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Efficiency Improving Fossil Fuel Technologies for Electricity Generation: Data Selection and Trends

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Summary
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Keywords: Climate Change, Technological Innovation, Energy, Patents, Fossil Fuels

JEL Classification: Q32, Q4, Q55

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Efficiency Improving Fossil Fuel Technologies for Electricity Generation: Data Selection and Trends

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1. Introduction

This paper studies innovation dynamics in fossil electricity technologies. We examine technologies that contribute to the mitigation of climate change impacts by improving efficiency in the use of fossil fuels for the generation of electricity. This issue is particularly important given the high contribution of fossil-fuel electricity to greenhouse gas (GHG) emissions and its potential for mitigation through the adoption and development of efficiency-improving technologies. Addressing climate change will necessitate innovation within the fossil-fuel electricity generating sector, and not just end-of-pipe solutions (CCS) or fuel substitution (e.g. renewables and nuclear).

Understanding the worldwide innovation and diffusion patterns of fossil electricity technologies is important for several reasons. First, according to some projections of energy use and related GHG emissions (e.g., IEA 2010), fossil fuel sources are likely to remain a major input in electricity generation. As a result, development and adoption of efficiency-improving (and thus emission-reducing) generation technologies would have to be a major component of any successful climate change mitigation policy in concerned countries. Second, projections show that the bulk of the increase in GHG emissions will originate from non-OECD countries, underlining the importance of international technology transfers as well as the development of domestic innovation capacities in these countries. Due to the large differences in innovation and absorptive capacity, as well as the market structure and competition, the dynamics of innovation and diffusion patterns could potentially be very different. Third, to date a number of analyses have dealt with innovation and diffusion patterns of renewable energy technologies, while innovation in fossil-based generation technologies has largely been ignored. In this paper, we address this gap in the literature and focus specifically on innovation in fossil fuel technologies with potential for GHG emission reductions.

The major challenge for the study of innovation, adoption and diffusion of energy technologies is data availability. Data on energy-specific R&D innovation is only rarely available and tends to be limited to measuring outcomes of public investments. For this reason, patents are often used as a proxy for innovation. Until recently, the only publicly available patent dataset was the one provided by the National Bureau of Economic Research (NBER) in the United States (Hall, Jaffe and Trajtenberg, 2001). However, the NBER database includes patents granted by the US Patent and Trademark Office, but not by other granting authorities. Consequently, data scarcity was less pronounced in the case of the USA, with a great number of empirical contributions focusing on the innovation, adoption and transfer dynamics in fossil fuel electricity generation (see, for example, Popp 2006). Any study of worldwide innovation dynamics based on this database would only give a partial picture.

More recently, increased availability of EPO data and the release of the EPO/OECD Worldwide Patent Statistical Database (PATSTAT) have improved data coverage to countries other than the US and resulted in a number of studies that provide information about innovation activity in a large number of countries[1] (e.g., Dechezleprêtre et al. 2011; Haščič and Johnstone 2011; Johnstone et al. 2010; Noailly 2010). While these studies cover different environmental and mitigation-relevant technologies (including renewable energy generation, SO_2 and NO_x abatement, buildings energy efficiency, etc.), no study has addressed innovation and transfer dynamics with respect to fossil-fuel electricity generation technologies.

This paper contributes to this body of literature in two respects. First, it develops a methodology for the identification of efficiency-improving fossil electricity technologies using patent data. Second, using the PATSTAT database (EPO 2010) it examines the trends and the overall dynamics of the invention and transfer of these technologies worldwide. We find that the USA, Japan and Germany have very high innovation rates in this sector, while other countries, such as Finland, Greece, Switzerland and Denmark, have a higher degree of specialization in efficient fossil technologies as compared to all fossil electricity technologies. Patent applications in the efficient sector have mostly been stable over time, with a decreasing trend. In particular, applications in efficient fossil fuel electricity generation technologies have declined as percentage of total applications. This result could indicate a shift from investment in fossil fuel electricity towards other types of technologies, such as renewables.

With respect to the flow of know-how in this sector, the majority of patents are first filed in OECD countries and in some cases protection of the intellectual property is then also sought (i.e. the patents are 'duplicated') in non-OECD or BRIC countries. On the other hand, non-OECD and BRIC countries tend to patent technologies that only target domestic markets. This result shows that the pattern of technology transfer in efficient fossil electricity technologies is primarily between North and North and from North to South. Such transfer has a potential to contribute to mitigating GHG emissions in emerging economies in the long run in two ways. On the one hand, it introduces novel efficient technologies that can be licensed and used in the market, with positive effect on fossil electricity production efficiency. On the other hand, availability of foreign knowledge can foster the development of domestic innovation capacities. Among the efficient technologies we examined, fluidized beds and ignition engines are the most common, although the latter has been declining in the last decade. An increasing number of patents is being filed in combined heat and power and combined cycles. Given the high efficiency of these technologies, this is an encouraging finding.

The remainder of the paper is organized as follows. Section 2 provides an overview of the electricity generation sector and underlines the importance of improving efficiency in the conversion of fossil fuels to electricity. Section 3 describes the frontier technologies for electricity production. Section 4 discusses the patent system and the selection methodology we adopted. Section 5 includes a descriptive analysis of

[1] The April 2010 release of PATSTAT has a comprehensive coverage including data from 92 patent offices worldwide.

past innovation trends. Section 6 concludes. Finally, Appendix I lists the technologies and the corresponding patent classification codes selected for this study.

2. The electricity sector: concerns for GHG emissions and energy security

Economic development has been mostly characterized by increasing use of energy as a production input. Fast-developing nations are currently witnessing similar dynamics, with energy use and intensity increasing as their economies and population grow and energy-intensive industrial sectors (such as cement and steel) rapidly expand (OECD 2009, IEA 2010). The developing countries' needs, coupled with the high energy consumption of developed countries, will translate into rising demand for energy. In the IEA Energy Technology Perspectives business as usual (BAU) scenario, primary energy use is expected to rise by 84% between 2007 and 2050 (ETP, 2010).

Fossil fuels were and are the major inputs to meet this energy demand[2] and of particular importance in the electricity sector. In 2007, coal and gas and oil accounted respectively for 42%, 21% and 6% of electricity generation, with a production of around 11 TWh. Predictions of future developments point to a significant role for fossil fuel electricity. In a BAU scenario, fossil fuels increase their share of electricity production slightly to reach almost 70% by 2050 (IEA, 2010).

As electricity production plays a major role in the overall emissions of GHG in the atmosphere, improvements in fossil fuel electricity generation are needed if climate change is to be addressed. The IPCC estimates that about 69% of all CO_2 emissions are energy related, while about 60% of all GHG emissions can be attributed to energy supply and energy use (IPCC, 2007). Currently, fossil electricity is responsible for 32% of global fossil fuel use and 41% of energy-related CO_2 emissions. In the future, according to a BAU scenario for the time period 2007-2050, CO_2 emissions could almost double due to continuous reliance on fossil fuels. However, potential CO_2 emission reductions from the electricity sector are very high and with appropriate policy to stimulate the deployment of existing and new low-carbon technologies, emissions by the electricity sector in an ambitious mitigation scenario could be reduced by 76% with respect to 2007 levels (IEA 2010).

Focusing on energy security, concerns are linked with the need to guarantee access to energy in face of rising prices resulting from increased demand for energy inputs. In addition, renewable sources (such as wind and solar) are still very costly relative to fossil electricity production, bound by geographical constraints or characterized by high intermittency. Due to the decentralised nature of renewable energy, these sources also face a somewhat different set of challenges, such as impact on the local environment and the accompanying resistance of local communities.

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[2] Fossil fuels accounted for 81.5% of the world primary energy supply in 2007 (OECD 2009) and are predicted to account for 80% in a BAU scenario by 2050 (IEA 2010). More in detail, coal accounts for 34% of primary energy use and is expected to become the predominant fuel. In absolute terms, primary demand for coal should be 138% higher in 2050 than in 2007. Oil should decline from 34% in 2007 to 25% in 2050, while natural gas is expected to stay constant at 21%. Liquid fuel demand increases by 58%, while primary demand for natural gas grows by 85%.

GHG emissions from fossil fuel-fired plants can be reduced by (1) improving conversion efficiency of existing plants through refurbishing[3], (2) deploying the best available technologies in new plants[4], (3) switching from coal to natural gas, (4) co-firing coal with biomass and adding biogas to natural gas, and (5) employing CCS.[5] The best combination of mitigation measures will depend on the existing power generation stock, the price of competing fuels and the cost of alternative technologies.

Improving the efficiency of fossil fuel energy is an opportunity to combat climate change, as lower energy intensity translates into lower GHG emissions per unit of production. Higher efficiency would also increase energy security, as it decreases the dependence on fossil fuel energy sources (at an unchanged level of demand or increasing the ability to meet a rising energy demand).[6]

A number of recently developed and potential technologies are expected to play a significant role in restructuring the fossil electricity sector. Deployment of these technological options will lead to an increase in average gross efficiency of fossil-fired generation in 2050.[7] The next section describes the technological options that may help reach higher levels of efficiency and decrease CO_2 emissions per unit of production.

3. Efficiency improving technologies for fossil electricity generation

This section reviews the most significant (efficiency-improving) developments in electricity generation technologies from fossil fuels including coal, natural gas and crude oil,[8] which are relevant for both the electricity supply industry (ESI) and for large "own" generation. Efficiency improvements have been achieved at various stages of the fuel-to-electricity conversion process.

First, efficiency gains have been achieved through improved combustion (more intermediate output - hot steam - per unit of input). These technologies use coal and natural gas and are at different levels of technological development. *Pulverised coal combustion* (PCC) is the most diffused technology in coal

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[3] An example is the replacement of an existing boiler or turbine with a newer one.

[4] For example, an old coal subcritical power plant can be replaced with a supercritical power plant.

[5] Carbon capture and storage (CCS) can be deployed only in efficient power plants since the process is energy-intensive. Increased efficiency is therefore a necessary condition for the deployment of CCS in power plants.

[6] The efficiency of fossil-fired plants depends on a range of factors including the technology employed, the type and quality of input used and operating conditions and practices. For example, average coal-fired generation efficiency in India in 2007 was 26% partly as a result of the widespread use of subcritical plants burning unwashed coal with high ash content, and of the use of coal-fired plants for peak load electricity production. By contrast, Denmark and Japan have some of the most efficient coal-fired power plants in the world, averaging efficiencies of almost 43% and 42% respectively, including a new generation of pulverised coal supercritical (SC) plants that were introduced in the 1990s (IEA 2010).

[7] Efficiency of coal-fired plants will change from around 32% to 50%, efficiency of coal-fired plants with CCS will be in the range of 45%, since the use of CCS incurs in a significant energy penalty. Efficiency of natural gas plants is expected to rise from 35% to almost 65%, while the efficiency of natural gas plants with CCS is expected to be around 55% (IEA 2010).

[8] We concentrate on coal and gas technologies because, as explained above, the role of oil in electricity production has been drastically reduced in the last few decades.

electricity generation (IEA 2010). PCC is divided in subcritical, supercritical and ultra-supercritical, depending on the pressures and the temperatures of the steam cycle and the consequent efficiencies achieved (higher in ultra-supercritical plants). A number of research efforts focus on increasing the efficiency of the existing technologies, in particular in the area of aerodynamic turbines, control equipments and achievement of higher temperatures.

Second, important efficiency gains have been achieved through 'integration' – that is, by combining alternative generation technologies in order to reduce waste at the level of the intermediate output. With respect to natural gas, the most widespread technology is the *natural gas combined cycle* (NGCC). This technology is the cleanest source of power available using fossil fuels and achieves the best-available efficiencies of about 60%. With respect to coal, *integrated gasification combined cycle* (IGCC) uses the fuel gas generated from the combustion of coal to run a turbine generator. The residual heat contained in the turbine is then used to produce electricity in a steam generator. IGCC is one of the electricity generation processes that are expected to play a central role in the next two decades (IEA 2008).

Third, additional improvements in efficiency have been achieved through better 'plant design' – notably by optimised production of alternative outputs (heat and electricity). *Combined heat and power* (CHP) involves simultaneous utilisation of heat and power from a single fuel source. CHP is well suited for all fossil fuels (and biomass) and is typically applied in district heating systems along with electricity generation. *Co-generation* is a proven technology and is mainly applied to industrial plants where both electricity and heat are needed. This technology achieves high levels of conversion efficiency, which could potentially reach 90 percent (IEA 2008).

To facilitate the identification of the relevant patent classes associated with the abovementioned electricity production processes, we divide the technologies in three groups according to the type of components involved: fuel preparation technologies, furnaces and burners, and boilers, turbines and engines. Often, it is possible to link each technology to a specific fuel (as in the case of coal gasification). In other cases, the mapping of the technology to the fuel inputs in not unique (such as boilers).

Table **1** summarises the technologies considered, which are then described in detail in the rest of this section, as well as the type of fuel they are applied to.

Table 1: Selected efficiency-improving technologies for fossil-fuel electricity generation

	Technology	Application
Fuel preparation technologies	Coal gasification	Coal
	Coal pulverisation	Coal
	Coal drying	Coal
Furnaces and burners	Improved burners	Coal, gas, oil
	Fluidised beds	Coal
Boilers, turbines and engines	Improved boilers for steam generation	Coal, gas, oil
	Improved steam engines	Coal, gas, oil
	Super-heaters	Coal, gas, oil
	Improved gas turbines	Coal, gas, oil
	Combined cycles (IGCC, NGCC, CHP)	Coal, gas, oil
	Improved compressed ignition engines	Oil
	CHP & co-generation (of electricity and heat)	Coal, gas, oil

3.1. Efficiency improving technologies for fossil electricity generation

Gasification is a method for extracting energy from many different types of organic materials. *Coal gasification* is a process that converts solid coal into carbon monoxide and hydrogen by reacting it at high temperatures with a controlled amount of oxygen and/or steam. The resulting gas mixture is called synthesis gas (or syngas). Syngas can then be used to produce electricity or manufacture chemicals, or also converted to liquid fuel. As with *coal liquefaction*, the benefit of this approach is that it improves combustion by producing a fuel (efficiency gains). Moreover, emissions of sulphur and nitrogen compounds are reduced and the basic technology can be applied to other fossil fuel feedstock, such as wood and biomass. During the 1970s, concerns over the supply of natural gas led to intensive R&D efforts in coal gasification but many of the R&D projects were discontinued as these concerns weakened.

Coal pulverization results in coal dust, a fine-powder form of coal produced by crushing, grinding or pulverizing of coal. Because of the brittle nature of coal, coal dust can be produced at mining, transportation, or by mechanically handling coal. A disadvantage is that coal dust suspended in air is explosive – it has far more surface area per unit weight than chunks of coal and is more susceptible to spontaneous combustion. Pulverized coal is currently the main input in electricity supply.

Low rank fuels such as sub-bituminous coals and lignite contain relatively large amounts of moisture compared to higher rank coals. High fuel moisture results in fuel handling problems and it affects station service power, heat rate, and stack gas emissions. *Coal drying* reduces fuel moisture and thus allows reducing water consumption by evaporative cooling towers, improving boiler performance and unit heat rate, and lowering emissions.

3.2. Furnaces and Burners

The process of converting fuel to electricity is rather similar for all types of fossil fuels. The first step after loading fuel into the plant is to burn it in giant burners or furnaces in order to release heat energy. Fuel combustion can take place in more or less conventional burners or in fluidized beds, which are currently considered to be an energy-efficient technology. In our search, we selected only patent classes that correspond to burners aimed at improvements in energy efficiency.

Burners are mechanical devices that burn fossil fuels in a controlled manner in order to generate heat energy. Whereas this is a conventional step, burners aimed at improving efficiency can also be used with different fuels or combinations of fuels. In other cases additional liquids are used to improve the heating process.

Conversely, *fluidised bed* combustion (FBC) has quickly won industry preference due to its ability to burn materials as diverse as low-grade coals, biomass, and industrial and municipal waste (Oka and Anthony 2004). Fluidised beds suspend solid fuels on upward-blowing jets of air during the combustion process. The result is a turbulent mixing of gas and solids which provides more effective chemical reactions and heat transfer. Fluidized-bed combustion evolved from efforts to find a combustion process able to control pollutant emissions without external emission controls (such as scrubbers). The technology burns fuel at temperatures of 760 to 930 °C, well below the threshold where nitrogen oxides form (at approximately 1370 °C, the nitrogen and oxygen atoms in the combustion air combine to form nitrogen oxide pollutants). The mixing action of the fluidized bed brings the flue gases into contact with a sulphur-absorbing chemical, such as limestone or dolomite. More than 95 percent of the sulphur pollutants in coal can be captured inside the boiler by the sorbent.

3.3. Boilers, Turbines and Engines

After the conversion of fuel into heat in the furnace, the next step is to convert the heat energy into mechanical energy. The heat energy is usually used to generate steam by means of a boiler. In the boiler, the heat from the furnace flows around pipes in order to boil water and produce steam. Steam is then used in gas turbines to produce kinetic energy, which is then converted to electric energy. Electricity plants can have a single engine or combine multiple types of engines in order to exploit the steam in different ways, and achieve greater conversion efficiency.

Boilers for steam generation achieve greater efficiency when combustion is homogeneous. This is achieved through spraying fine aerosol droplets into the boiler by a mechanical process, or through the action of an auxiliary fluid (air or steam) under pressure, or even through a combination of both. In *efficient steam engines* the pressure applied to steam is increased in order to better exploit its kinetic energy and thus increase conversion efficiency.

Process heaters and super-heaters are heat transfer units in which heat from fuel combustion is transferred to materials used in a production process (Sorrels 2002). The process fluid stream is heated primarily to raise the temperature for additional processing. They are devices used to raise temperature much above the boiling point of water, resulting in higher efficiency for the power plants (Wadhwa 2010). They are made of a group of tubes heated by the heat of flue gases going from the furnace to the chimney, which are used to heat the steam coming from the boiler.

Gas turbines are used to create mechanical energy from steam or gases. By means of an axial compressor, pressurised air is driven into combustion chambers where the fuel injectors are connected. During the combustion reaction, the gas is heated up and when its temperature reaches between 1000 and 1350 °C it is introduced into the turbine. These hot gases are depressurised in the turbine, which simultaneously drives both the air compressor and the alternator where electricity is generated. In the ‘open cycle’ configuration, combustion gases are released directly into the atmosphere at a temperature of >450 °C. The thermal efficiency is then between 30 and 40 percent. The conversion efficiency of gas turbines can be improved with the use of extra liquids.

Combined cycle can be defined as a combination of two thermal cycles in one power plant, thanks to which efficiency is higher than in single-cycle power plants (Kehlhofer et al. 1999). Thermal cycles can have different working media that can complement one another. In the power plant one cycle operates at higher temperature (topping cycle). The waste heat produced is then used in a second cycle operating at lower temperatures (bottoming cycle). The most usual combination will have a gas topping cycle and a water/steam bottoming cycle.

A *compressed ignition (diesel) engine* is an internal combustion engine which operates using the diesel cycle. Diesel engines use compression ignition, a process by which fuel is injected into compressed air in the combustion chamber causing the fuel to self-ignite.[9] Most diesel engines have large pistons, therefore drawing more air and fuel which results in a bigger and more powerful combustion. This was originally implemented in very large vehicles such as trucks, locomotives and ships, (and also as stationary engines for generation of electricity), as a more efficient alternative for the steam engine.

A major progress in realising greater conversion efficiency was achieved through *co-generation*, also referred to as 'combined generation of heat and power' (CHP). Compared with the conventional electricity generation step, in co-generation the heat generated in the process is utilised (recycled) for other uses.

In order to give some perspective, we also compare innovation trends in efficient fossil fuel technologies with overall patents in fossil fuel electricity generation and with total patent applications. Patents for the fossil fuel electricity generation sector as a whole have been selected by eliminating the restrictions on the technology's orientation towards mitigation or improvements in efficiency as well as by selecting those IPC classes that in general refer to fossil combustion technologies. This provides a benchmark to assess the trends in efficiency improving fossil technologies.

4. The patent system and the patent data selection

A patent is a legal title protecting a product or a process. Patents grant their owner a set of rights of exclusivity over an invention (a product or process that is new, involves an inventive step and is susceptible of industrial application) usually for a period of 20 years from the filing date and in the country or countries concerned by the protection. Article 28 of the Trade-Related Intellectual Property Rights (TRIPS) Agreement states that a patent confers the exclusive rights to prevent third parties not having the owner's consent from (a) making, using, offering for sale, selling, or importing the product or (b) using the process, and using, offering for sale, selling, or importing the product obtained directly by that process. In addition, the patent ensures the owner the right to assign, or transfer by succession, the patent and to conclude licensing contracts.

In order to obtain a patent, an inventor has to file an application to a patenting authority. The patenting office will check whether the application fulfils the relevant legal criteria and will grant or reject the patent accordingly. There are different alternative "routes" for patent protection available to inventors: the *national route*, the *international route* or the *regional route*.

In the national route, the inventor files an application with a national patent office (generally, but not always, the national office of the applicant's country). The first application filed worldwide (in any patent office) for a given invention is known as the priority application, to which a priority date is associated.

[9] This is in contrast to a gasoline engine, which is based on the Otto cycle, in which fuel and air are mixed before ignition is initiated by a spark plug.

If the inventor wishes to protect their invention in more than one country, under the standardized procedure of the Paris Convention,[10] she can file for protection in other Convention countries within 12 months of the priority filing. Although the time elapsed from the priority filing to the duplication filings can be up to 12 months, if the patent is eventually granted, protection applies from the priority date onwards in all the countries. Alternatively, inventors can use the PCT (Patent Cooperation Treaty) procedure, which has been in force since 1978 and is administered by the World Intellectual Property Organization (WIPO).[11] This is currently the most popular route among inventors targeting worldwide markets (OECD 2009). In all cases, the subsequent patent applications are called "duplicates", as opposed to the (first) priority application.

One last option for applicants is to submit a patent application to a regional office, such as the European Patent Office (EPO), established in 1977, which searches and examines patent applications on behalf of member 38 countries. The EPO grants "European patents", which are valid in all the member states where the holder has validated his rights (OECD 2009).[12]

The EPO's Worldwide Patent Statistical Database (PATSTAT) is a patent statistics database produced by the European Patent Office (EPO). It has been developed in cooperation with other members of the OECD Patent Statistics Taskforce.[13] PATSTAT includes raw patent data from over 90 patent offices worldwide, including regional offices and WIPO. The database includes the full set of bibliographic variables concerning each patent application, such as priority, application and publication numbers and dates, information on inventors and applicants, legal status, and references (citations) to prior-art patents and to non-patent literature.

PATSTAT is therefore a very important resource for those interested in studying innovation and technology diffusion. In particular, it is possible to select patents pertaining to different technologies by using the patent's International Patent Classification (IPC) codes, developed by WIPO and assigned to each patent to classify the invention.

For the scope of this paper, we selected specific technology classes including efficient technologies for electricity generation. In order to develop the search strategy, we first conducted a careful and extensive review of technological developments in the area of fuel-efficient technologies for electricity generation

[10] The Paris Convention signed in 1883 and about 170 signatory countries in 2006.

[11] The PCT procedure makes it possible to delay national or regional procedures significantly (until the end of the thirtieth month from the priority date) through a unified filing procedure (see Chapter 3 of OECD 2009 for more details). Applicants therefore have more time to fulfil national requirements and can use the time to evaluate chances of obtaining patents and of exploiting the invention (such as estimating competition and find licensed parties).

[12] Validation may require translation into the national language and payment of national fees. In this national stage, European patents are subject to national laws.

[13] The taskforce members include the OECD Directorate for Science, Technology and Industry, the European Patent Office (EPO), the Japan Patent Office (JPO), the United States Patent and Trademark Office (USPTO), the World Intellectual Property Organisation (WIPO), the National Science Foundation (NSF), Eurostat, and the European Commission Directorate-General for Research.

described in the previous section. On this basis, we collected a set of technology-specific keywords. To determine the appropriate IPC classes related to each of the technologies considered, we first screened the titles and abstracts of patents found through keyword search. Only classes that were sufficiently 'clean' were retained (for example, class F27B15 for "Fluidised-bed furnaces"). Next, a sample of patents pertaining to a given IPC class was examined closely and classes containing excessive 'noise' were eliminated. These are for instance classes on incineration techniques applicable to different sectors (power generation, transport, heating, etc.). This iterative process has been repeated where necessary.

In some cases, when the noise was sufficiently systematic, we were able to exploit the multi-dimensional character of patents, i.e. the fact that a single patent may have several IPC classes assigned. We used these 'co-classes' to exclude patents that were not relevant to the desired technology groups. For example, to exclude the patent applications relative to motor vehicles, which are not within the scope of this paper, we eliminated the patents that are also classified in IPC classes describing motor vehicles technologies.

The complete list of selected IPC classifications used to extract patents from the April 2010 version of PATSTAT is provided in Appendix I. Note that the IPC classification does not allow us to distinguish between certain fuel preparation technologies. For instance, in coal pulverisation, it is not possible to differentiate between mills that deal specifically with coal as opposed to other kinds of material. Similarly, for coal drying, there is no distinction between patents specifically applied to this field, as opposed to drying bulky material in general. For this reason, these technologies are excluded from the dataset and empirical analysis.

5. Patent data description

We identified a total of 113,096 patent applications in efficiency-improving fossil electricity technologies deposited between 1978 and 2007.[14] These include 54,753 singular patents, 12,248 claimed priorities (CPs) and 46,095 duplicate patents.[15] Of these, 84,781 have information not only about the application office but also about the inventor country (see Table 2).[16] In the analysis that follows, we exploit the distinction between claimed priorities, duplicates and singular patents to (a) characterize the value of a given innovation and (b) describe the patterns of international technology transfer in efficient fossil technologies for electricity production.

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[14] We use data on patent applications between 1978 and 2007, a time period for which reliability is strongest.

[15] Claimed priorities are patents that are registered in a patent office and subsequently in other ones. Patents that have already previously been registered in other offices are referred to as duplicates. Note that we clean the data by eliminating all priority-duplicates couples with duplication lag smaller than zero or greater than 4. We also exclude cases where patents appear to be duplicated in the same country of their priority, a ramification of the complicated patenting process. Finally, in order to avoid double counting, duplicate patents which have given rise to duplicates themselves have been counted only once.

[16] For consistency, the analysis that follows is based only on those patents for which we have information on both the inventor country and the patenting authority.

Table 2: Patents in efficiency-improving fossil electricity technologies, 1978-2007

	Information on Inventor Country		
Type	**No**	**Yes**	**Total**
Duplicates	675	45,420	**46,095**
Claimed priorities	311	11,937	**12,248**
Singulars	32,380	22,373	**54,753**
Total	**33,366**	**79,730**	**113,096**

In particular, an inventor may decide to patent anywhere in the world if she intends to sell, use or licence the new technology in more than one market. One expects CPs (and duplicates) to be more valuable than singulars. Since the patenting procedure is costly, patenting in more than one country indicates that the inventor expects that his/her discovery will yield a higher stream of profits than if an invention is patented in a single country (for empirical evidence supporting this argument see Guellec and van Pottelsberghe 2000; Harhoff et al. 2003).[17] The difference between CPs and singulars helps distinguish between qualitatively different innovation efforts exerted by countries. We can therefore distinguish market-specific innovations from those that can have a more general "across the border" application.

When analyzing patents classified by the inventor's country, we can assess the quality of its inventive activity.[18] If we focus instead on the application authority, the distinction between CPs, singulars and duplicates illustrates the composition of a patent portfolio present in each national market. Note that while most inventors tend to first patent in their home country, this is not always the case. In our sample, about 67.1% of the priority (CP and singular) filings are patented in the home country(s) of the inventor(s). Conversely, the remaining 32.9% is applied for in countries different from the one of the inventor. As a result, the majority of duplicates are requested in a country different from the one where it was invented.

Conversely, when summarizing patent data based on the patenting office where patent applications are deposited, we can learn about the composition of a patent portfolio present in each national market. In what follows, we show descriptive statistics relating both to invention country (the country where the technology was invented) and application country (the market in which the technology is protected).

Looking at the duplication patterns of patents also allows for the analysis of technology transfer between countries. Patterns of duplication reflect both market/technology and non-market/information transfer between the sending country and the receiving country.

One important clarification is that our data and the statistics we show pertain to patent applications (and not granted patents). They therefore inform on the level of activity that is exerted at the country and international level, but does not allow us to distinguish those patent applications that subsequently passed the test of patentability, or to speculate in any way on the length of the patenting process.

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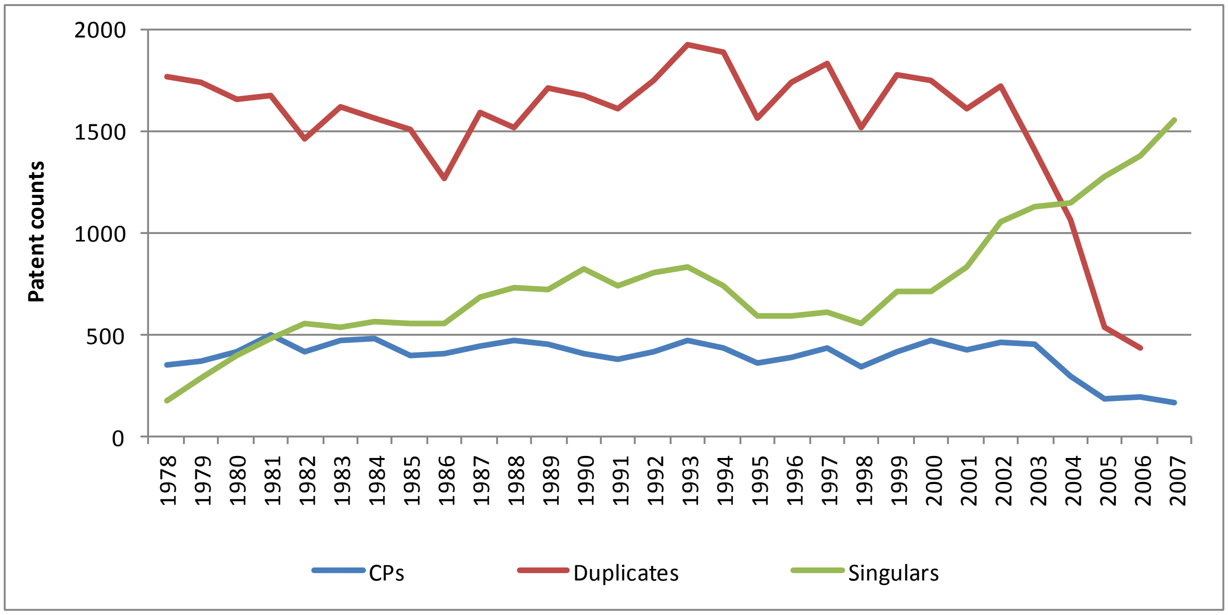
[17] The derivation of CPs based on an economic threshold criterion was advocated by Faust 1990.

[18] The address given in the patent document is usually the professional address of the inventor – e.g. the address of the lab at which the inventor works, but differences may exist across patent offices (OECD 2009).

5.1. Innovation over time

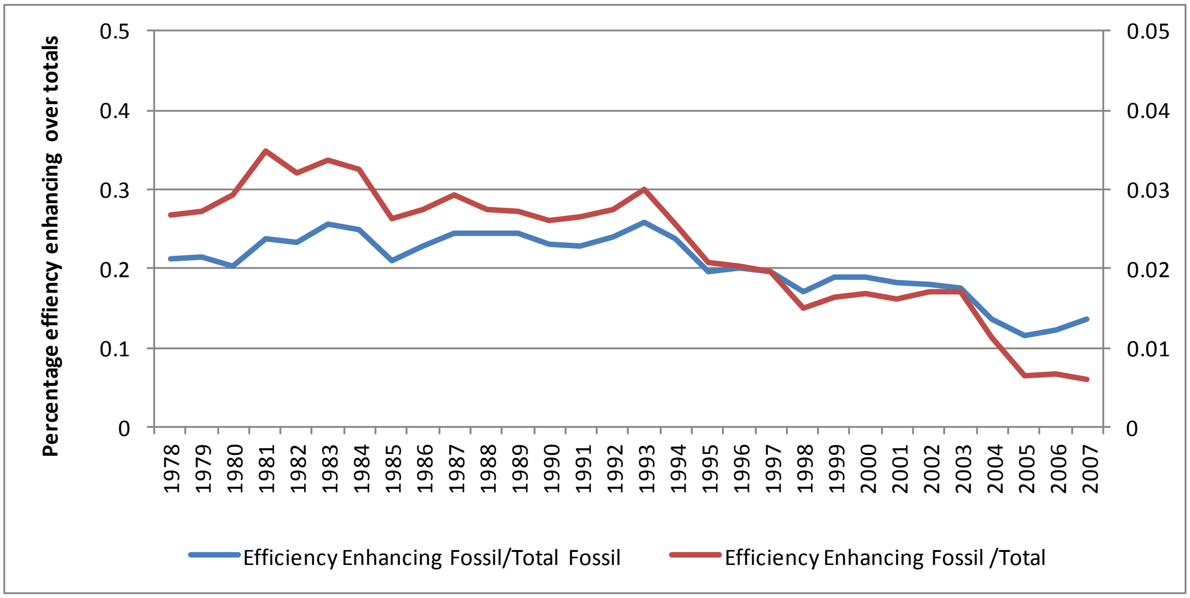
Patenting activity in efficient fossil fuel technologies has been rather stable and with a general slight positive increase over time, as illustrated in Figure 1. The decline of duplicates in the recent years (and hence decline in CPs) may be partially explained by publication lags of the duplicate applications. On the contrary, the increase of singulars in the recent years is attributable to a very strong growth in patenting in countries with a relatively low propensity to patent abroad (e.g., China, Korea).

Figure 1: Innovation in efficient fossil fuel technologies, 1978-2007



Nevertheless, if the patent activity in efficient technologies is considered as percentage of the whole fossil fuel electricity generation sector, there is a substantial decline from the mid-1990s, as illustrated in Figure 2. Not only has the rate of invention in efficient fossil declined relative to general fossil, it also declined relative to total patenting (in all technological fields, not only fossil). Thus, we can identify two interacting effects in the time dynamics of innovation in this sector. First, the rate of innovation in this specific field has declined from 23% in 1990 to 14% in 2007. Second, the rate of innovation has declined even more substantially relative to the trend in patenting overall (in all technological fields) – from 2.6% in 1990 to 0.6% in 2007. However, the latter may be partly attributable to phenomena like strategic patenting or the fast growth of patenting in fields such as pharmaceuticals and semi-conductors that have increased the number of total patents substantially, making the decrease in this sector appear stronger once the data are normalised over totals.

Figure 2: Percentage of efficient over general fossil fuel patents for electricity production (left axis) and over total patents (right axis)

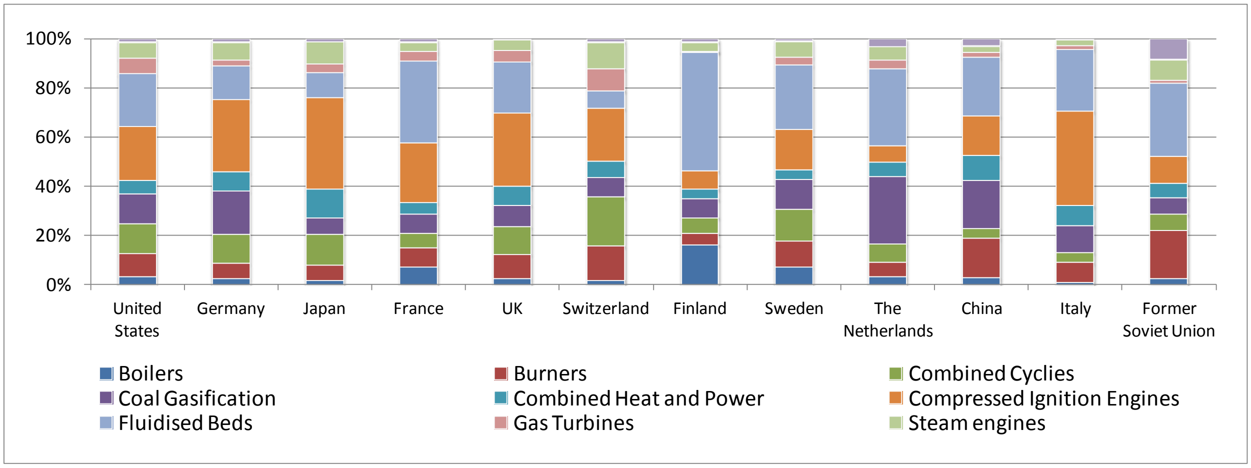


This evidence suggests a negative trend in innovation in efficiency improving fossil electricity technologies, which raises concerns with respect to the potential for GHGs emission reductions from fossil input. However, a number of other contributions have shown positive trends in innovation in renewable technologies (see for example Popp et al. 2010). As such this evidence may indicate a shift in inventive activity from fossil to renewable energy sources (see e.g., Lanzi et al. 2010).

5.2. Innovation by type of technology

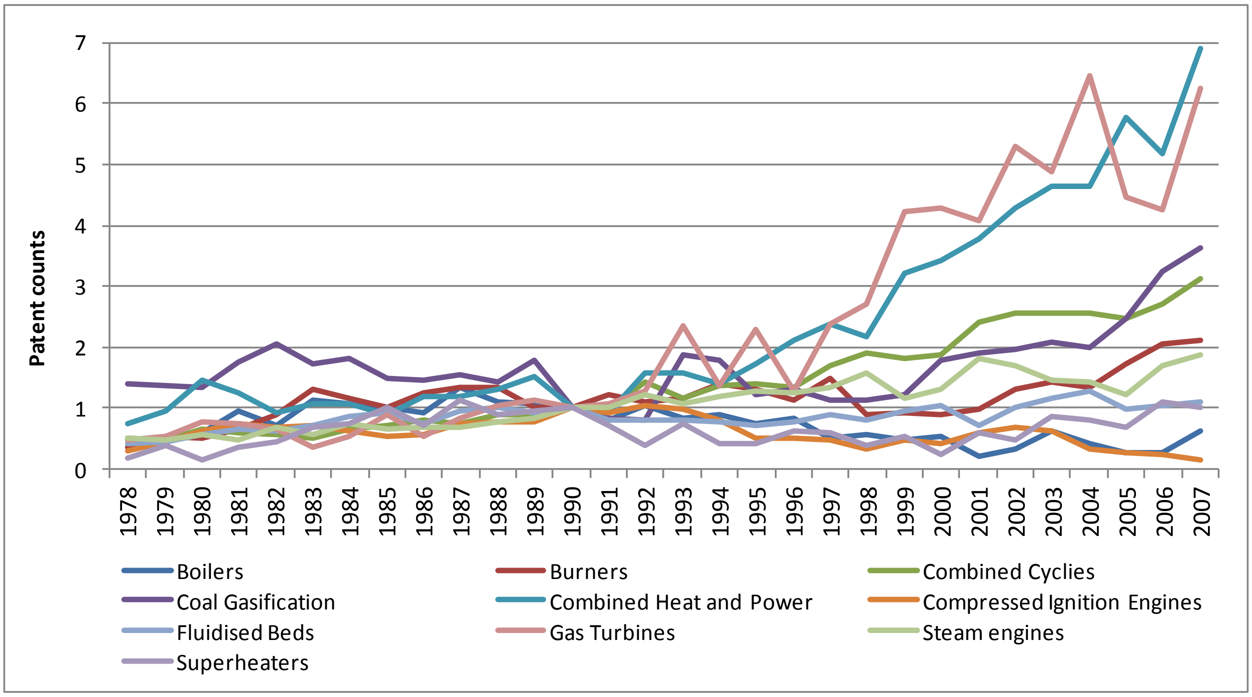
Analyzing the trends of patent application by single technology in different countries shows that there is a certain degree of specialisation (Figure 3). For instance Finland and the Netherlands have high counts of fluidised beds, but while Finland is specialized also in boilers, the Netherlands are more specialized in coal gasification. Innovation in Switzerland on the other hand focuses more on combined cycles and compressed ignition engines. Finally, the former USSR has particularly high counts in super-heaters and burners in addition to fluidized beds.

Figure 3: Distribution of national patenting (by inventor country) by technology



Looking at the evolution of technologies over time (Figure 4), we see that innovation in furnaces and burners, fuel preparation technologies (coal gasification) and boilers, turbines and engines has been rather stable. There has been a substantial increase in combined methods such as combined cycles and combined heat and power. This is an encouraging result given that these technologies are among the most efficient and that they offer flexibility in terms of type of fuel and applications.

Figure 4: Trends in patenting by technology (claimed priorities only)

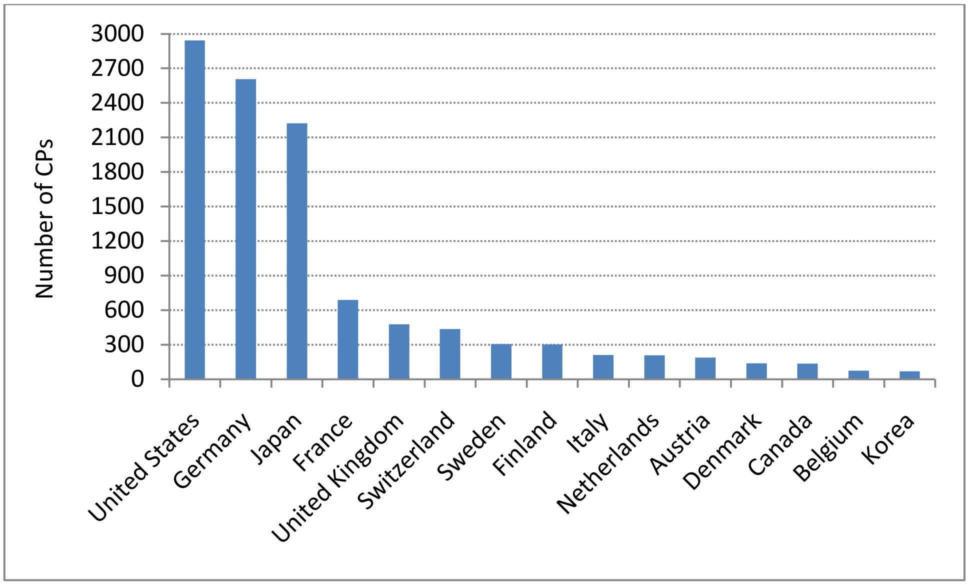


Note: Innovation in fossil fuel efficient technologies over time by technology (indexed at 1990)

5.3. Patents by inventor country

The majority of claimed priorities in efficient fossil fuel technologies for the production of electricity are applied for by inventors from the USA, Germany, and Japan (between 2224 and 2943 patents - Figure 5).[19]

Figure 5: Patenting by inventor country (counts of claimed priorities only, 1978-2007)

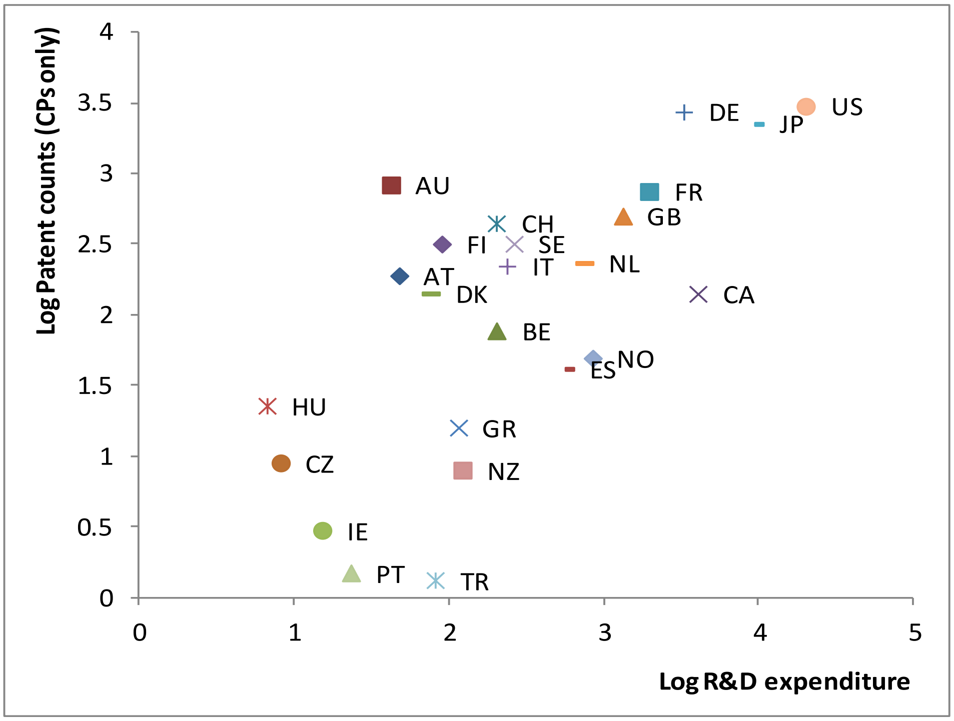


France, the UK and Switzerland follow, albeit with a significantly lower innovation level (between 434 and 687 patents). All other countries have less than 300 patent applications in efficiency improving fossil technologies over the whole period analyzed. This finding is hardly surprising, given that the majority of R&D investment (both general and energy-related) takes place in the developed OECD countries. Countries with the highest investments in R&D in fossil-fuel technologies are the USA, Germany and Japan (Figure 6)[20] and the correlation between efficient patents and R&D in this sector is quite strong (over the whole period it is higher than 0.80).

[19] For co-invented patents these calculations are performed by assigning an equal fractional percentage to each inventor country.

[20] R&D data are taken from IEA (2010).

Figure 6: Patenting and R&D expenditures for efficiency by inventor country (CPs only)

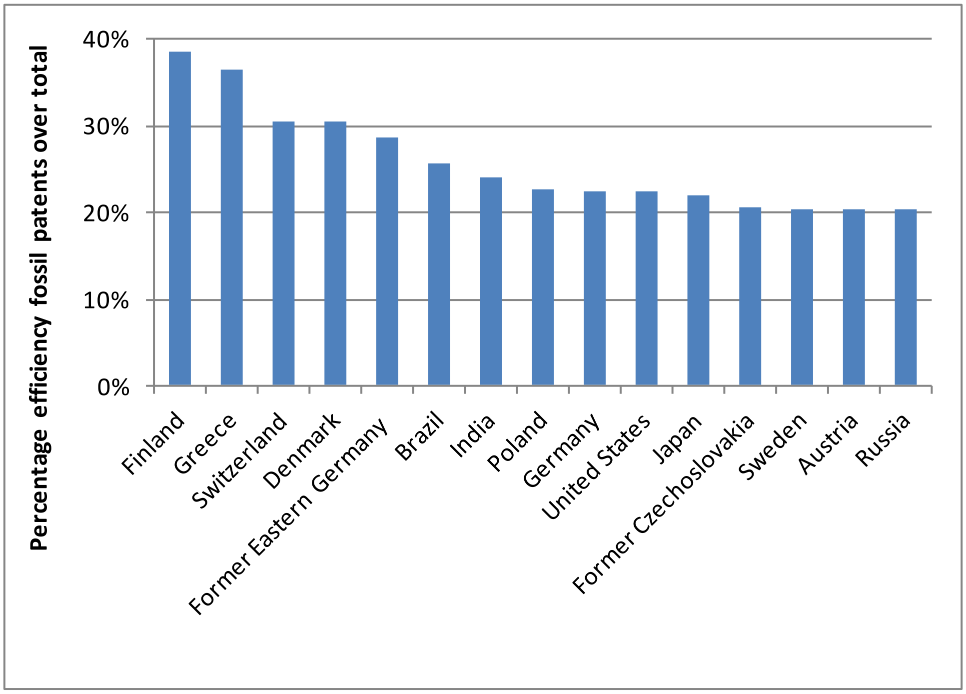


Country codes: Austria (AU), Australia (AT), Belgium (BE), Canada (CA), Switzerland (CH), Czech Republic (CZ), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), United Kingdom (GB), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Japan (JP), The Netherlands (NL), Norway (NO), New Zealand (NZ), Portugal (PT), Sweden (SE), Turkey (TR), United States (US)

Looking at the absolute value of CP counts shows the most important inventors in terms of volume. However, to assess the relative contribution of different countries in terms of efficient technologies in the fossil electricity production (as compared to overall innovation) we calculate the percentage of efficient technologies within fossil-related innovation.

Figure 7 shows countries with the highest ratios of efficient over general fossil-related patents, with Finland (38%), Greece (36.4%), Switzerland and Denmark (30.5%) having the highest share of fossil-related innovation characterized by efficient fuel use. Interestingly, a number of fast developing economies show a relatively high degree of specialization in efficient fossil-related innovation, including Brazil (25.7%) and India (24%). Conversely, the US and Japan, which in absolute terms have more patents than any other countries, rank only 10th and 11th, respectively.

Figure 7: Share of efficient over general fossil electricity patents (CPs), by inventor country



Note: Includes countries with at least 10 efficiency-related patents (claimed priorities) filed between 1978 and 2007.

5.4. Composition of patent portfolios

We now turn to the analysis of patent portfolios by inventor country. As explained above, the difference between CPs and singulars provides information on the value of inventions. Figure 8 shows the breakdown of patents between CPs, duplicates and singulars in top-innovating countries, including OECD and non-OECD countries and BRIC countries. As such, this Figure provides information about the 'value' and 'generality' of inventions originating from any given country'. We see that the USA and Germany produce most CPs, as already pointed out, but also a great number of market-specific innovations (singulars).[21] In addition, we notice that their CPs give rise to a high number of duplicate patents. The trend is similar for Japan, but for the fact that Japanese inventors produce more CPs (globally variable technologies) and singular (market specific technologies). This trend is also visible for the OECD countries at the aggregate level.

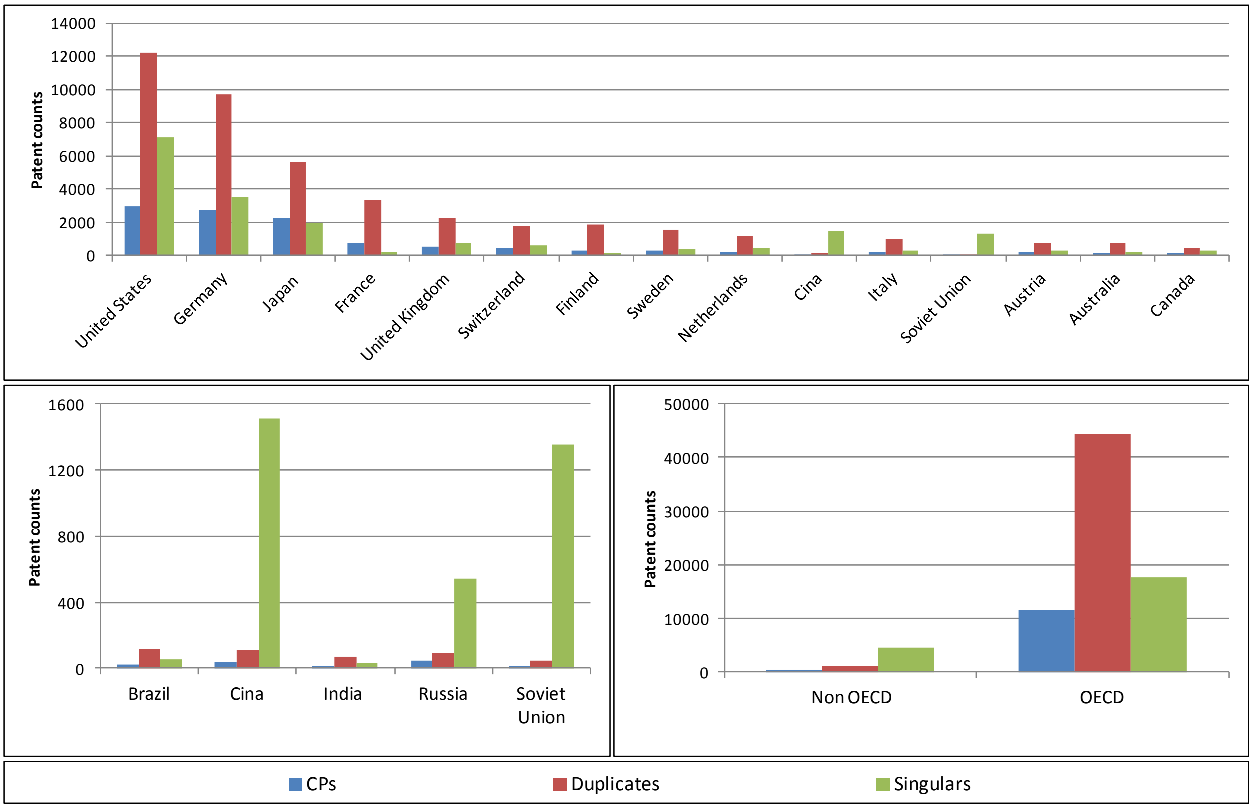
China, Russia and the former Soviet Union[22] show a completely different trend. Their patents are mostly market-specific and very few of their innovations are duplicated. This trend is representative of the non-OECD countries at the aggregate level, although there are important exceptions. Among the BRIC

[21] Theses might be different from the country of innovation, as explained above. See below for a more detailed analysis of cross-border patenting.

[22] We keep data for the former Soviet Union for comparison with current Russia.

countries, Brazil and India display a lower overall level of innovation in efficient fossil technologies for the production of electricity. However, they show a very different composition of the patent portfolio produced by their inventors, with singulars being lower in number than the duplicates deriving from their (very few) CPs. This could be taken as an indication of the higher "general marketability" of innovations from these countries.

Figure 8: CPs, Singulars and Duplicate patents by inventor country



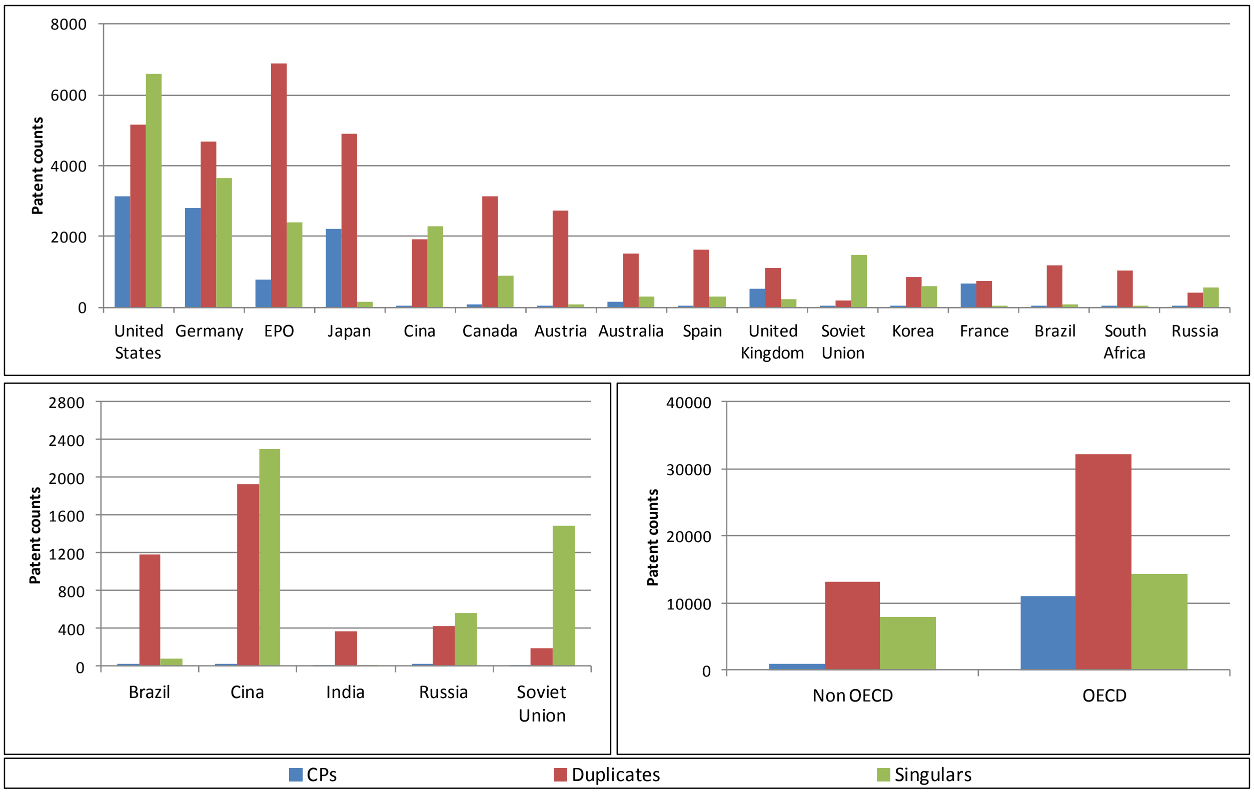
5.5. Cross border patenting

The analysis of patent portfolios can be also carried out by looking at the kind of patents protected in any market (thus looking at application authorities instead of inventor countries). In this case, analysing the composition of patent portfolio between CPs, singulars and duplicates informs on the 'quality' and 'generality' of patents available in any given country. It also highlights if a given market was the first target of a new invention (through a 'priority' application - CP or singular) or a subsequent target (through a duplicate).

Examining the portfolio of CPs, duplicates and singulars by application authority can also provide information on the relative importance of domestic versus foreign innovation in a given market for technology. To begin with, recall from Section 5.1 that around 67% of CPs are applied for in the country of the inventor and that the majority of duplicates are applied for in a country different from the inventors' country.

Figure 9 shows that in the biggest markets for technologies, which to a great extent coincide with the top inventor countries, all types of patents are widely represented: claimed priorities subsequently protected also in other markets, duplicate patents that have been claimed in other countries first and market-specific patents (singulars). This indicates that top innovating (richer) countries are both the first markets targeted (through CPs) and important duplication outlets.

Figure 9: CPs, Singulars and Duplicate patents by application authority



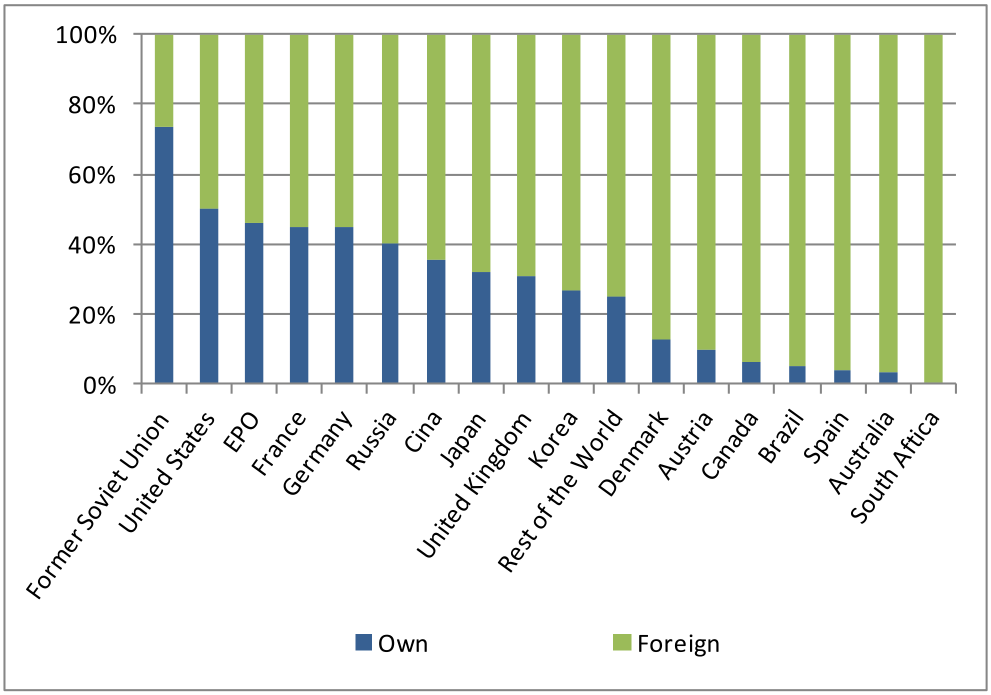
Notwithstanding these common trends, there are important differences among top markets for technologies. In the US there is a prevalence of singular patents, which have not been duplicated abroad. Among top inventors, this trend is common only to China and the former Soviet Union. In Japan and Germany there is a prevalence of duplicated patents, showing that these markets are attractive outlets also for foreign inventors. In particular, the Japanese market for efficiency improving technologies for fossil electricity production is characterized by a very low number of singular patents. With the exception of the UK and France (and China and the former Soviet Union, as mentioned above), all other countries are characterized by a predominance of duplicate patents. This indicates that in these markets a significant share of technologies are transferred from aboard but not developed specifically for that market.

Among the BRIC countries, China, Russia and the former Soviet Union are characterized by high levels of both market-specific and more global technologies, with the former being however predominant. India and Brazil, on the other hand, show a higher number of duplicate patents (from other priority markets) and very low number of market-specific innovation. The trend showed by Brazil and Russia is also representative of the non-OECD countries at the aggregate level.

The case of France is also interesting, as the level of singulars is very low. This could possibly be due to the fact that France has a high percentage of nuclear electricity production. As such, "market-specific innovations" (namely, singular patents) for France are not developed. On the other hand, most innovation is either also patented abroad (CPs) or transferred from abroad (duplicates).

As a result of the different composition of the national patent portfolios, we can also analyse the importance of foreign patents in any given market for technology. Figure 10 shows the heterogeneity of the top 17 markets for technologies. In the case of the USA, France, Germany and the European Patent Office,[23] patents of domestic versus foreign origin are of equal importance. Other countries, both developed and developing, rely more on foreign technologies than on own innovative capability. This is the case for countries such as Canada, Australia, Austria, but also Brazil and South Africa. Interestingly, the former Soviet Union relied extensively on own technologies. The trend is reversed in Russia, for which more than 60% of patent applications are foreign.

Figure 10: Domestic and Foreign Patents (CPs, Singulars and Duplicates) by Application Authority



[23] A domestic patent in the EPO is a patent application by any of the following countries: Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Liechtenstein, Luxembourg, Monaco, Netherlands, Portugal, Spain, Sweden, Switzerland, Turkey and the UK. These were the EU members as of 2000. Conversely, a foreign patent is a patent application by any other country.

5.6. Bilateral trends in technology transfer

This section focuses more specifically on bilateral technology transfer between the countries in our sample. Table 3 shows the trends of technology transfer between OECD and non-OECD patenting authorities. The majority of patents (68%) are duplicated from an OECD country to another OECD country. The flow of technology between OECD and non-OECD is also significant in our sample, and amounts to around 28%. On the contrary, CPs of non-OECD countries are rarely duplicated in OECD countries (3%). In addition, the flow of technology between two non-OECD countries represents less than 1% of the transfers in our sample. These trends in efficient fossil electricity generation are comparable with those found previously for other mitigation technologies (see e.g., Dechezleprêtre et al. 2011).

Table 3: Technology Transfer between OECD and non-OECD countries

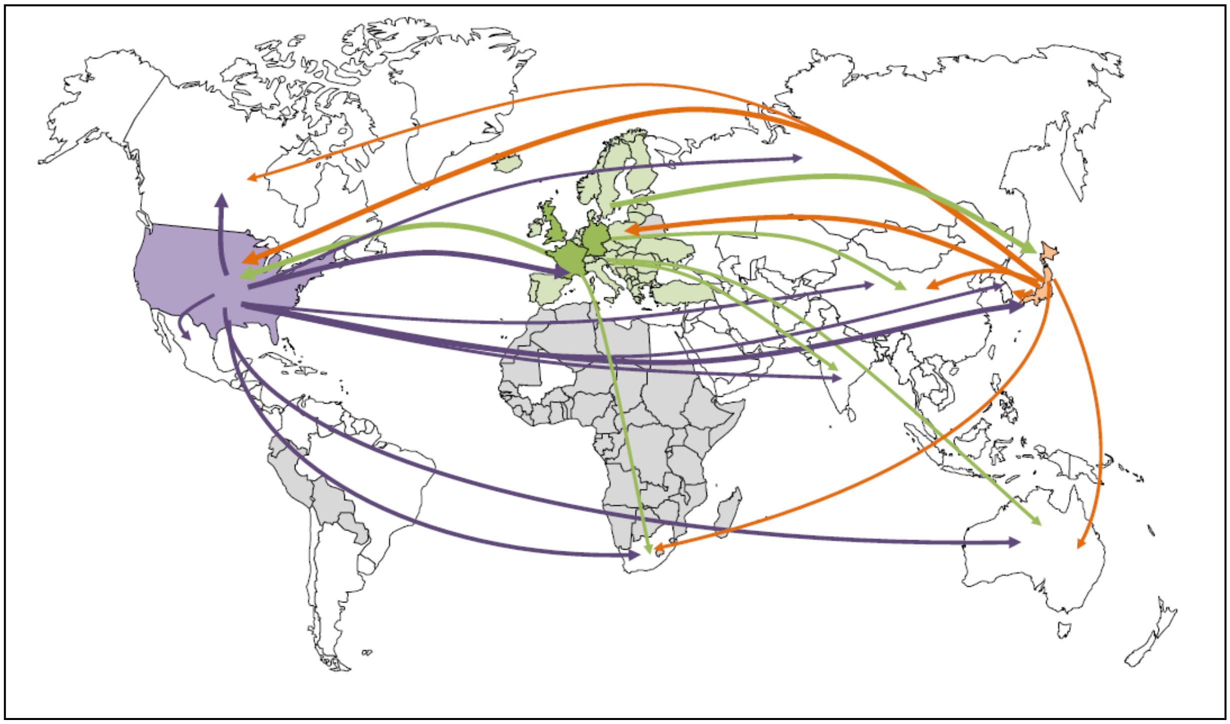
	Duplication Authority		
Priority Authority	**OECD**	**Non-OECD**	**Total**
OECD	68.4%	27.7%	39,812
Non-OECD	3.3%	0.6%	1,620
Total	29,708	11,724	41,432

Figure 11 and Table 4 explore in detail bilateral technology transfer and summarize the trends of patent duplication between priority authorities (in the first column) and duplicating authoring (across the top row).[24] Table 3 illustrates that, in general, the top priority countries are also the ones where most patents from other countries are duplicated. The US, Germany and Japan rank among the first both as sending and receiving. The European Patent Office (EPO), on the other hand, ranks 8th as a priority (origin) of duplicated patents, but ranks 1st as a destination of duplicates.

Among the BRIC countries, Brazil and China rank 19th and 24th respectively as priority (origin) of duplicate patents, while Russia and India do not appear within the top 24 countries. The BRIC countries receive a significant number of patents from priority offices of more developed (OECD) countries, with China being the 8th world receiver of duplicates, Brazil the 19th and India and Russia following in places 21th and 22nd. Figure 11 shows some of the flows of technologies commented so far, which are also shaded in Table 4.

[24] Recall that for 67% of CPs, application country and inventor country is the same.

Figure 11: Duplication of patents from priority to duplicating authority (1978-2007)



Note: The map shows major 'flows' among selected OECD and BRIC countries. Grey areas are those not covered by PATSTAT, the other ones show there most patents are registered. The EU is considered as a whole, although darker countries correspond to major patent exporters. The arrows illustrate the transfers and their magnitude. Thus a thicker arrow represents a larger technology transfer.

Table 4: Pattern of patent duplication from priority authority to duplicating authority, 1978-2007

Priority Office	Duplication Authority																										
	Singulars	CPs	Duplicates	EP	US	JP	DE	CA	AU	AT	CN	ES	BR	GB	ZA	DK	FR	KR	NO	FI	PL	IT	MX	IN	RU	SE	CZ	PT	ROW
US	6315	2868	12028	1731	0	1732	1344	1544	1027	247	482	381	440	350	275	109	177	221	164	106	103	131	270	128	114	85	83	48	736
DE	3521	2530	9316	1705	1397	1275	0	353	416	418	251	366	225	359	287	217	325	75	94	111	154	177	41	85	64	75	71	44	731
JP	145	2176	6038	1097	1705	0	1226	284	192	33	418	86	43	154	11	68	92	288	38	25	16	35	12	19	18	20	11	11	136
FR	14	605	2956	524	339	289	389	164	91	141	71	191	82	30	87	68	0	37	41	55	27	28	13	47	20	11	7	32	172
GB	229	453	2164	317	287	228	235	150	192	67	54	68	66	0	104	36	24	19	39	21	16	12	11	25	17	2	8	8	158
SE	56	267	1349	172	188	166	178	44	78	52	24	69	38	28	11	66	19	10	33	72	13	4	5	8	10	0	4	10	47
FI	123	238	1307	161	151	115	139	91	108	96	55	55	24	14	16	31	9	23	13	0	27	3	7	3	19	29	14	11	93
EP	2209	357	1284	0	116	118	231	25	44	367	83	44	15	3	18	56	1	22	8	18	15	1	2	5	7	0	4	8	73
IT	55	180	818	139	87	68	124	30	33	36	17	77	30	21	12	15	26	4	10	3	3	0	9	3	11	3	1	5	51
NL	29	125	716	97	68	74	83	52	65	41	9	28	17	7	29	21	6	3	15	9	6	4	4	12	3	3	0	10	50
CH	43	138	653	88	76	90	114	28	15	26	11	16	7	11	7	33	16	9	11	18	16	19	0	2	0	6	1	1	32
DK	114	89	550	57	40	59	60	20	39	24	29	32	16	5	7	0	2	20	21	18	14	3	5	3	14	2	3	9	48
AT	280	128	500	89	53	45	86	21	25	0	6	19	10	8	11	9	6	5	2	6	12	4	2	2	5	4	7	5	58
DD	588	60	210	2	1	9	56	0	6	12	1	1	0	13	0	2	10	0	0	3	10	2	0	4	0	3	0	0	75
KR	581	54	176	18	32	32	12	8	12	3	27	1	5	1	7	0	0	0	0	0	0	2	0	0	8	0	2	0	6
NO	109	34	175	21	20	18	13	12	17	4	5	3	4	5	3	7	3	0	0	9	2	0	0	0	4	6	2	0	17
CA	842	55	149	24	38	10	13	0	18	4	6	0	7	4	2	1	2	2	4	1	0	0	5	1	2	1	0	0	4
BE	27	31	120	26	14	11	12	6	9	7	4	4	5	0	2	2	0	1	2	2	2	0	0	0	1	0	2	2	6
AU	73	27	112	19	23	8	3	8	0	2	10	1	4	2	4	0	1	2	2	0	2	0	2	0	2	1	1	0	15
BR	82	20	91	9	9	6	9	5	3	2	4	1	0	8	1	1	4	0	3	1	1	2	4	0	1	5	0	3	9
HU	54	18	82	3	3	7	14	0	1	2	0	1	0	9	0	1	7	1	0	0	4	6	0	0	0	1	0	0	22
IL	5	14	77	9	10	5	6	4	7	1	0	4	3	2	4	1	2	0	0	0	0	2	2	1	2	2	0	2	8
ES	274	27	76	18	7	8	10	3	3	0	0	0	5	4	0	1	2	0	2	2	0	1	1	0	0	1	0	2	6
LU	13	29	74	11	6	5	10	1	4	6	1	6	0	2	0	2	2	0	2	0	0	2	0	0	0	2	0	2	10
CN	2302	24	64	9	17	8	2	5	10	1	0	1	2	0	1	1	0	0	1	0	0	0	0	0	2	0	0	1	3
ROW	3298	116	340	41	35	20	36	14	49	6	11	8	4	12	4	1	9	2	6	4	5	2	2	3	15	3	3	2	43

Note: Includes countries that are a source (priority office) of at least 60 duplicate patents or countries that are a destination (duplicate office) of at least 200 duplicate patents. The remaining duplicates are aggregated and shown as "rest of the world" (ROW). Selected transfers (above 100 duplicates) are shaded here and illustrated in the map in Figure 11.

6. Conclusion

This paper studies innovation dynamics in mitigation-oriented fossil electricity technologies using patent data. The patent dataset was obtained by selecting relevant IPC classes and using them to extract data on patent applications from the PATSTAT database. This paper contributes to improving the availability of data on innovation related to mitigation-oriented technologies. This is a significant contribution that allows extending research, so far focused mostly on renewable energy, energy efficiency in buildings or transportation. This increase in data availability will allow studying innovation in the electricity sector, which is one of the major contributors to GHG emissions.

We find that the USA, Japan and Germany produce most patented inventions in this sector, while other countries, such as Finland, Greece and Switzerland, as well as Brazil and India, show a higher degree of specialization. Patents in this sector have been stable over time, although with a slightly decreasing trend. The majority of patents are first filed in OECD countries and then in non-OECD or BRIC countries, which tend to protect innovations that are only marketed domestically. The prevailing technologies are fluidized beds and ignition engines, although the latter has shown a declining trend in the last decade. An increasing number of patents is being filed in combined heat and power and combined cycles. Given the high efficiency of these technologies, this is an encouraging result.

We also explore the dynamics of intended technology transfer both among developed countries and to developing countries, showing that the biggest innovators are also the ones which export more innovations. Among the top receiving market for technologies we find all the fast developing countries. This flow of patented fossil efficient technologies can significantly contribute to mitigating greenhouse gases emissions in the long run.

A number of topics can be explored using the data presented in this paper. This includes detailed studies of the contribution of patent and knowledge availability to electricity production efficiency and GHG emissions reduction (see, for example, Verdolini et al., 2010), or studies comparing innovation in the fossil and alternative electricity generation sectors (see, for example, Lanzi et al., 2010; Lanzi and Sue Wing, 2010). The availability of data on patent applications in efficiency improving fossil electricity generation technologies allows extending current results which are based only on patent applications from the USPTO (see, for example, Popp, 2002; Verdolini and Galeotti, forthcoming). Such studies provide useful guidance for the modelling community with respect to the construction and calibration of applied climate-economy models, in which the role of the energy sector is paramount.

Moreover, this data can be used to develop indicators of technology transfer and study issues such as the effect of national policy context on globalisation of innovation markets (see, e.g., Johnstone and Haščič 2011); study the determinants of technology transfer including the role of domestic absorptive capacity and other factors (see, e.g., Haščič and Johnstone 2011). Finally, the data could be used to develop indicators of co-invention and knowledge spillovers.

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Annex I – Description of IPC Codes

Table A1. IPC Codes for Efficiency Improving Fossil Fuel Technologies for Electricity Generation

COAL GASIFICATION	
C10J3	Production of combustible gases containing carbon monoxide from solid carbonaceous fuels
IMPROVED BURNERS	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F23C1	Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent
F23C5/24	Combustion apparatus characterized by the arrangement or mounting of burners; Disposition of burners to obtain a loop flame.
F23C6	Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel)
F23B10	Combustion apparatus characterized by the combination of two or more combustion chambers (using only solid fuel)
F23B30	Combustion apparatus with driven means for agitating the burning fuel; Combustion apparatus with driven means for advancing the burning fuel through the combustion chamber
F23B70	Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber
F23B80	Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel
F23D1	Burners for combustion of pulverulent fuel
F23D7	Burners in which drops of liquid fuel impinge on a surface
F23D17	Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel
FLUIDIZED BED COMBUSTION	
B01J8/20-22	Chemical or physical processes (and apparatus therefor) conducted in the presence of fluidised particles, with liquid as a fluidising medium
B01J8/24-30	Chemical or physical processes (and apparatus therefor) conducted in the presence of fluidised particles, according to "fluidised-bed" technique
F27B15	Fluidised-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion
F23C10	Apparatus in which combustion takes place in a fluidised bed of fuel or other particles
IMPROVED BOILERS FOR STEAM GENERATION	
F22B31	Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus
F22B33/14-16	Steam generation plants, e.g. comprising steam boilers of different types in mutual association; Combinations of low- and high-pressure boilers
IMPROVED STEAM ENGINES	
F01K3	Plants characterised by the use of steam or heat accumulators, or intermediate steam heaters, therein
F01K5	Plants characterised by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type
F01K23	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids

SUPERHEATERS	
F22G	Superheating of steam
IMPROVED GAS TURBINES	
F02C7/08-105	Gas turbine plants - Heating air supply before combustion, e.g. by exhaust gases
F02C7/12-143	Cooling of gas turbine plants
F02C7/30	Gas turbine plants - Preventing corrosion in gas-swept spaces
COMBINED CYCLES	
F01K23/02-10	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled
F02C3/20-36	Gas turbine plants characterised by the use of combustion products as the working fuel
F02C6/10-12	Combinations of gas-turbine plants with other apparatus; Supplying working fluid to a user, e.g. a chemical process, which returns working fluid to a turbine of the plant
IMPROVED COMPRESSED-IGNITION ENGINES	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F02B1/12-14	Engines characterised by fuel-air mixture compression ignition
F02B3/06-10	Engines characterised by air compression and subsequent fuel addition; with compression ignition
F02B7	Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel
F02B11	Engines characterised by both fuel-air mixture compression and air compression, or characterised by both positive ignition and compression ignition, e.g. in different cylinders
F02B13/02-04	Engines characterised by the introduction of liquid fuel into cylinders by use of auxiliary fluid; Compression ignition engines using air or gas for blowing fuel into compressed air in cylinder
F02B49	Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake.
COGENERATION	
F01K17/06	Use of steam or condensate extracted or exhausted from steam engine plant; Returning energy of steam, in exchanged form, to process, e.g. use of exhaust steam for drying solid fuel of plant
F01K27	Plants for converting heat or fluid energy into mechanical energy
F02C6/18	Using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants
F02G5	Profiting from waste heat of combustion engines
F25B27/02	Machines, plant, or systems using waste heat, e.g. from internal-combustion engines
TRADITIONAL FOSSIL FUELS	
C10J	Production of fuel gases by carburetting air or other gases without pyrolysis
E02B	Hydraulic Engineering
F01K	Steam engine plants; steam accumulators; engine plants not otherwise provided for; engines using special working fluids or cycles
F02C	Gas-turbine plants; air intakes for jet-propulsion plants; controlling fuel supply in air-breathing jet-propulsion plants
F22	Steam generation
F23	Combustion apparatus; combustion processes
F24J	Production or use of heat not otherwise provided for
F27	Furnaces; kilns; ovens; retorts
F28	Heat exchange in general
	Plus all of the energy efficient classes

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