as an expected major field of innovations. Numerous studies limit CSP technologies to parabolic trough and linear Fresnel collector systems, as well as solar tower and solar dish concepts (e.g., DOE, 2008; Greenpeace International et al., 2009; ESTIA et al., 2005; World Resources Institute, 2009). In the subsequent patent analysis we follow this differentiation and do not separately consider solar updraft towers for electricity generation. Although updraft towers use direct solar irradiation for power generation, its components do not show reflective characteristics as a common principle of the considered CSP technologies. Moreover, it does not concentrate solar irradiation and the working temperatures are low compared to the above mentioned technologies. Thus, materials for high-temperature applications as well as selective coatings and mirrors are of limited importance or do not apply to solar updraft towers.

For each of the technologies under consideration we conduct an engineering system analysis to focus our patent analysis on innovations in solar heat and CSP, see the scheme depicted by Figure fig:scheme For parabolic trough systems, this includes optical devices (collectors), receivers (heat absorbing components), enclosure technologies for receivers, mounting systems, heat transfer fluids, and heat storage devices. We conduct a similar analysis for each of the above mentioned technologies. In addition to this systemic view, we analyze process technologies and materials being used in solar thermal component production to define the scope of the subsequent patent data.

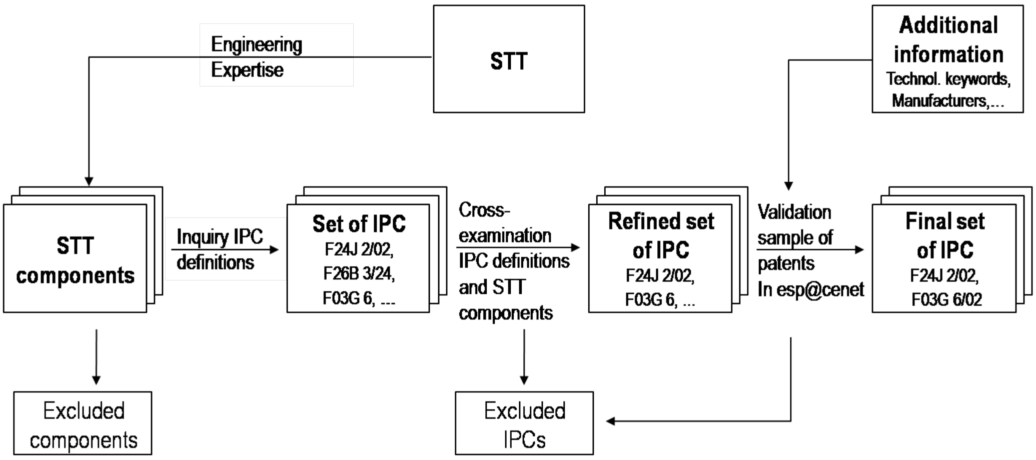

Figure 5: Scheme developed to identify international patent classes (IPC) associated with CSP.

Technological progress in solar thermal heat and power generation is also driven by technology transfers and knowledge spillovers. For instance, high temperature heat exchangers are a critical component in the design and efficiency of solar power tower plants. In general, power plants' thermodynamic efficiency depends on the temperature difference in the underlying thermodynamic cycle. Thus, developments in improved heat exchange cannot be attributed to solar thermal applications alone, but apply to fossil-fueled plants as well. Overlaps to other technologies also exist in materials science and production process technologies. We take this into account in our patent analysis by considering patents in these technology fields separately.

5.3 Patent Search Strategy and Classification

We apply a step-wise search strategy in accordance with Johnstone and Ivan Hascic (2009), who use a detailed patent identification procedure for environmentally sound technology innovations. We first review publications from internationally recognized research institutions, associations and manufacturers in solar thermal power production to properly identify the relevant technological options (Greenpeace International et al., 2009; World Resources Institute, 2009; Viebahn et al., 2008; Aerospace Center (DLR), 2005; EC, 2007). In a second step we conduct a comprehensive review of the IPC division descriptions to identify the relevant classes for innovations in CSP, using the WIPO database.[13] Subsequently, we use the European Patent Office's world patent search engine[14]) as an additional tool to determine relevant patent classes by keywords in patent names and abstracts. Moreover, we check multiple IPC classes in CSP patents to identify further relevant classes for CSP innovations.

This search strategy might suffer from two potential types of error: On the one hand, irrelevant patents might be included, which would bias the subsequent analysis. On the other hand, relevant patents might be left unidentified. Preventing from the first error (i.e. the inclusion of irrelevant patents), we use the esp@cenet database to crosscheck the identified classes on its 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 match these combinations, these classes are left out (Lanjouw and Mody, 1996). The IPC class F26B 3/28 ("Drying solid materials or objects by processes involving the application of heat by radiation, e.g. from the sun" is an example for this approach. In contrast to Dechezleprêtre et al. (2009a), we do not include this class for CSP because less than 10% of the class' patents fit relevant keywords (e.g. "solar", "sun", "visible light") in the patent title or abstract. An additional analysis of a sample of patent abstracts in this class has underlined that the majority of patents is not related to CSP and would therefore bias our analysis. Leaving out relevant patent classes leads to underestimated total patent counts. This error 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 (Johnstone and Ivan Hascic, 2009).

As a result we identified IPC classes according to Table 3. Overlaps with fossil-fueled power plant technologies remain, being caused by common technical designs and physi-

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[13] www.wipo.int/classifications/ipc/ipc8/?lang=en

[14] esp@cenet can be found at www.espacenet.com/index.en.htm

cal principles for these applications. CSP thermal plants and fossil-fueled thermal power plants do not or marginally differ in its designs apart from the primary heat source. Thus, heat exchangers, boilers, pipes, turbines, transformers, cooling tower designs, pumps, and other components are similar for both technologies. Innovations in CSP plants (e.g. cooling concepts for power production in arid regions) will also affect fossil-fueled power plant design, and "vice versa" overall efficiency increase in thermal power plant development will ultimately improve the efficiency of CSP as well. We will address this issue by two separate analyses of patent classes: a set with a narrow classification will analyze solar heat and CSP-specific patents (bold print, see Table 3). A second set additionally includes components, which are crucial for CSP development (e.g., high-temperature heat exchangers, boilers), but show overlaps with other thermal power plants.

6 Innovation activity in CSP Technologies

This article analyses innovation from an output perspective by using patenting activity in solar thermal technologies. Strong lessons can be learned from this approach, as patent data are an important indicator of successful research and convey valuable insights on the dynamics and the geography of innovation. In the following, we consider the three major patent offices worldwide - the EPO, USPTO and JPTO. Worldwide innovation dynamics is first inferred by investigating the evolvement of patent applications in CSP compared to the trends in overall patenting behavior. Second, we use counts of patent applications at the country level, a common approach in the literature (e.g., Dechezleprêtre et al., 2009a; Johnstone et al., 2009), to refine our analysis to drivers of this certain technology. Results have been obtained for the broad as well as for the narrow definition of CSP.

6.1 Innovation activity at the EPO

It is well-established that the number of patents in general has been strongly growing over time. The trend can be attributed to various factors like strengthened intellectual property rights, ease of access to 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 being unity in 1978, the first year where data become available.

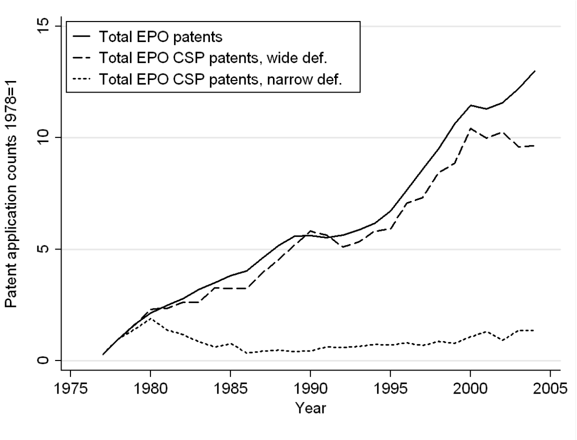

Figure 6: Comparison total to CSP patent applications at the EPO, 1978–2004

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 some increased patenting activity in the years after. 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%. To evaluate this share, note that around 2.5% of all patents are roughly estimted to green technologies (Lanjouw and Mody, 1996). A different picture emerges when considering the CSP technologies in the broad definition, i.e. technologies which are important element of CSP, but are not exclusive to CSP. Their patenting activity mostly resembles the path of the benchmark, though slightly less dynamic in most years.

The innovation pattern of the narrowly defined CSP technologies is striking, particularly when considering the sizable capacity expansions currently being planned. Technological progress as depicted by the patent applications is very weak. This, however, reflects the evolution of public R&D support, as shown by Figure 2. Research activities have been the most active in the time before the 1980s, apparently effective in inducing CSP innovation output. The same way as R&D deteriorated after 1980, the patenting activity went down as well. One could also consider the hypothesis that CSP technologies are rather a mature technology and for this reason innovation activity would be rather low. In this respect, solar thermal power generation is an interesting case for innovation studies, as it is a combination of both established mature (e.g. turbines, though not included in our patent classification, see Section 5.2) and novel highly innovative technologies. The application of well-established components for a new purpose i.e. using solar radiation to generate power is novel and constitutes an innovation respectively an emerging technology. To reconcile this, the technology components are in some, but not all, cases scientifically well understood and can be considered as mature in that sense. However, usually maturity refers to more than a technology being available for implementation, but particularly to a technology being in a significant and long-lasting use in the marketplace. Installed capacity of CSP is still rather low. The maturity argument might therefore not be strong enough to explain the strikingly low patenting activity.

Though the narrowly defined CSP technology development has underperformed, the broadly defined CSP technologies show a different innovation path. Hence there is still active knowledge creation in technological advances that are critical to CSP. These technologies may in some cases not be one-to-one applicable to CSP, however, as described in Section 5.2 they can be easily adapted for CSP and therefore still constitute elements of CSP technologies. We can think of these CSP technologies in the broad definition as a strongly related knowledge pool / base for CSP development. The role of such strongly-related technology fields for inducing innovation is non-negligible as Braun et al. (2010) show. These findings do 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. So far studies 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.

It is important to consider how these trends evolve at the country-level (Figure 7). Little is known so far on the geography of innovation in CSP. Geographic dispersion of technology development as depicted here by patent counts, can shed some light on the role of different energy policy regimes, market demand or natural potential in promoting innovation (Figure 7). Germany is the leading innovator in these technologies. The mean number of patents filed with the EPO is around 18. Two time periods showed particularly active patenting – the time around 1980 and then again from 1995 on. Germany supports CSP research and has set up demonstration plants, but it is not a relevant market for applying CSP technology due to unfavorable radiation conditions. The U.S. are second to Germany, but on an overall lower level with a mean of around 8. It is important to note that these are U.S. patents filed abroad i.e. at the EPO - apparently the U.S. consider Europe to be a promising market for their newly developed technologies. The U.S. were very supportive in terms of public R&D funding to CSP at the beginning of the 1980s resulting also in intensive patenting. After R&D support was strongly cut by

1981, we observe a decline in patenting. Hence the U.S. appear not have been able to build up a sufficient knowledge base in CSP during the phase of intensive R&D support which they were able to exploit in later years (the so called "Standing on shoulder of giants effect"). CSP innovation is hence strongly associated with R&D support. The U.S. are closely followed by Japan and only France and Switzerland are relevant European countries showing significant CSP innovation output. Japan's innovation performance is nonetheless interesting as – different from the U.S. – Japan phased out its CSP R&D support and only few solar power plants have ever been built (for instance 1 MW plant in Nio). All these top innovators show high innovation activity at the early 1980s and a moderate innovative activity afterward, except for Germany where patenting activity gains momentum after 2000.

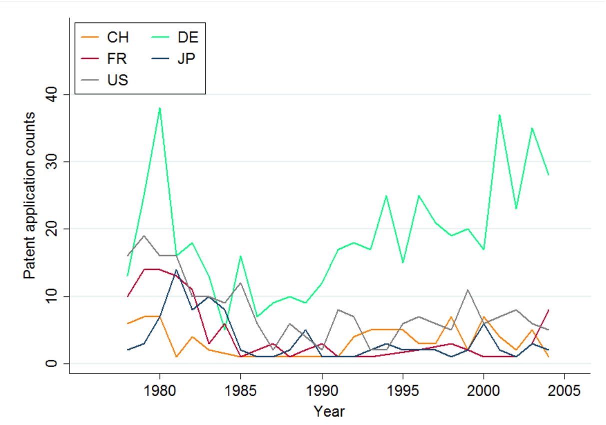

Figure 7: EPO patent applications by major countries, 1978–2004. CSP technologies, narrow def.

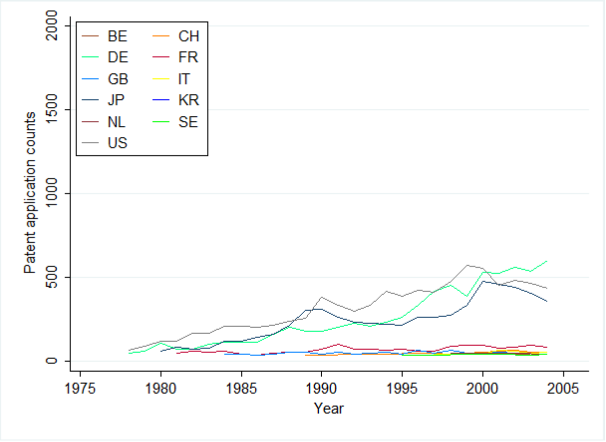

Figure 8: EPO patent applications by major countries, 1978–2004. CSP technologies, broad def.

Patenting activity in the broadly defined CSP technologies is, not surprisingly as it covers a wider set of IPCs, substantially higher than for the narrow definition. The U.S. have been in a lead position over most time periods – different from what we found for CSP in the narrow definition. Particularly dynamic were the 1980s and the 1990s, though at the end of the 1990s we observe a decline in U.S. patenting. Patent filings from Japan decreased from the end of 1990s as in the U.S. case. Different from Japan or the U.S., patenting from Germany follows an upward trend and overtook the U.S. about 2002.

Overall the end of the 1990s appears to be a critical time period. Germany, Japan or France could accelerate their performance, whereas the U.S. slowed down. Dechezleprêtre et al. (2009a) argue that the 1997 Kyoto Protocol has been vital for spurring the innovation performance of the main inventor countries – except for the U.S and Australia.[15]

Further country-level details are illustrated by Figure 9. All inventor countries differ in terms of their size and innovative capability (e.g., scientific personnel), but also in their market size / natural potential for applying CSP. Over time, CSP technology development has peaked in 1980, followed a downward trend and shows some upward trend since 1990. The five leading countries by patent application counts, Germany, U.S., Japan, France and Switzerland, account for a substantial share of the total innovation activity that, however, dropped over time (1978: 74.6%, 2004: 45.8%). Technology development is still quite concentrated in traditional high-tech countries, many of which have rather limited potential to use solar power plants (Switzerland or Germany). Over time the composition of innovators has become more heterogenous: Great Britain, Australia, Israel and Italy join the group of important innovators, whereas Japan and Switzerland loose shares towards the end of the sample period. Australia, Israel and Italy are potentially large market for CSP application and already have capacity installed. Comparing Spain and Italy is interesting in this regard – both are potentially large markets for CSP with already some CSP power plants in use. They are usually considered to be among the less innovative Western European countries. In spite of these common characteristics, Italy is showing a much higher patenting activity than Spain. As presented in 4, Italy has devoted substantial funds on CSP technology development which appears to have been successful in inducing innovation. Its funding is quite varying over time and resulting in a relatively unstable innovation path with high activity in the early and very late phase.

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[15] This finding covers all climate change mitigating technologies, but in the case of solar innovations they rather find a decline. Note however, that their analysis relies on a much broader categorization of solar technologies – including power generation (solar PV, solarthermal 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 in discussion of technological change dynamics in climate mitigating or renewable technologies.

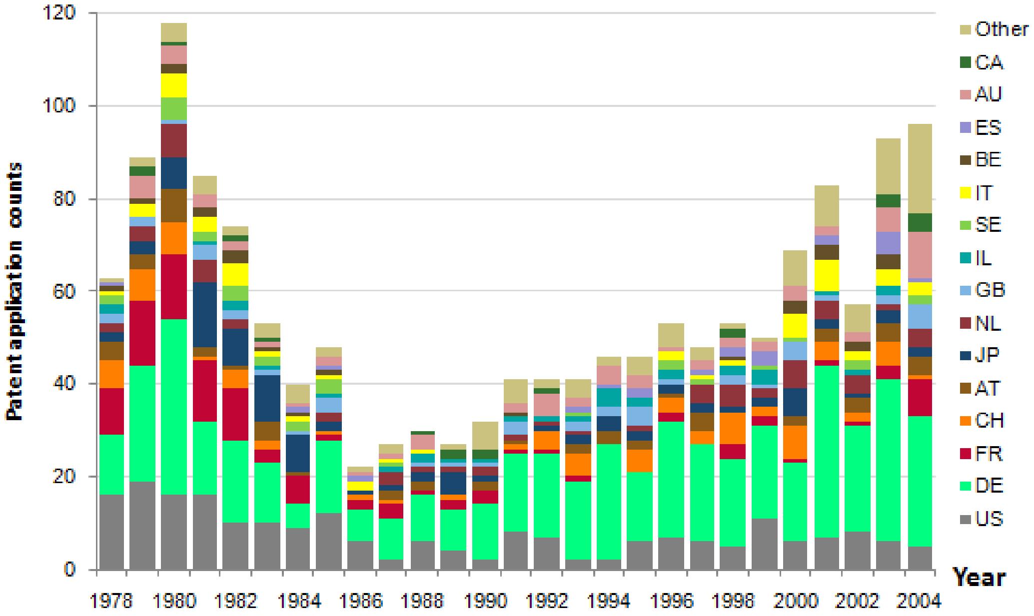

Figure 9: Total CSP EPO patent applications by countries of origin, 1978–2004. Narrow definition of CSP.

Overall, there is evidence for a demand side impetus on innovation – natural potential may stimulate innovation. Natural potential alone is yet not sufficient to generate CSP innovation as the case of the MENA countries shows which are not among the relevant innovators. It can be concluded that natural potential plays a role, but that in addition adequate technological, scientific and research capability are critical to the innovation performance.

Within the field of broadly defined CSP technologies, the U.S., Germany and Japan are the leading countries , accounting for over 80% of CSP patent applications from 1978 to 2004 (Figure 10). Although patent filings in general tend to be concentrated in a few countries – U.S., Japan, and Germany amounted to 60% of the total patent filings in *all* technologies for 2004 –, the figure for CSP suggests a disproportionally high concentration for CSP.

Japan and U.S. have a particular 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. Remarkably stable is also the middle field such as France, Great Britain or Switzerland, but considering their smaller

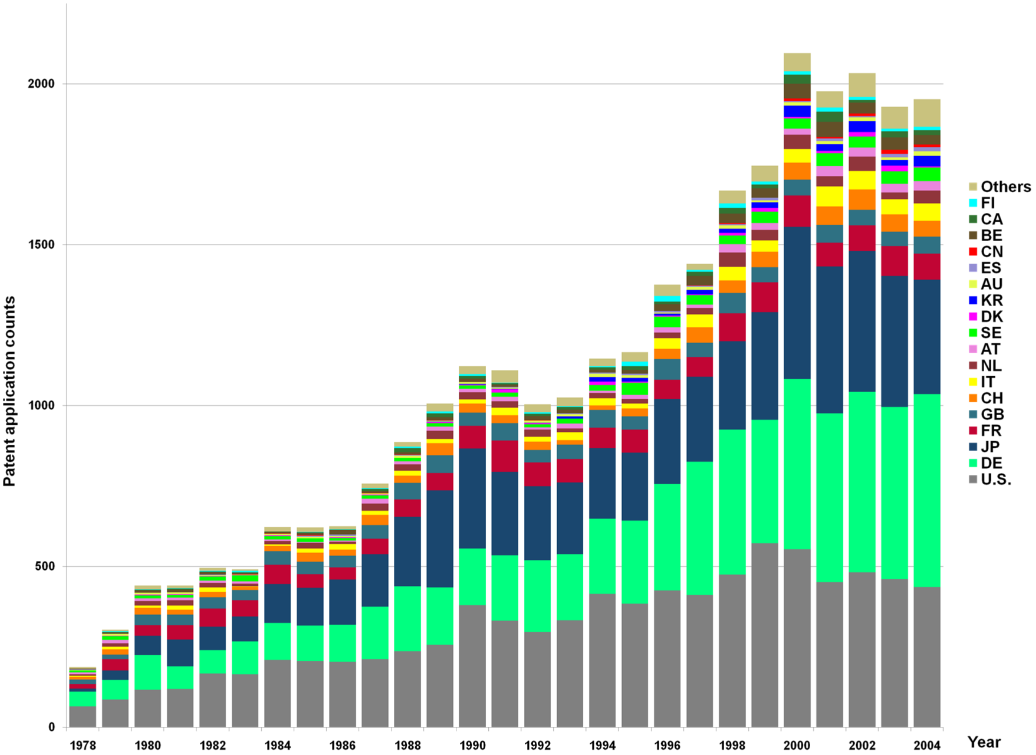

Figure 10: Total CSP EPO patent applications by countries of origin, 1978–2004. Broad definition of CSP.

size not surprisingly on much lower level. The rest of the patenting activity is dispersed over more than 40 countries.[16]

As shown by Figure 9 and 10, the leading innovative countries are typically highly innovative OECD countries with often limited natural potential for the use of CSP technologies themselves. These countries have to 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 – as it is also starting to be addressed by transnational initiatives such as SolarPACES.

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[16] South Korea is one of few emerging countries showing some innovation and recently, but at a much lower level than South Korea, China is entering the group of innovators. Their overall role is nonetheless negligible. Dechezleprêtre et al. (2009a) find China, South Korea and Russia to be strong new entrants accounting for up to 15% of patent filings in climate mitigating technologies such as geothermal, CCS or ocean technology.Note that their analysis covers almost all patent offices worldwide and also the domestic officies of the countries aforementioned which may explain their much stronger overall position in the study of Dechezleprêtre et al. (2009a).

6.2 Innovation Activity at the USPTO

The patent application activities at the USPTO display a very dynamic picture (Figure 11. Total patenting increased strongly from 1978 until 2002, where it experienced a sharp drop in 2003 and 2004. CSP, according to our broad definition, follows the overall patenting activity in a quite similar fashion, suggesting that the innovation activity is driven by similar influences such as business cycles. There is one important distinction, the much more pronounced drop in patent filings from 2000 onward. Compared to a recently constant innovative activity in Europe, the sharp decline at the USPTO suggests that the two regions have responded very differently to the climate change challenge – the U.S. hesitant and with state-led initiatives, whereas many European countries followed a more ambitious plan for the deployment of renewables, including also concentrating solar power as for instance in Spain. These different positions also influenced the relative attractiveness of the two markets as found here – though both undergo a decline, Europe appears to be relatively more attractive than the U.S.

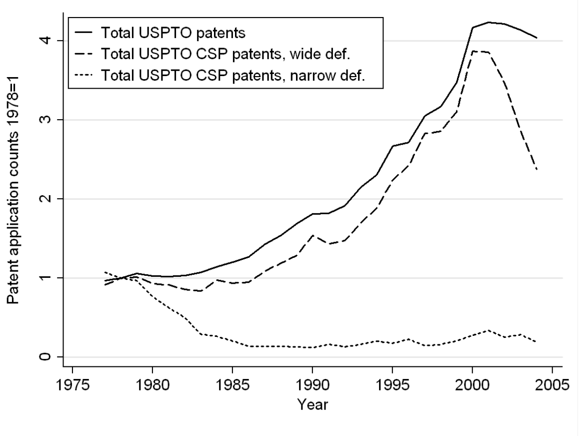

Figure 11: Comparison total to CSP patent applications at the USPTO, 1978–2004

Coming to the innovation pattern drawn by the narrow definition of CSP technologies corroborates the remarkable insights gained from the analysis with EPO applications. Also for the USPTO, we observe a peak in patenting around 1980 followed by a sharp decline until 1985. Afterwards, the narrowly defined CSP technologies never recaptured importance in the innovation process. Obviously, little new knowledge is generated in this field, in an era, where the worldwide awareness for climate change and the challenges for a sustainable energy system has been heightened.

Proceeding now to the country-level analysis, we first focus on the broad definition of CSP technologies to gain further insight especially into the recent drop in innovative

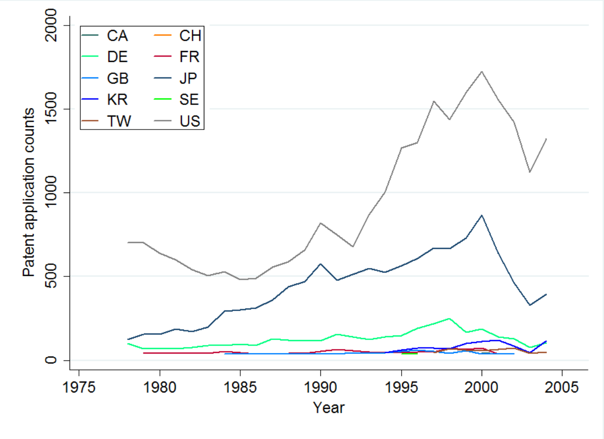

Figure 12: Patent applications by major countries, 1978–2004. CSP technologies, broad def.

activity. CSP patent counts of the USPTO are much higher than those of the EPO – the figures are in some years up to twice as high (Figure 12 or 13). The set of main inventor countries resembles the European case and, not surprisingly, the U.S. are the main inventor with their home patent office. Japan is second in patent filings and Germany third. Their innovation outputs follow each other along very similar lines with a particular sharp decline from 2000 on. In contrast to this, only the U.S. patenting activity with the EPO, but not filings from Germany and Japan, decreased. Hence U.S. innovative performance has overall weakened, both applications at the home and the European office have declined after the 1990s.

Patent applications are again highly concentrated, but with a clear dominance of domestic U.S. patents with a share of 60.13% among the CSP patents in 2004 (see Figure 13). The second most important player is Japan (2004: 19.68%), followed with some distance by Germany (2004: 4.81%). Interestingly, Japan is pursueing an active strategy of patenting abroad to seeking protection for its technology. It is an indication that inventors in Japan consider these foreign markets, i.e. Europe and the U.S., as lucrative to enter. In contrast to this, German inventions are to a much smaller degree being patented abroad at the USPTO. Great Britain and France agan rank in middle tier of inventor countries at the USPTO.

Similar to the EPO case, the ranking of innovative countries is quite stable. Few emerging countries are entering as innovators, for instance South Korea, Taiwan or China. Their performance is more remarkable than observed with EPO filings. The share of Korea with the USPTO was 5.22% compared to 1.64% at the EPO in 2004. Korea is ranking third in 2004, sending Germany off to a fourth place.[17] There is indication that protection of German CSP knowledge in the U.S. is rather declining and that Germany is challenged by others such as Korea. The evidence is based on counts of patens – it can nonetheless be that Germany is selective in patenting abroad in the sense that it only applies for protection for its most valuable developments or those suited for the U.S. conditions.

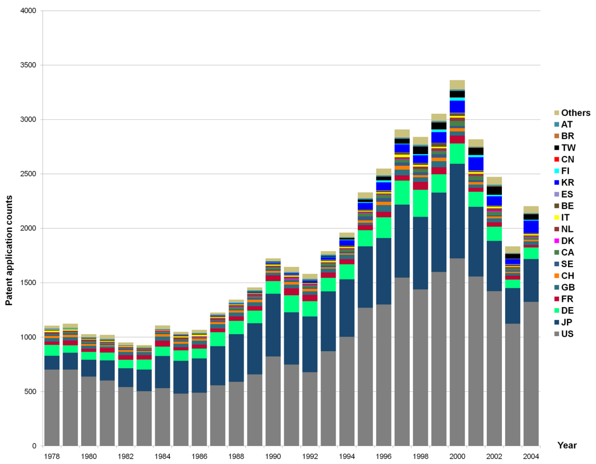

Figure 13: Total CSP USPTO patent applications by country of origin, 1978–2004. Broad definition of CSP.

Focusing on the narrow definition of CSP reveals again that the U.S., Germany and Japan are the key players in this field. The U.S., not surprisingly, are dominant with their home patent office ("home bias") and accounts for 78.9% of all CSP patent applications in 1978 and around 72.6% in 2004. In the early years Germany is ranking second and France third, but France looses significance over time. Japan on the other hand is gaining influence and overtakes France. We observe some newcomers among the innovators which are Israel and Taiwan. Overall the innovation dynamics at the USPTO were high at the early 1980s when the CSP demonstration plants raised hopes for a significan U.S. CSP market, but afterwards the activity slowed down strongly. As in the case of the EPO, it showed some signs of recovery after 1997, but, different from the European case, it lost drive in the last two years of our sample.

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[17] The share of Taiwan in 2004 at the USPTO was Taiwan 2.31%. Note that Taiwan is not included as a country with the EPO. Comparisons across the patent offices is therefore not possible.

6.3 Innovation Activity at the JPO

Normalized 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 to the development at the European or American patenting authority. 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.

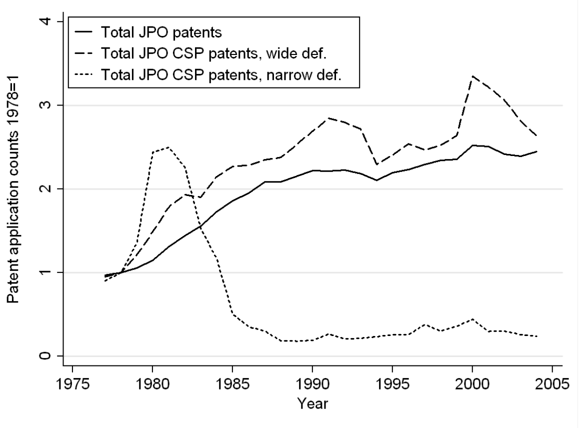

Figure 14: Comparison total to CSP patent applications at the JPO, 1978–2004

A note of caution is necessary when interpreting JPO applications. The quality of data in our data base for the EPO and the USPTO is higher especially with respect to the inventors country of origin. This information 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. Given their share in patent applications, we can say that CSP dynamic at the JPO is in parts driven by the growing patenting activity in Japan - using our broad definition - which corroborates our finding that Japan is one of the leading countries in CSP innovation. Only Germany and the United States are also found to patent substantially at the JPO but in a negligible share compared to the 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 because of 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.

7 Conclusions

Tackling climate change will require significant reductions in the carbon intensity of the economy. Developing low carbon technologies and adopting them globally is therefore an immediate priority. The innovation challenge spans the discovery of new energy supply technologies as well as - and possibly even more pressing - improving the performance, efficiency, and particularly lowering the costs of existing low carbon technologies.

Understanding the evolution of these technologies is therefore important for the design of government policy instruments like R&D funding or market creation incentives. This empirical study sheds light on innovative activity and innovation dynamics in CSP technologies. Innovative activity is approximated by patent applications since they have to be new by legal definition and are comparable with respect to procedure, admission and granting procedures across countries as well as widely available. Detailed information about the technology of the underlying invention to classify it as belonging to the field or not. This information is consistently available in case of patents, but not for other indicators like publications or the introduction of new products. Hence, despite some shortcomings, which we discussed in the paper, the usage of patents enables us to substantially contribute to the literature on "green" innovation.

A crucial necessity to describe innovation in solar thermal technology is the derivation of a classification scheme mapping the technology of interest to the IPC scheme. Hence, one of the key contributions of this paper is the development of this scheme based on engineering expertise following a stepwise search strategy as suggested in the relevant literature. We therefore review publications from internationally recognized research institutions, associations and manufacturers in solar thermal power production to properly identify the relevant technological options and conduct a comprehensive review of the IPC devision descriptions to identify the relevant classes for innovations in CSP. Relying on engineering expertise and careful assessment of the technological features, we developed two schemes mapping solar thermal technologies to the patent classification: one using a narrow definition of CSP focusing on solar heat and a broad one which encompasses the development of components being crucial to CSP. We can think of the latter as a pool of strongly-related knowledge which developers of CSP can easily exploit and assimilate for own technological advances. This classification can stimulate further research in this field by enabling researcher to clearly identify innovation in CSP and compare it to previous work. A promising direction for further investigation would be the extension to the micro level and analyze firm-level innovation and performance in CSP technologies within a cross-country comparison.

The aim of this article was an in-depth analysis of CSP and to provide an overview of the evolution of technology, industry and policy framework. Support of CSP through R&D expenditures was unstable and rather falling over time: while the US have been a strong supporter of research in this technology in in the late 1970s and early 1980s, Japan and Germany as the other major high tech countries granted support much more moderately and Asian countries like South Korea only started funding in 2000. After 2000 the interest has however revived; it may be attributed to the awareness of altering the carbon intensity of the energy system after the Kyoto protocol and, as a consequence, increased support for CSP.

The innovation performance in the narrowly defined CSP technology field is rather weak compared to the overall innovative activity in the economy. The early 1980s to mid 1990s appear to be a “lost decade” in the sense that innovative activity of CSP was at very low levels. Strong eras of innovative activity were the early 1980s and then again the end of the 1990s until the last sample period 2004. Both are time periods in which CSP and renewable energy technologies were receiving increasing attention for their contribution to energy security and sustainable energy supply. Though the recent signs of recovery are stronger at the EPO than the USPTO, it nonetheless provides a more optimistic view on the current state of technological advancement in CSP technologies. Innovation is highly concentrated, the set of leading innovators are the high-tech countries U.S., Germany and Japan. They are clearly dominating the technology development path, though only the U.S. have a large market potential for CSP application. We also observe some promising and innovative newcomers such as Israel at both the USPTO and EPO and Australia or Italy at the EPO. What our analysis shows is that nations regarded as being innovative in general can transfer this strength on new technologies (Japan, U.S., Germany), probably via knowledge spillovers and adaptive capacity. There is some evidence for an influence of so called market pull factors – possible adopters of CSP, i.e. countries with favorable radiation conditions - such as the U.S., Australia or Italy, are active innovators in this technology field. However, having favorable conditions for CSP is not sufficient, only developed Western countries with correspondingly adequate scientific capacities and economic background are found to be able to respond to these market pull factors.

Promising issues for further research are: first, even though probably a time consuming analysis in terms of computing, we could enlarge our understanding of the dynamics in this field by focusing on the research behavior of equipment manufactures of CSP. 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, econometric techniques could be used to explore how factors such as policy instruments are driving innovative activity using a cross-country setting.

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Table 3: 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	–

Note that IPC classes of the narrow definition are included in the broad definition (indicated by bold face).

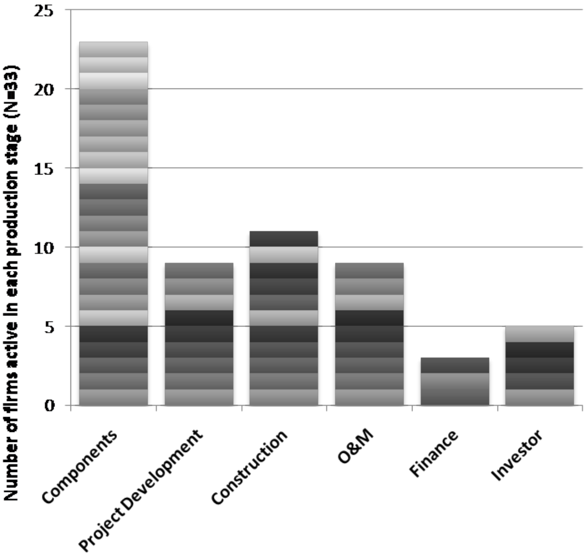

Figure 15: Stages of activity