Research Paper 22 | **2013**

KNOWLEDGE SPILLOVERS FROM RENEWABLE ENERGY TECHNOLOGIES, LESSONS FROM PATENT CITATIONS

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Knowledge spillovers

from renewable energy technologies:

Lessons from patent citations

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December 2013

Abstract

This paper studies the knowledge spillovers generated by renewable energy technologies, unraveling the technological fields that benefit from knowledge developed in storage, solar, wind, marine, hydropower, geothermal, waste and biomass energy technologies. Using citation data of patents in renewable technologies at 17 European countries over the 1978-2006 period, the analysis examines the relative importance of knowledge flows within the same specific technological field (intra-technology spillovers), to other technologies in the field of power-generation (inter-technology spillovers), and to technologies unrelated to power-generation (external-technology spillovers). The results show significant differences across various renewable technologies. While wind technologies mainly find applications within their own technological field, a large share of innovations in solar energy and storage technologies find applications outside the field of power generation, suggesting that solar technologies are more general and, therefore, may have a higher value for society. Finally, the knowledge from waste and biomass technologies is mainly exploited by fossil-fuel power-generating technologies. The paper discusses the implications of these results for the design of R&D policies for renewable energy innovation.

Keywords: Renewable energy, innovation, patents, knowledge spillovers, technology policy.

Acknowledgement. This study is part of the research project “Directed technical change and the environment” initiated by the Dutch Ministry of Economic Affairs. We are grateful to the representatives of Dutch ministries: Victor Joosen, Frans Duijnhouwer, Jochem van der Waals, Bert Knoester, Matthijs Neerbos; and our colleagues Rob Aalbers, George Gelauff, Free Huizinga, Bas Straathof, and Henry van der Wiel for their feedback during the project. We also would like to thank Ivan Haščič from the OECD for providing us with the most updated classification codes on technologies for the analysis.

The program and data files that the authors used for the analysis in this paper are available upon request at v.shestalova@cpb.nl.

1. Introduction

Climate change mitigation will require the increasing development of renewable energy technologies in the power generating sector. Today, renewable energy sources, such as solar, wind, geothermal, marine, hydropower, waste and biomass energy, represent only 19% of electricity production against 52% for fossil-fuels[1] (EEA, 2009). Increasing the share of electricity produced by renewable sources could thus greatly reduce the levels of greenhouse gas emissions from the power generation sector, currently responsible for about 30% of carbon emissions in Europe. Technological innovation is key to lower the costs of renewable energy technologies, as today even the most advanced renewable energy technologies, such as onshore wind power plants, are still too costly compared to traditional fossil-fuel technologies (IEA, 2011).

Public policies play an important role in stimulating innovation in this sector, since private firms have too weak incentives to invest in clean technologies (Jaffe et al., 2005). This occurs because the consequence of pollution is not borne by the firm itself but by third parties (the so-called 'environmental externality') and because innovating firms cannot prevent other firms from benefiting from their new knowledge (the 'knowledge externality'). Recently, the economic literature has pointed to another obstacle to the development of clean innovation, namely the presence of 'path-dependency' in knowledge production (Acemoglu et al., 2012). This literature argues that, without policy intervention, firms that have innovated a lot in polluting technologies in the past will continue to do so in the future. The underlying argument is that knowledge builds on the 'shoulders of giants', i.e. future innovations in a technology are building on the existing stock of knowledge in that technology. Since dirty technologies have historically accumulated a larger knowledge stock than new clean technologies, they continue to benefit from greater knowledge spillovers which further increase their advantage over clean technologies. As a result, public policies need to combine the standard environmental policies (such as carbon taxes or permits) with R&D subsidies to increase knowledge in clean technologies. Once the knowledge base in clean energy is large enough, firms will continue to innovate in this field; therefore, policy intervention is only temporary (Acemoglu et al., 2012, Aalbers et al., 2013).

This study aims to examine the extent of knowledge spillovers generated by renewable energy technologies. Since knowledge is a public good, part of an inventor's original idea necessarily spills to other firms, other sectors and other technological areas, generating positive externalities (the so-called 'knowledge spillovers') for the economy. The question addressed in this study is: Where does the knowledge from renewable energy go to? Or in other words: which technologies build on knowledge

[1] The rest being nuclear energy. Renewable energy is mostly hydropower.

developed in renewable energy? This question is relevant for the design of technology policy for renewable innovation for several reasons. First, public policies are generally predicated on the extent of knowledge spillovers and, typically, inventions generating larger knowledge spillovers and finding applications across a broader set of sectors are deemed to receive more public support since they have a high value for society. Hence, if renewable (REN) technologies generate more spillovers than fossil fuel (FF) technologies, or if solar technologies generate larger spillovers than wind technologies, these technologies may be eligible for more governmental support. Second, a better understanding of cross- (or within-) technology spillovers sheds light on the importance of path-dependency in knowledge creation. More precisely, it shows how much knowledge from REN technologies 'spills over' to new technical advances in both REN and FF areas. If inventors in renewable energy mostly learn from knowledge developed in REN technologies and not from external knowledge, then R&D subsidies targeted at REN energy will be particularly useful to increase the knowledge base of REN innovation.

We analyze the knowledge flows from renewable technologies to other technologies, using citations of patents in eight renewable energy technologies filed in 17 European countries over the 1978-2006 period. Along the analysis, we compare the results for renewable technologies with those for fossil-fuel power-generation technologies. We make a distinction between intra-technology knowledge spillovers (knowledge flows within the same technology), inter-technology spillovers (knowledge flows to other REN and FF power-generating technologies) and external technology spillovers (knowledge flows to unrelated technologies outside the field), which are measured by the respective numbers of patent citations. We find significant differences across the various technologies. While wind technologies mainly find applications within their own technological field, a large share of innovations in solar energy and storage technologies find applications outside the field of power generation, suggesting that these technologies are more general, and therefore may be more valuable to society. Finally, the knowledge from waste and biomass technologies is mainly exploited by fossil-fuel power-generating technologies.

Our work is related to the empirical literature using patent counts to measure innovation in energy technologies (Popp, 2002, Dekker et al, 2012, Johnstone and Haščič, 2010, Braun et al., 2011, Noailly and Smeets, 2013). There are two main strands in the literature looking at knowledge spillovers of energy technologies. The first strand of the literature is concerned with estimating knowledge spillovers as the effects of past knowledge stocks on current innovation in energy technologies. Looking at patents in eleven different energy technologies, Popp (2002) finds clear evidence for significant intra-technology knowledge spillovers. Johnstone and Haščič (2010) find evidence for inter-technology spillovers, as they find that past knowledge accumulated in storage technologies has a positive impact on innovation in other clean technologies, especially intermittent technologies. Noailly and Smeets (2013) find that the past accumulated knowledge stock in fossil-fuel technologies has a positive, yet only minor, impact on current innovation in renewable technologies for some large firms conducting both renewable and fossil-fuel innovations. Finally, Braun et al. (2011) find that solar and wind innovation greatly benefit from intra-technology spillovers. Yet, only wind seems to be affected by inter-sectoral spillovers (mainly from the field of energy machinery). By contrast to these studies that focus on the effects of the accumulated knowledge stock on future innovation, the current analysis gives insights in the process of knowledge flows between inventors, showing how these knowledge flows are formed.

Hence, our study fits into the second strand of the literature, which investigates knowledge spillovers using data on patents citations, assuming that references included in patents represent a learning trail from one inventor to the other. Nemet (2012) finds that most valuable advances in energy technology, i.e. most frequently cited inventions, make use of knowledge originating in other technological areas, suggesting that 'external' knowledge, acquired from outside the field of energy, has been essential to the most important energy inventions. Our work is more closely related to Popp and Newell (2012) who use patent citations to address the question of the social value of energy R&D, in comparison to non-energy technologies. After correcting for factors that affect the likelihood of citations, they find that energy patents have more chance to be cited than other patents and that they are also more 'general' than other patents (i.e., they contribute to a broader set of patent classes). Popp and Newell (2012) conclude therefore that energy technologies can be compared to general purpose technologies. Also the recently released citation analysis by Dechezleprêtre et al. (2013), covering four technological fields – namely, energy production, automobiles, fuel, and lighting – finds that clean inventions generate substantially more knowledge spillovers than dirty inventions. The analysis shows that, on average, clean patented inventions receive 43% more citations than dirty inventions, thus supporting the view that stronger public support for clean R&D is warranted. Compared to these studies, we provide novel evidence on how the direction of spillover effects varies across diverse REN technologies, as well as compared to FF technologies for electricity generation. This new evidence is informative with respect to the degree of path dependencies in this sector, and therefore, also relevant in the context of allocation of public R&D within the sector (see Aalbers et al., 2013, for discussion).

The study is organized as follows. Section 2 describes the patent data used in the analysis. Section 3 presents the results on knowledge spillovers; and Section 4 concludes and draws implications for policies.

2. Data

2.1 Patents data and citations

Following the recent empirical literature on innovation in energy technologies, we measure innovation by patents counts (Popp, 2002, Dekker et al, 2012, Johnstone and Haščič, 2010). Since the pioneering work by Grilliches (1990), patents have become a popular measure of innovations for the following reasons: (i) at the macro-economic level, patent activity over time is linked to the returns to R&D (Caballero and Jaffe, 1993); (ii) comprehensive data are available; (iii) technical characteristics are described in detail; (iv) the categories are well documented; and (v) it is possible to track definitions over time.[2]

We consider patent applications in the field of renewable (REN) and fossil-fuels (FF) power generation technologies filed at the European Patent Office and 17 national European patent offices (EU-15, Norway, Switzerland) over the 1978-2006 period. The patent invention data are extracted from the EPO/OECD World Patent Statistical Database (PATSTAT). For each patent application, we have information on the year of application, the field of invention given by the International Patent Classification (IPC) code, and the citations, i.e. the references to prior art used by this patent.

We focus on patents in eight renewable and eight fossil-fuels technologies selected using the relevant IPC codes for each technology[3] as borrowed from earlier work by Johnstone et al. (2010) for renewable technologies, Johnstone and Haščič (2010) for storage technologies, Lanzi et al. (2011) and Haščič et al. (2009) for fossil-fuel technologies. Table 1 summarizes the REN and FF technologies that we investigate in this study.

[2] Yet, there are also drawbacks to patents data: (i) not everything is patentable; (ii) not all patents are equally important; (iii) the data are affected by strategic behavior of some applicants and inventors, such as strategic patenting or the preference of secrecy. Nevertheless, most of these issues can be addressed by adding the required controls.

[3] Details on the IPC codes are given in Appendix 1. We thank Ivan Haščič from the OECD for providing us with the most updated classification codes.

Table 1. Technology classes included in this study

REN technologies	FF technologies
wind **solar** **geo:** geothermal **marine**: ocean energy **hydro***:* hydropower energy **biomass** **waste** **storage***:* batteries for electricity storage	**coal:** production of fuel gases by carbureting air **engines:** steam engines plants **turbines:** gas turbines plants **hotgas:** hot-gas or combustion-product positive displacement engine **steam:** steam generation **burners:** combustion apparatus **furnaces** **ignition:** improved compressed-ignition engines

Patent applications often include citations to prior art added by the patents' applicants. There is a well-established literature arguing that patent citations represent a form of learning trail or knowledge flow from one inventor to the other. The analysis of R&D manager surveys by Jaffe et al. (2000) shows that patent citations do provide a reasonably good indication of communication between inventors in the knowledge transfer process. According to Jaffe et al. (1993), forward citations can measure "knowledge spillovers" under the assumption that "a citation of Patent X by Patent Y means that X represents a piece of previously existing knowledge upon which Y builds".

For each patent, two types of citations can be identified: 1) *backward citations* are the citations made by the current patent: this reflects the knowledge on which the current patent builds on (Jaffe et al., 2000); 2) *forward citations* are the citations subsequently received by the patent over time; reflecting the knowledge spillover from this patent to follow-on inventions. The number of forward citations also reflects the value of the inventions since highly-valuable patents tend to be cited more often (Trajtenberg, 1990). In our empirical analysis in Section 3, we will focus on *forward citations* to analyze the knowledge flows from each REN technology to other technologies, which we will also compare to knowledge flows from FF technologies.[4]

To enable citation analysis, we link our dataset of European energy-technology patents to data of their backward and forward citations by other patents. Since European patents also contribute to the knowledge developing outside Europe, we also consider citations by patents filed at the US Patent Office and at the Japanese Patent Office, as these two countries are the largest contributors to the world patents. There are several caveats to be aware of when working with patent citations. First, it is important to

[4] By contrast to forward citations, backward citations reflect the knowledge flows from other technologies to REN technologies, giving insights on the technologies on which REN innovations build on. In a companion paper, we provide a more detailed analysis of the pattern of backward citations, which shows close similarities with the pattern of forward citations (Noailly and Shestalova, 2013).

realize that not all the citations that are included in the patent are included by inventors. In some countries, notably the US, many references to prior art are added by patent attorneys and examiners; and there is evidence that examiners often add citations that were actually not known to the inventor. As examiner-added citations do not carry correct information on knowledge spillovers, this might affect our analysis of forward citations. Yet, since we present many of our results in terms of shares of citations our analysis is not vulnerable to bias, as long as the examiners are not biased towards a particular field and simply include more citations in all the fields.[5]

Second, some citations take place within the same family of patent, a patent family being a group of equivalent patents which have been granted in several different countries for the same invention. We thus exclude intra-family citations, for which both cited and citing patents were referring to the same invention. The share of patents including intra-family citations, however, is negligible (about 1%) and leaving them in the dataset would not significantly affect the result.

Third, we also exclude self-citations from the analysis. Presumably citations to patents that belong to the same assignee represent transfers of knowledge that are mostly internalized, whereas citations to patents of "others" are closer to the pure notion of spillovers.[6] Furthermore, firms may include self-citations for strategic reasons. The share of self-citations is of about 7% (about 2% of all citation records in total).[7]

At last, there are truncation issues for forward citations as the dataset cannot possibly include the patents that will be granted in the future. Related to this, the number of citations received by a patent is affected by the age of the patent. Earlier patents tend to be cited more often since they exist for a longer time period, thus, having more opportunities to be cited. We will correct for the likelihood of citation by conducting regression analysis in Section 3.

[5] In addition, we checked in Section 3 that our regression results are robust to excluding US and Japanese patents.

[6] Hall et al (2001) find that on average self-citations represent about 11% of all citations to US patents. For the US patents falling into the energy field, Nemet (2012) reports that 9.8% of records were self-citation pairs.

[7] These are the numbers on backward citations. In addition, 10% of patents will receive a forward citation by the same applicant.

2.2. Sample descriptives

Our dataset includes 156,312 European patent applications (hereafter: patents) in the selected energy technologies, among which 117,114 (75%) are from FF technologies, and 41,491 (25%) are from renewable technologies. About 1.5% of these patents fall into both categories.[8]

Figure 1 presents the evolution of the number of REN and FF patents over time. While the number of FF patents is largely above the number of REN patents over the most of the period, in recent years, the number of renewable energy patents has been catching up with the number of fossil-fuel energy patents, as the latter has been declining over time. Yet, the annual patent number in renewable technologies is still substantially lower than that in fossil-fuel technologies.

Figure1 Evolution of the total patent number for REN and FF technologies

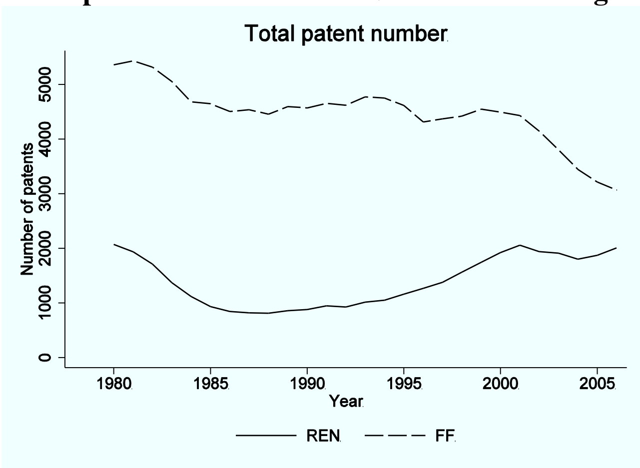


Figure 2 shows the evolution of patenting activities per technological field. Solar, storage and wind technologies represent the three largest technology classes of renewable energy patents accounting together for about 80% of all the patents in this group. These three technologies have experienced a renewed interest in the mid-1990s. While the number of REN patents rises after the oil crisis at the end of the 1970s, it then drops considerably in the 1980s and remains low until the mid-1990s. The number of patents in solar energy starts increasing slowly over the period to reach about 600 patents per year today. The increase in the number of wind patents at the end of the 1990s is also remarkable and is in line with the rise in installation capacity of wind turbines at that time, supported by government programs promoting wind energy (e.g., in Denmark, UK and Germany, see Klaassen et al. (2005)). Electricity

[8] In addition, there is overlap within each type. Some patents may for instance be classified into both waste and biomass, or into both wind and marine technologies. Nonetheless, 90% of all patents fall into a single technology category from our list of 16 technologies.

storage technologies reach a peak at around 600 patents in 2000 and decrease afterwards.[9] The number of patents in geothermal energy and biomass is almost negligible.[10]

Among fossil-fuel technologies, the largest categories are burners and furnaces, accounting for about 50,000 and 25,000 patents respectively as shown in Figure 2b. Over the 1978-2006 period the number of patents in most FF technologies has decreased over time, except for turbines. The large decrease in patenting on burners and furnaces in the last few years explains the drop in the total patenting intensity in FF towards the end of the period.

Figure 2 Evolution of patent numbers per technology: (a) REN technologies; (b) FF technologies

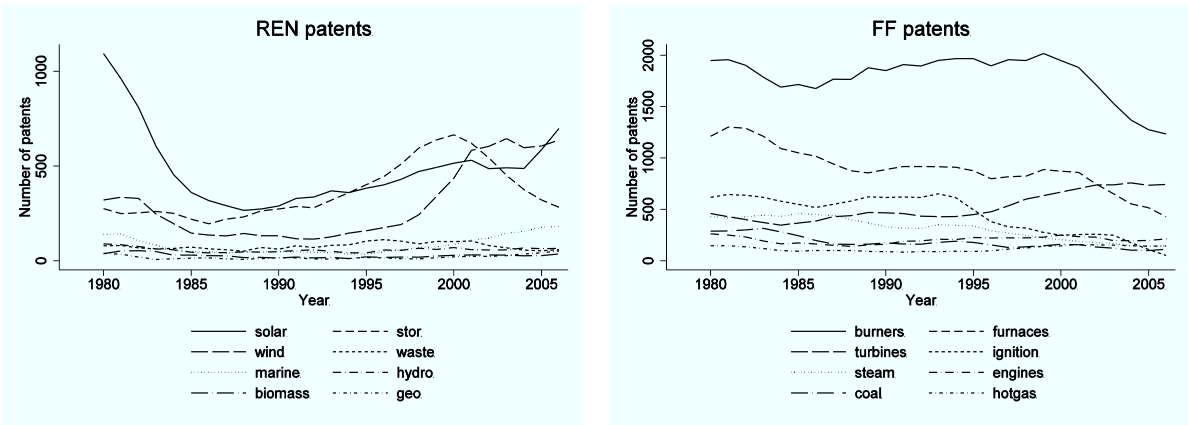


Table 2 summarizes descriptive statistics for both REN and FF technology types. REN patents are on average two years younger than FF patents (since the respective average application years are 1993 and 1991). We observe that, on average, patent applications of both technology types include roughly the same number of (backward) citations (4.8 and 4.4 for REN and FF respectively), and receive approximately the same average number of (forward) citations (3.4 for both types). Looking at the forward citation lag, we find that both REN and FF patents are cited on average 7.5 years after the patent application year.[11] 69% of patents in our sample have not received subsequent citations. The number of forward citations included in one patent ranges from 0 to 229. There is one patent in burner technology which is being cited 229 times in future work.

[9] Note that our classification codes for storage technologies (see Appendix 1) capture only the development in batteries, but not in other storage types, which have been recently actively developing, including pumped hydro-storage, compressed air energy storage, and hydrogen storage.

[10] As the number of patents in geothermal, waste, hydro and biomass energy is relatively small, most of our interpretation will therefore focus on the three main categories, namely solar, wind, and storage and to some extent waste/biomass and hydro/marine technologies.

[11] As expected, the lag is shorter for forward citations than for backward citations, since they cover only the period 1978-2006, while backward citations are tracked back to the 1900s.

Table 2 Descriptive statistics on citations

REN technologies	Obs	Mean	Std. Dev.	Min	Max
Application year	41491	1993,0	9,2	1978	2006
Num. of backward citations	17313	4.8	3.1	1	113
Num. of forward citations	13746	3.4	3.8	1	101
Backward citation lag	17241	12.7	9.9	0	100
Forward citation lag	13711	7.5	5.7	0	29
FF technologies	Obs	Mean	Std. Dev.	Min	Max
Application year	117114	1991.0	8,2	1978	2006
Num. of backward citations	49393	4.4	2.6	1	44
Num. of forward cit.	34637	3.4	3.9	1	229
Backward citation lag	49069	15.1	10.3	0	90
Forward citation lag	34552	7.4	4.8	0	30

3. Knowledge spillovers

In this section, we use forward citations to examine knowledge spillovers generated by the various REN and FF technologies. We aim to investigate which technological fields mostly benefit from knowledge in REN technologies.

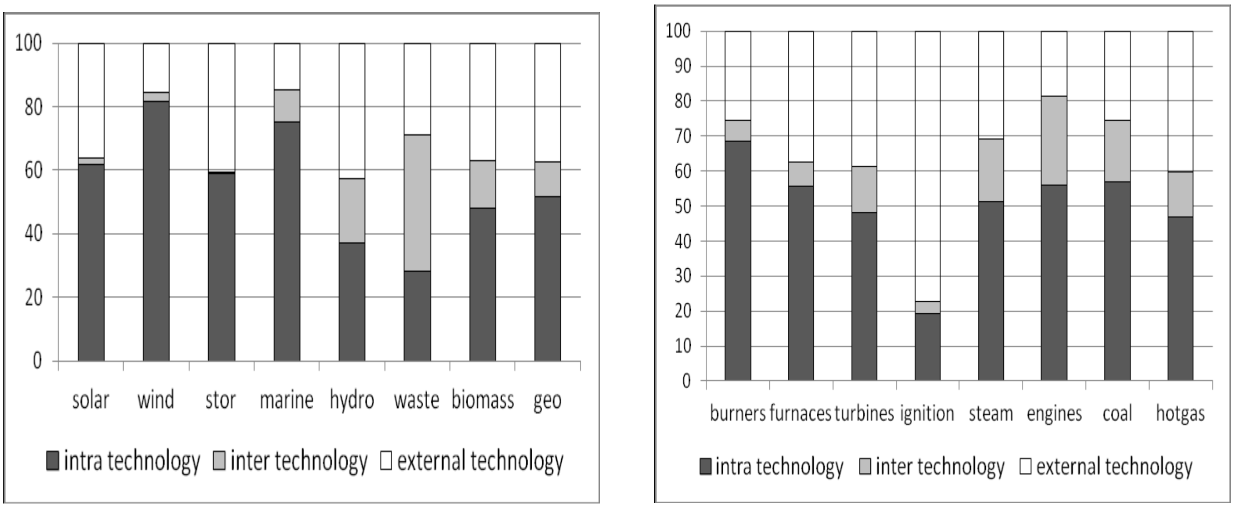
We focus on the subsample of 47,677 energy patents (one third of the total sample) that have been cited subsequently; and thus exclude the non-cited patents. Together, these patents represent 164,062 cited-citing patent pairs, which characterize the technological relationship between the two inventions. For each cited-citing pair, we consider whether the technology classes embedded in the two patents are the same (intra-technology spillovers), related to power generation (inter-technology spillovers) or unrelated (external technology spillovers) as in Jaffe et al. (1998). To clarify these concepts, we provide the following illustration of these three types of spillovers:

- *intra-technology* spillovers, e.g., both patents of the cited-citing pair are classified into the field of solar technologies;
- *inter-technology* spillovers, e.g., a solar patent is cited by a patent in a technological field related to power generating technologies (either REN or FF), but excluding solar;
- *external* spillovers, e.g., a solar patent is cited by a patent unrelated to power generating technologies, representing ‘external’ knowledge.

3.1. Descriptive results

The resulting allocation into the three types of knowledge spillovers per technology is shown in Figure 3, panels (a) and (b) for REN and FF technologies, respectively. The bars in Figure 3 represent the share of cited-citing pairs in each category of spillovers.

Figure 3. Forward citation categories per REN technology (a: on the left) and per FF technology (b: on the right)



Overall, most forward citations come from patents in the same technology, indicating that REN patents often find applications in the same technological fields. As shown in Figure 3 the share of intra-technology spillovers is generally high: on average, about 70% for REN and 60% for FF technologies. Among REN technologies, the share of intra-technology spillovers is very high for wind patents (above 80%), medium for solar and storage technologies (around 60%) and low for waste technologies (30%).[12] Hence, current innovation in wind, solar and storage depends for a large part on past innovation in these specific technologies, indicating some form of path-dependency in knowledge creation. Figure 3b also suggests that 50 to 70% of citations of the various FF technologies come from the same technological field, with a much lower share for ignition technologies (20%).

Looking at the share of inter-technology spillovers, i.e., spillovers to other related technologies in the field of power generation, Figure 3a shows that an important part of knowledge from waste, hydro and biomass technologies spills to other power-generation technologies. The shares of inter-technology spillovers of these technologies are 40%, 20% and 15%, respectively. By contrast, solar, wind and storage generate almost no inter-technology spillovers (less than 3%). A further disaggregation of these numbers reveals that knowledge embedded into waste technologies mainly spills over to FF technologies, in particular, to burners, steam, coal and furnaces technologies (see Table A1 in Appendix). For instance,

[12] Braun et al (2010) also find that intra-technology spillovers play a greater role for innovation in wind than in solar technologies.

51% of the citations of waste patents come from patents in burners technologies. This suggests that these technologies rely on the same type of knowledge, because technologies developed to burn one type of fuel (such as coal) may also be used to burn another type of fuel (namely waste or biomass). This has led to the development of co-firing techniques, using biomass and waste as supplementary fuel in coal and gas electricity generators and boilers (e.g., Maciejewska et al., 2006). In contrast, hydropower patents are mainly cited by innovations in marine technologies, and do not generate spillovers to FF-technologies. As seen in Figure 3b, FF technologies also generate small inter-technology spillovers, however, the share of inter-technology spillovers is more evenly distributed across the various FF technologies. About 20% of all citations to engines, steam and coal technologies come from other power-generation technologies. Only ignition technologies do not generate much inter-technology spillovers (4%).

The last notable result that emerges from Figure 3 is the relatively high share of external technology spillovers, both for REN and FF technologies. The share of forward citations to external technology is about 40% for most of the REN technologies, except for wind and marine technologies where the share is below 20%. Hydropower, storage, waste and solar in particular exhibit a relatively high share of external-technology spillovers. Regarding FF technologies, the share of external citations also ranges from 20 to 40%, with the notable exception of ignition for which 80% of the citations contributes to technologies outside power-generation technologies.

These insights on external-technology spillovers raise the question of what are the specific research fields outside power-generating technologies that benefit from knowledge in REN technologies. To further investigate this, we classify the external citations into technological sectors according to the WIPO Technology Concordance Table linking the International Patent Classification (IPC) symbols with 35 sectors (Schmoch, 2008). Table 4 illustrates the results for the REN technologies and one specific FF technology (coal).[13] We find that solar patents are mainly cited by other patents in the field of semiconductors, thermal processes and apparatus and civil engineering. Wind patents, but also marine and hydropower patents, are mainly cited by other patents in the field of electrical machinery, engines, pumps and turbines, mechanical elements, and transport; while storage patents are mainly cited by inventions in electrical machinery. Finally, waste and biomass patents find applications into the fields of basic materials chemistry, chemical engineering and environmental technology. These application areas overlap greatly with many of the technological fields that are also relevant for fossil-fuel technologies. Coal technologies, for instance, also find applications in these three technological areas.

[13] More details are given in Table A2 in Appendix. In these tables, we exclude the patents directly related to power-generation (as defined by the IPC codes listed in Table A3 in Appendix). Yet, some patents classified as ‘external’ to power generation may still fall into the field of ‘electrical machinery’ for instance.

Table 4. External technological fields receiving the highest (>10%) spillovers from REN technologies See Table A2 in Appendix for a more detailed list.

	% external-spillovers		% external-spillovers
solar		**hydro**	
Semiconductors	13	Engines, pumps, turbines	25
Civil engineering	12	Civil engineering	18
Thermal processes and apparatus	11	Electrical machinery	16
		Mechanical elements	13
wind		**biomass**	
Electrical machinery	24	Basic materials chemistry	34
Transport	20	Environmental technology	11
Engines, pumps, turbines	14	Chemical engineering	10
Mechanical elements	10	Machine tools	10
storage		**waste**	
Electrical machinery	61	Basic materials chemistry	21
		Environmental technology	19
		Chemical engineering	18
marine		**coal**	
Engines, pumps and turbines	40	Basic materials chemistry	22
Electrical machinery	21	Materials, metallurgy	19
Transport	12	Chemical engineering	18
		Environmental technology	14

What explains that some REN technologies find applications only in a small number of technological fields while others find application in a much broader set of technologies? A first potential explanation is that this technologies combining knowledge from one or more technology areas are by definition ‘technically close’ to those areas. Solar technologies for instance are technically close to semiconductor technologies and, therefore, there are interactions between the two knowledge bases (Nemet, 2012). Second, the power generation sector is characterized by the presence of large firms. Knowledge spillovers across various technological fields are more likely to arise within large firms seeking to exploit scope economies. For example, large multinational firms, which have an innovation history in a given FF technology (e.g. burners) may want to diversify their technology portfolios and start innovating either in other FF technology fields or in waste technologies, a renewable technology related to their specialization in FF technologies (Noailly and Smeets, 2013).

3.2. Regression results

An important issue when analyzing patent citations is that the likelihood for a patent to be cited varies over time. Earlier patents are cited more often than later patents since they have more opportunity to be cited, and they precede to a larger set of patents that can cite them. Newer patents also tend to have more citations reflecting the increasing use of computerized searchable databases. In Figure 3, the shares of citations could be affected by the age of the patents. If external citations appear later than intra-technology citations, then the age distribution of patents may affect the share of external citations. It could then be for instance that the large share of external-technology spillovers of hydropower patents occurs because hydropower technologies are older than other technologies.

Hence, in this section we conduct regression analysis to correct for the likelihood to be cited. The likelihood for a patent to be cited depends on the age of the patent (older patents have had more opportunities to be cited) and the type of technologies (e.g., patents in rapidly-developing technologies are more likely to be cited). We estimate the number of forward citations by a negative binomial regression, including technology dummies and year fixed effects as explanatory variables as Popp and Newell (2012). We consider four distinct dependent variables, namely the total number of patent citations, and the number of citations in each category discussed below (namely: intra-, inter- and external citations). We provide the estimation results in Table 5. Since we aim to compare REN with FF technologies, we conduct two types of regressions, choosing the respective baseline technologies in such a way that simplifies the interpretation of the regression results. In panel A of Table 5, we include all REN technology dummies but no FF dummies, so that the coefficients of REN dummies are interpreted in comparison with an average fossil-fuel technology patent. Instead, in panel B, we include all FF technology dummies but no REN dummies, so that the coefficients are interpreted in comparison with an average REN patent. Columns (1)-(4) correspond to the four dependent variables. The estimation is conducted at the patent level, for the complete sample of REN and FF patents. We report the results in the exponential form so that the coefficients reflect the likelihood of citation in this technology relative to the base case.

Table 5. Regression results

PANEL A	(1)	(2)	(3)	(4)
Dependent variable : number of forward citations	Total citations	Intra-technology citations	Inter-technology citations	External-technology citations
solar	1.361***	1.538***	0.337***	1.189***
	(16.24)	(20.60)	(-9.87)	(5.35)
storage	1.295***	1.363***	0.0316***	1.316***
	(9.93)	(10.46)	(-6.75)	(8.05)
wind	1.856***	2.794***	1.098	0.679***
	(24.33)	(37.29)	(1.00)	(-8.68)
waste	0.908	1.065	1.753***	0.631***
	(-1.90)	(1.12)	(4.33)	(-5.57)
marine	1.031	1.473***	1.744***	0.393***
	(0.59)	(7.34)	(3.63)	(-9.90)
hydro	0.551***	0.416***	2.087***	0.609***
	(-8.89)	(-11.67)	(4.55)	(-4.95)
biomass	0.932	0.929	1.894***	0.838
	(-0.87)	(-0.72)	(3.64)	(-1.56)
geothermal	1.258*	1.419**	1.176	1.026
	(2.30)	(2.80)	(0.54)	(0.19)
Constant	1.232***	0.740***	0.0396***	0.446***
	(8.48)	(-10.59)	(-37.27)	(-20.23)
N	156312	156312	156312	156312
Log-likelihood	-190397.8	-141212.2	-16397.0	-106167.5
PANEL B	(1)	(2)	(3)	(4)
Dependent variable : number of forward citations	Total citations	Intra-technology citations	Inter-technology citations	External-technology citations
burners	0.797***	0.953**	1.082	0.557***
	(-15.01)	(-2.79)	(1.45)	(-24.37)
furnaces	0.551***	0.525***	0.624***	0.597***
	(-30.32)	(-28.22)	(-6.10)	(-18.20)
turbines	1.124***	0.980	1.428***	1.312***
	(5.54)	(-0.81)	(4.94)	(8.85)
ignition	1.424***	0.469***	1.419***	3.074***
	(15.82)	(-23.68)	(4.24)	(41.37)
steam	0.673***	0.678***	0.886	0.620***
	(-13.71)	(-11.63)	(-1.17)	(-10.91)
engines	0.818***	1.057	2.478***	0.413***
	(-6.00)	(1.44)	(10.06)	(-14.98)
coal	0.863***	0.911*	2.499***	0.644***
	(-4.18)	(-2.39)	(10.78)	(-7.42)
hotgas	0.828***	0.755***	1.735***	0.981
	(-4.59)	(-5.61)	(4.81)	(-0.33)
constant	1.589***	1.054	0.0306***	0.527***
	(17.93)	(1.77)	(-37.43)	(-14.69)
N	156312	156312	156312	156312
Log-likelihood	-189768.7	-141320.9	-16493.7	-103806.4

There is a large literature that relates the social value of innovations by the number of citations that a patent receives. Lanjouw and Schankerman (2004) and Popp and Newell (2012) assume that more frequently cited patents have more value to society, as they provide the building blocks to a larger number of future innovations.[14] Schoenmakers and Duysters (2010) also assume that a high number of forward citations reflect the technological importance of the invention for future technological advances and use it as a criterion for identifying radical patents from non-radical ones.

According to column (1) of panel A, REN technologies are more likely to be cited than FF technology. The significant coefficients above 1 for wind, solar, storage, geothermal and hydropower show that these patents are more cited - and thus more valuable - than FF patents. In particular, solar patents are 36% more likely to be cited than fossil-fuel patents; and wind patents are 85% more likely to be cited than fossil-fuel patents. In column (1) of panel B, we find as expected that most FF technologies are on average less likely to be cited than REN technologies (coefficient lies below 1). Here again, as in the case of external citations, turbines and ignition technologies are notable exceptions. Ignition technologies are on average 42% more likely to be cited than the base REN technologies. Also, turbines patents are 12% more likely to be cited than REN patents. This points towards a larger social value of these two FF technologies.

Regarding intra-technology citations, column (2) in panel A shows that, compared to FF technologies, wind technology patents are about 2.8 times more likely to be cited by patents in the same technological field. In other words, correcting for age and technology effects, wind technologies are characterized by very large intra-technology spillovers, in line with our earlier qualitative findings. We also find that solar, storage and marine patents are 40-50% more likely to be cited by patents in the same technological field. Hydropower patents, by contrast, are about 60% less likely to be cited by other hydropower inventions.

Column (2) in panel B shows that FF patents are typically less likely to be cited by inventions from the same technology than REN technologies (most coefficients lie below 1). We observed in Figure 3 that FF patents were characterized by a lower percentage of intra-industry citations than REN patents, which points towards relatively low intra-technology spillovers for FF technologies. The coefficient values below 1 in column (2) of panel B lend support to the same conclusion.

[14] Another indicator often used to measure the social value of patents is the ‘generality index’, which asks whether a patent is cited by other patents from many different technological fields, or just by other similar patents. The assumption is that more general patents provide more social value, as they provide building blocks to innovations in more sectors of the economy. In our study, the question of patent generality is addressed by means the analysis of the external citation category in column (4) of Table 5 and the discussion of Table 4.

Looking at inter-technology spillovers in column (3) of panel A, we find that only four REN technologies generate more inter-technology spillovers than the baseline FF technologies, namely: hydro, waste, marine and biomass. Again, this is in line with our earlier results pointing out that knowledge in waste and biomass mainly spills over to other FF technologies, while new inventions in hydro and marine technologies mainly contribute to each other's knowledge base. By contrast, solar, wind and storage patents generate less inter-technology spillovers than an average FF patent. Since the share of these three technologies in REN patents is high, an average REN patent generates fewer spillovers in comparison to an average FF patent. In line with this, column (3) of panel B confirms that many technologies (coal, engines, turbines and ignition) are more likely than REN technologies to be cited by patents in a technological field related to power generation, as FF technologies mainly spill knowledge to other FF technologies.

The results in column (4) of panel A show that only solar and storage technology generate substantial spillovers to external fields, exceeding the spillovers of FF patents. Therefore, column (4) of panel B also shows relatively low external spillovers for most FF technologies, with the notable exception of ignition and turbines. The high coefficient on ignition confirms that ignition technologies have application in external fields (mainly in the automobile industry), which is what we also see in Figure 3.

We can summarize our results on the knowledge spillovers from REN and FF technologies as follows:
(1) Wind technologies are characterized by important intra-technology spillovers. Past technological advances in wind technologies have been particularly useful to develop current wind technologies. Yet, knowledge from wind technologies does not much flow to other technologies, whether they are related or unrelated to power-generation.
(2) Solar and storage technologies also benefit from intra-technology spillovers, although to a lower extent than wind technologies. Knowledge from these technologies finds applications in many technological fields outside the field of power generation, suggesting that these two technologies have a high social value as they are highly cited in general; and moreover, they are also cited by a broader and more diversified set of technologies, outside their own field.
(3) Hydropower and marine technologies are intertwined with wind technologies and contribute to the knowledge base of these three technologies. They, however, hardly contribute to technologies outside the field of power-generation.
(4) Waste and biomass technologies mainly find application in technologically close fields of power generation (such as FF). Past advances in waste and biomass technologies have been useful in developing recent knowledge in FF technologies. There are many interactions between the waste and biomass and the FF technologies knowledge bases. Finally, as turns out from the discussion of external applications of

these inventions, knowledge from these technologies does not find broad application outside the field of power-generation.

(5) Knowledge from most FF technologies mainly flows to other FF technologies, and not to REN technologies or technologies unrelated to power-generation. From REN technologies mainly waste technology benefits from the knowledge developed in FF technologies.

4. Conclusions and policy implications

This paper unravels knowledge spillovers accompanying the development of renewable energy technologies by distinguishing several technologies and three types of spillovers (intra-, inter-and external-technology spillovers). We show that knowledge from renewable energy technologies mainly contributes to the same technologies. Yet, the size and the composition of knowledge spillovers differs significantly between technologies. On average, about 60% of the citations received by renewable patents come from patents in the same technological field. The three main groups of renewable energy technologies, namely solar, wind and storage technologies, exhibit high levels of intra-technology spillovers, while waste technologies contribute the least to knowledge developed in the same field. We also find that innovations in solar, wind and storage hardly contribute to the knowledge base of other power-generation technologies (inter-technology spillovers), with the notable exception of waste technologies.

It is a well-established result that since the stock of knowledge in REN technologies is still much lower than knowledge in FF technologies, while technology-specific knowledge is highly important for their development, specific subsidies targeted at the REN sector would help to 'turn on the innovation machine' (Veugelers et al., 2009). Yet, how should such policies be designed to take into account the specific characteristics of each renewable energy technologies? Aalbers et al. (2013) argue that the strength of the argument for technology-specific R&D support depends (among other things) on the size of spillover effects between REN and FF technologies. In particular, the justification for R&D support is weaker for renewable technologies that are characterized by larger knowledge spillovers from fossil-fuel technologies, and thus by lower levels of path-dependencies. In contrast, technologies with larger contribution to the REN knowledge base may be eligible for public R&D. Therefore, the empirical evidence regarding the direction of knowledge spillover effects of different REN technologies reported in our study provides a concrete tool for the design of innovation policies in the power sector.

The magnitude of intra-technology spillovers tells us how powerful the innovation machine is for each specific technology. For wind technologies, once the stock of wind inventions is large enough, specific innovation subsidies will no longer be needed since the technology will benefit from large intra-technology spillovers, ensuring that these technologies will continue to develop fast.

Solar and storage technologies might instead - ceteris paribus - need longer policy support: intra-technology spillovers are less strong than for wind technologies. In addition, these technologies have high social value for society: they receive a large number of citations and find applications in a large set of diverse fields - two characteristics of highly valuable innovations (Lanjouw and Schankerman, 2004; Popp and Newell, 2012). These technologies exhibit thus certain features of general purpose technologies worthwhile to support on a larger scale. Marine technologies benefit from a well-functioning ‘innovation machine’ and are currently developing fast, building upon the past knowledge stocks of both marine and hydropower technologies. Only specific temporary policy support will probably be needed for these technologies.

Waste and biomass technologies present characteristics that are very different from wind or solar technologies and more similar to most FF technologies. Indeed, we find that the knowledge from waste and most FF technologies (except ignition) mainly flows to other FF technologies, and not much to other REN or to technologies unrelated with power-generation. New inventions in these fields find applications mainly in FF technologies. Hence, policy support for waste, biomass and FF technologies may contribute to further increases of the FF knowledge base and the gap with other REN technologies. Also, the results on citations suggest that waste, biomass and FF technologies have on average a lower social value - ceteris paribus - than knowledge from other REN technologies and hardly contribute to other technologies unrelated to FF-power generation (with the exception of ignition and turbines). If the policy goal is purely to stimulate a transition away from FF power generation, then public R&D does not need to be directed to these technologies. Even generic innovation policy would simply encourage future developments of FF technologies, rather than REN or other technologies useful to society.

While our focus in this study lies in innovations contributing to knowledge spillovers in the context of climate change mitigation, other policy consideration (other policy goals, such as security of supply) may need to be taken into account in the integral policy framework. Other relevant factors include evaluating the risk of crowding out between energy and non-energy patents and checking the differences in productivity effects between own and government supported R&D (Trajtenberg, 2000).

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Appendix

Table A1 Percentage of intra- and inter-technology citations

	solar	wind	stor	marine	hydro	waste	biomass	geo	burners	furnaces	turbines	ignition	steam	engines	coal	hotgas
solar	62	1	0	0	0	0	0	0	0	0	1	0	1	1	0	0
wind	2	82	0	3	2	0	0	0	0	0	0	0	0	0	0	0
stor	0	0	59	0	0	0	0	0	0	0	0	0	0	0	0	0
marine	1	11	0	75	7	0	0	0	0	0	0	0	0	0	0	0
hydro	1	13	0	13	37	0	0	0	0	0	2	0	0	0	0	0
waste	0	0	0	0	0	28	4	0	51	3	1	0	5	4	6	1
biomass	0	0	0	0	0	13	48	0	9	0	1	3	0	1	4	0
geo	5	3	0	1	0	0	0	52	0	0	1	0	1	5	0	0
burners	0	0	0	0	0	2	0	0	68	4	6	1	3	1	2	0
furnaces	0	0	0	0	0	0	0	0	9	56	0	0	1	0	1	0
turbines	0	0	0	0	0	0	0	0	16	0	48	0	2	11	1	1
ignition	0	0	0	0	0	0	0	0	3	0	1	19	0	0	0	1
steam	1	0	0	0	0	2	0	0	20	3	4	0	51	9	2	1
engines	2	1	0	0	0	2	0	1	9	0	36	1	12	56	3	7
coal	0	0	0	0	0	4	1	0	22	4	4	0	4	4	57	0
hotgas	1	0	0	0	0	1	0	0	4	0	5	3	3	12	0	47
REN	24	20	15	4	1	1	1	1	2	0	0	0	0	1	0	0
FF	0	0	0	0	0	1	0	0	31	10	9	4	4	4	3	2

Table A2 Percentage of external citations

	solar	wind	stor	marine	hydro	waste	biomass	geo	burners	furnaces	turbines	ignition	steam	engines	coal	hotgas
Electrical machinery, apparatus, energy	7	24	61	21	16	1	1	1	4	5	4	1	3	11	1	9
Audio-visual technology	2	0	1	0	0	0	0	2	0	1	0	0	1	1	0	0
Telecommunications	1	1	0	1	0	0	0	3	0	0	0	0	0	0	0	0
Digital communication	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Basic communication processes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Computer technology	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0
IT methods for management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Semiconductors	13	0	2	2	0	0	0	0	0	1	0	0	1	0	0	1
Optics	5	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0
Measurement	2	3	2	1	1	0	0	2	3	4	2	2	6	1	2	1
Analysis of biological materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Control	1	1	0	0	2	1	0	0	2	1	2	1	2	4	0	1
Medical technology	1	0	1	0	1	2	0	0	1	1	0	0	2	0	0	0
Organic fine chemistry	1	0	2	1	1	1	1	0	1	1	1	1	1	3	5	0
Biotechnology	0	1	0	0	0	3	2	0	0	0	0	0	0	1	2	0
Pharmaceuticals	0	0	0	1	1	1	0	0	1	1	0	0	0	0	1	0
Macromolecular chemistry, polymers	1	1	6	1	0	1	3	0	1	1	0	1	1	0	2	0
Food chemistry	0	0	0	0	0	1	2	0	0	0	0	0	0	0	1	0
Basic materials chemistry	3	1	2	0	0	21	34	1	4	3	1	7	2	3	22	1
Materials, metallurgy	4	0	8	0	2	7	5	1	7	41	4	2	2	8	19	1
Surface technology, coating	7	1	3	0	1	1	0	0	2	5	8	1	2	1	1	0
Micro-structural and nano-technology	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chemical engineering	5	2	3	2	3	18	10	2	16	9	3	6	14	9	18	2
Environmental technology	1	2	0	2	1	19	11	5	19	3	3	18	4	5	14	7
Handling	1	1	0	1	0	1	5	0	1	3	0	0	3	0	1	0
Machine tools	1	1	1	2	2	5	10	0	3	4	3	1	6	1	3	1
Engines, pumps, turbines	2	14	0	40	25	2	5	8	9	1	48	51	11	21	1	34
Textile and paper machines	3	0	2	0	0	1	3	0	1	1	0	0	1	1	1	0
Other special machines	5	4	2	1	5	6	3	2	3	8	1	0	1	1	2	1
Thermal processes and apparatus	11	2	0	1	0	6	0	34	10	2	2	0	19	12	1	21
Mechanical elements	2	10	0	4	13	0	1	2	3	2	7	3	4	3	1	4
Transport	5	20	1	12	6	1	0	1	3	0	7	2	1	6	1	12
Furniture, games	1	1	0	0	0	0	2	0	1	0	0	0	5	0	0	1
Other consumer goods	1	0	0	1	0	0	1	0	1	0	1	0	4	1	0	2
Civil engineering	12	6	0	7	18	1	1	33	1	1	1	1	1	1	0	0

Table A3 Classification into technology classes for Renewable Energy Generation Technologies

Technology	Description	IPC classes
WIND POWER	Wind motors	F03D
SOLAR ENERGY	Devices for producing mechanical power from solar energy	F03G6
	Use of solar heat, e.g. solar heat collectors	F24J2
	Drying solid materials or objects by processes involving the application of heat by radiation - e.g. from the sun	F26B3/28
	Devices consisting of a plurality of semiconductor components sensitive to infra-red radiation, light – specially adapted for the conversion of the energy of such radiation into electrical energy	H01L27/142
	Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation, specially adapted as devices for the conversion of the energy of such radiation into electrical energy, including a panel or array of photoelectric cells, e.g. solar cells	H01L31/042-058
	Generators in which light radiation is directly converted into electrical energy	H02N6
GEOTHERMAL ENERGY	Devices for producing mechanical power from geothermal energy	F03G4
	Production or use of heat, not derived from combustion – using geothermal heat	F24J3/08
MARINE (OCEAN) ENERGY	Tide or wave power plants	E02B9/08
	Submerged units incorporating electric generators or motors characterized by using wave or tide energy	F03B13/10-26
	Ocean thermal energy conversion	F03G7/05
HYDRO POWER	Water-power plants; Layout, construction or equipment, methods of, or apparatus for; and not Tide or wave power plants	E02B9; and not E02B9/08
	Machines or engines for liquids of reaction type; Water wheels; Power stations or aggregates of water-storage type; Machine or engine aggregates in dams or the like; Controlling machines or engines for liquids; and NOT Submerged units incorporating electric generators or motors characterized by using wave or tide energy	[F03B3 or F03B7 or F03B13/06-08 or F03B15] and not F03B13/10-26
BIOMASS ENERGY	Solid fuels based on materials of non-mineral origin - animal or vegetable substances	C10L5/42-44
	Engines or plants operating on gaseous fuels from solid fuel - e.g. wood	F02B43/08
WASTE-TO-ENERGY	Solid fuels based on materials of non-material origin - sewage, town, or house refuse; industrial residues or waste materials	C10L5/46-48
	Incineration of waste - recuperation of heat	F23G5/46
	Incinerators or other apparatus consuming waste - field organic waste	F23G7/10

	Liquid carbonaceous fuels; Gaseous fuels; Solid fuels; and Dumping solid waste; Destroying solid waste or transforming solid waste into something useful or harmless; Incineration of waste; Incinerator	[C10L1 or C10L3 or C10L5] and [B09B1 or B09B3 or F23G5 or F23G7]
	Plants for converting heat or fluid energy into mechanical energy – use of waste heat; Profiting from waste heat of combustion engines; Machines, plant, or systems, using particular sources of energy – using waste heat. And Incineration of waste; Incinerator constructions; Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels.	[F01K27 or F02G5 or F25B27/02] and [F23G5 or F23G7]
STORAGE	Lead-acid accumulators gastight accumulators	H01M10/06-18
	Alkaline accumulators	H01M10/24-32
	Gastight accumulators	H01M10/34
	Other types of accumulators not provided for elsewhere	H01M10/36-40

Sources: Johnstone et al. (2009) and Johnstone and Haščič (2010) for storage technologies.

Table A4 Classification into IPC classes for Fossil-Fuel Energy Generation Technologies

Technology	Description	IPC classes
COAL	Production of fuel gases by carburetting air or other gases without pyrolysis	C10J
ENGINES	Steam engine plants; steam accumulators; engine plants not otherwise provided for; engines using special working fluids or cycles	F01K
TURBINES	Gas-turbine plants; air intakes for jet-propulsion plants; controlling fuel supply in air-breathing jet-propulsion plants	F02C
HOTGAS	Hot-gas or combustion-product positive-displacement engine; Use of waste heat of combustion engines, not otherwise provided for	F02G
STEAM	Steam generation	F22
BURNERS	Combustion apparatus; combustion processes	F23
FURNACES	Furnaces; kilns; ovens; retorts	F27
IGNITION	[Classes listed below excluding combinations with B60, B68, F24, F27]	
	Engines characterised by fuel-air mixture compression ignition	F02B1/12-14
	Engines characterised by air compression and subsequent fuel addition; with compression ignition	F02B3/06-10
	Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel	F02B7
	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	F02B11
	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	F02B13/02-04
	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.	F02B49

Source: Lanzi et al. (2011) and Haščič et al. (2009). We thank Ivan Haščič for providing us the last updated version of fossil-fuels IPC codes.

Publisher:

CPB Netherlands Bureau for Economic Policy Analysis
P.O. Box 80510 | 2508 GM The Hague
T (070) 3383 380

December 2013 | ISBN 978-90-5833-624-8