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On which technologies do renewable energy innovations build on?

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Abstract

In this study, we use patent citations analysis on patents in renewable and fossil-fuel energy filed at 17 European countries over the 1978-2006 period to address the research question: on which technologies does renewable energy innovation build on? Our descriptive analysis shows that renewable technology mainly builds on its own technology-specific knowledge stock, as we find that on average more than 80% of the prior art citations by patents in the renewable energy field refer to patents in the same specific technology field. Yet, we also find that renewable technologies rely to a large extent on technology developed outside the field of energy. We find very little spillovers to renewable technologies from fossil-fuel technologies, a notable exception being the field of waste energy.

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1 Introduction

The objective of this document is to identify empirically the technological knowledge base on which renewable energy innovations build on. To this end, our methodology analyses the *backward* citations (previous inventions cited in the current patent) of patents in eight REN technologies, namely: storage, solar, wind, marine, hydropower, waste and biomass technologies. We also look at how the trends evolve over time. Our descriptive analysis shows that renewable technologies mainly build on their own technology-specific knowledge stock, as we find that on average more than 80% of renewable patents citing prior art refer to at least one patent in the same technological field. This lends support to the hypothesis that knowledge creation takes place along a path-dependent process. Yet, we also find that renewable technology relies to a large extent on technology developed outside the field of power generation. We find very few spillovers from fossil-fuel technologies to renewable innovation, a notable exception being the field of waste and biomass energy. The results on REN technologies will be compared to a set of results on selected FF technologies.

Our study is organized as follows. Section 2 provides an overview of the literature. Section 3 describes our dataset on renewable and fossil-fuel patents and provides some basic information on citations. Section 4 presents the descriptive analysis of backward citations, i.e. focuses on the question on which technologies renewable innovation build on. Section 5 concludes.

2 Related literature

Most of the work on knowledge spillovers in the economic literature is based on patent data following 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. Yet, they are imperfect measure of innovations, because (i) not everything is patentable; (ii) not all patents are equally important; (iii) the data are affected by strategic behaviour of some applicants and inventors, such as strategic patenting or the preference of secrecy.

Patent data have also been increasingly used to study the factors affecting innovation in clean technologies (Popp, 2002, Dekker et al., 2012, Johnstone et al., 2010, Noailly and Smeets, 2013). These studies generally estimate the effect of energy prices, environmental policy or market size on the number of patents in clean technologies. Several studies have also introduced knowledge stocks (i.e. the cumulative number of patents in clean technologies) in the estimation function to capture the fact that current innovation benefits from the stock of past knowledge in the field. In particular, looking at patents in eleven different energy technologies, Popp (2002) finds clear evidence for significant *within-*

technology knowledge spillovers as well as diminishing returns in energy R&D, reflecting the fact that increases in current R&D make future R&D more difficult.[1] Overall, he finds that, in an average year, change in the stock of available knowledge would increase patenting activity by about 24%. In contrast, change in prices would spur patenting activity by only 2%. He concludes that the supply of ideas accumulated in the past plays a significant role in affecting the rate and direction of innovation.

A few other papers have looked at *cross-technologies* spillovers in energy innovation by estimating the impact of knowledge stocks in fields of research related to the specific technology. For instance, Johnstone and Hascic (2010) find large spillover effects from the storage technologies to other clean technologies, especially to 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. Positive effects of the knowledge stock of one technology on innovations in another technology may generally arise for two reasons: because of direct knowledge spillovers between these technologies and/or because of their complementary use. In the current study, we use patent citations to evaluate the contribution of the first effect. This adds new insights to earlier literature results. In particular, our finding that direct knowledge spillovers from storage technologies to electricity generation technologies are minor implies that that the positive effect of the knowledge stock in storage technologies on renewables (reported in Johnstone and Hascic, 2010) is mainly due to their complementary use. For comparison, our finding of substantial knowledge spillovers between fossil-fuel and certain renewable technologies (namely: waste and biomass, but not other renewables) explains why incumbent firms traditionally doing research in fossil-fuel technologies mainly extend the scope of their research activities to waste and biomass (as discussed by Noailly and Smeets (2013)).

Another strand of the literature, which is closer to our study, uses patent citations to measure knowledge flows. 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, "albeit one that also carries a fair amount of noise. Hence we should see them as a noisy signal of the presence of spillovers. This implies that aggregate citation flows can be used as proxies for knowledge-spillover intensity, for example, between categories of organizations or between countries". Empirical literature on technology and innovation has applied two measures based on patent citations. The first measure is *backward citation counts*; that uses the number of references to prior art as indicators of knowledge transmission between inventors (Jaffe et al., 2000). The main assumption is that previous patents cited by a new invention should be a good indicator of knowledge used by the inventor. The second measure is *forward citation counts*; that is, the

[1] In a complementary study, Popp (2006) finds that a 10% increase in the stock of energy patents reduces subsequent citations from 3 to 5%. This implies that energy R&D becomes less productive over time. Yet, he also argues that government sponsored R&D can help to offset this decline, as government energy patents, especially in basic fundamental energy R&D are 12% more likely to be cited than private energy patents, suggesting important knowledge spillovers from government sponsored R&D to the private sector.

number of times a patent is cited by subsequent patents to measure its importance or quality (Trajtenberg, 1990).

The main insight from these studies is that many factors affect the likelihood of citations and the major results are the following: i) most patents are never cited ii) a large share of patents cite patents within their own technology class[2] iii) 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[3] iv) newer patents tend to have more citations reflecting the increasing use of computerized searchable databases, v) important breakthrough patents are cited more often, vi) important patents are both more general (they receive citations from a broader set of patent classes) and more original (they cite patents from a broader set of patent classes), vii) the propensity to cite may vary across time and across technological fields.

The literature also highlights certain caveats to be aware of when working with patent citations. First, it is important to realize that not all the citations that are included in the patent are included by inventors. In particular, in the US, a relatively large share of backward citations is included by examiners or professional searchers. Hence, such citations probably do not measure actual knowledge transmission or the importance of the prior patent for the patent in question.[4] 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. Third, it might be important to correct for self-citations. 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.[5] Furthermore, firms may include self-citations for strategic reasons. Hall et al. (2005) find that highly cited patents (i.e. patents with more forward citations) generally have a higher market value; and self-citations are more valuable than external citations. At last, there are truncation issues for forward citations as the dataset cannot include the patents that will be granted in the future

Only a handful of papers have conducted patent citations analysis in the field of energy innovation. Nemet (2012) assesses whether important advances in energy technology have made use of knowledge originating in other technological areas. Nemet (2012) classifies citations into 'near' (from the same technological domain as the citing patent) and 'external' (outside the citing patent's technological domain) and compares the effect of these two classes on the quality of the citing patent measured by the number of forward citations (i.e. how much this patent is subsequently cited). He finds that knowledge acquired from outside

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[2] Jaffe et al. (1993) find that about half of all patents citations are to patents in the same classification.
[3] Hall et al. (2001) find that 50% of US patents cite patents that are more than 10-years old.
[4] Alcácer et al. (2009) estimate the share of examiner added citations at 63%, based on an American dataset of patents granted since 2001, when new reporting rules finally made distinction between applicant-added and examiner-added citations, to 2003. Alcácer and Gittelman (2006) point out that most American firms employ patent attorneys - many of whom were formerly patent examiners - to draft patent applications and to maximize the chances of an approval by the examiner.
[5] 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.

the field of energy, i.e. ‘external’ knowledge, has been essential to the most important energy inventions. This result is specific to the field of energy, as an earlier study from Nemet and Johnston (2012) found no significant contribution from external knowledge for several other technology fields. Even highly-cited fields, such as computers and medical patents, showed no benefits from external citations. Our study is related to the work by Nemet (2012) since we also look at backward citations to assess which technologies significantly contribute to innovations in the field of power generation technologies. Yet, our study is mainly descriptive and we do not conduct regression analysis to estimate the impact of near and external knowledge on the value of energy patents. By contrast to Nemet (2012), our analysis compares the knowledge spillover patterns within and across renewable and fossil-fuel energy technologies.

Knowledge spillovers can be analyzed by means of both backward and forward citations. While backward citations link the patent to past inventions, forward citations relate it to future inventions. Popp and Newell (2012) use forward citations to address the question of the social value of energy R&D. They argue that energy R&D is of higher value to society than other type of R&D, simply because energy plays a role in many sectors, but also because energy innovation is still relatively new and knowledge in this field might give rise to more opportunities for big breakthrough than more mature 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 (they receive citations from a broader set of patent classes). Popp and Newell (2012) conclude therefore that energy technologies can be compared to general purpose technologies.

As explained in the introduction, our research question in the current study concerns knowledge flows towards various technologies in the field of power generation and storage. Thus, our analysis will mainly focus on backward citations, just briefly touching upon the subject of forward citations for a comparison. A complementary and more comprehensive analysis of forward citations is provided in a companion paper (Noailly and Shestalova, 2013).

3 Data description

We use data on renewable (REN) and fossil-fuels (FF) patent applications, 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 (hereafter: *patent*), 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. references to prior art used by this patent. Some patent applications are related to each other via priority claims[6] (so-called *patent families)*. It has been argued in the literature (e.g., Straathof and

[6] The priority right allows the claimant to file a subsequent application in another country for the same invention, effective as of the date of filing the first application. When filing the subsequent application, the applicant ‘claims the priority’ of the first application in order to make use of the right of priority.

Veldhuizen, 2012) that a larger number of priority claims signifies a larger patent value. Therefore, the inclusion of such 'claimed priorities' in our sample is a natural way to correct for differences in patent values. Therefore, more valuable patents automatically receive larger weights in the computation of citation shares in Section 4.[7] Here we describe the technology classes covered by this study and their relative sizes (Section 3.1), and provide general information about both backward and forward citations of these patents (Section 3.2).

3.1 Technology classes and patent counts

We focus on patent counts in eight renewable and eight fossil-fuels technologies selected using the relevant IPC codes for each technology.[8] Table 3.1 summarizes the REN and FF technologies considered in this study. Regarding renewable energy, we include the following technologies: *wind*, *solar*, *hydro*, *marine*, *biomass*, *geothermal*, *waste* and *storage*. The IPC codes for these technologies are borrowed from earlier work by Johnstone et al. (2009) and Johnstone and Hascic (2010) for storage technologies. Regarding fossil-fuel power generation, we consider the following technologies: production of fuel gases by carbureting air (hereafter, *coal*), steam engines plants (*engines*), gas turbines plants (*turbines*), hot gas or combustion-product positive displacement engine (*hot gas*), steam generation (*steam*), combustion apparatus (*burners*), furnaces (*furnaces*) and improved compressed-ignition engines (*ignition*). These technologies and patent classification codes have been described in more detail in Lanzi et al. (2011) and Hascic et al. (2009).[9] There is some overlap between technologies as some patents fall into several classifications. For instance, some patents may be assigned IPC codes from both *waste* and *burners* classifications and thus fall into both REN and FF technologies.

Table 3.1 Technology classes included in this study

REN technologies	FF technologies
1. wind	1. *coal*: production of fuel gases by carbureting air
2. solar	2. *engines :* steam engines plants
3. *geo*: geothermal	3. *turbines:* gas turbines plants
4. *marine*: ocean energy	4. *hot gas:* hot gas or combustion-product positive displacement engine
5. hydro: hydropower energy	5. *steam:* steam generation
6. biomass	6. *burners:* combustion apparatus
7. waste	7. *furnaces*
8. *storage:* batteries for electricity storage	8. *ignition:* improved compressed-ignition engines

Our dataset includes 156,312 patents, among which 117,114 (75%) are from FF technologies, 41,491 (25%) are from renewable technologies. About 1.5% of these patents fall into both categories.[10] Figure 3.1 presents the evolution of the number of REN and FF

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[7] As a robustness check, we have repeated our analysis focusing purely on 'claimed priorities', thus, further restricting the sample to the most valuable inventions. No notable differences have been encountered between the two sets of results.
[8] Details on the IPC codes are given in Appendix 1.
[9] We thank Ivan Hascic from the OECD for providing us with the most updated classification codes. See Appendix 1.
[10] In addition, there is overlap within each type; however, about 90% of all patents fall into a single technology category from our list of 16 technologies.

patents over time. While the number of fossil fuel patents is largely above the number of REN patents over most of the period, in recent years (as many countries have been adopting policies to reduce emissions and promote renewables), the number of renewable energy patents has been catching up with the number of fossil fuel patents. Yet, the annual patent number in renewable technologies is still substantially lower than that in fossil-fuel technologies.

Figure 3.1 Evolution of the total patent number for REN and FF technologies

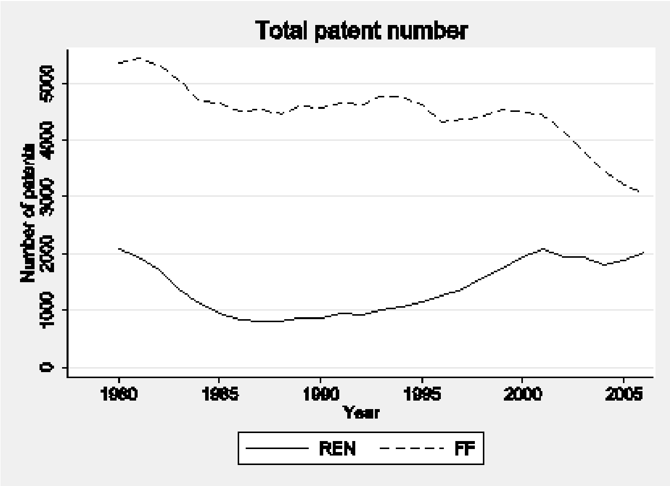
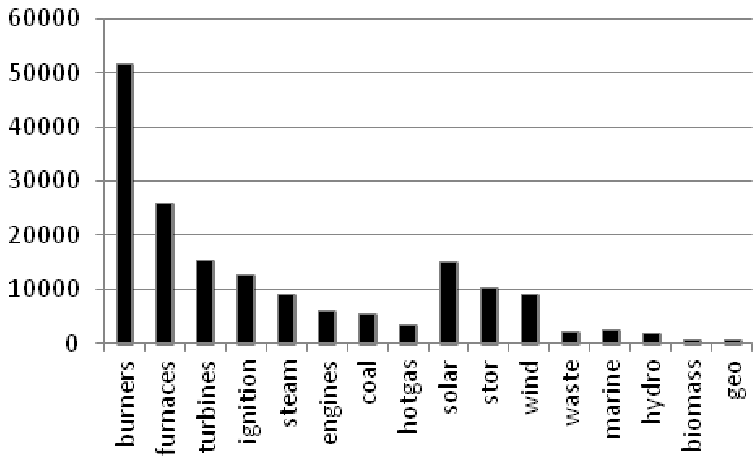


Figure 3.2 shows the allocation of the patents in our dataset over the different specific technologies. Among fossil-fuels, the largest categories are burners and furnaces, accounting for about 50,000 and 25,000 patents respectively. Among renewable technologies, solar, storage and wind technologies represent the three largest technology classes, which together cover 80% of all the patents in this group. The number of patents in geothermal energy and biomass is almost negligible.

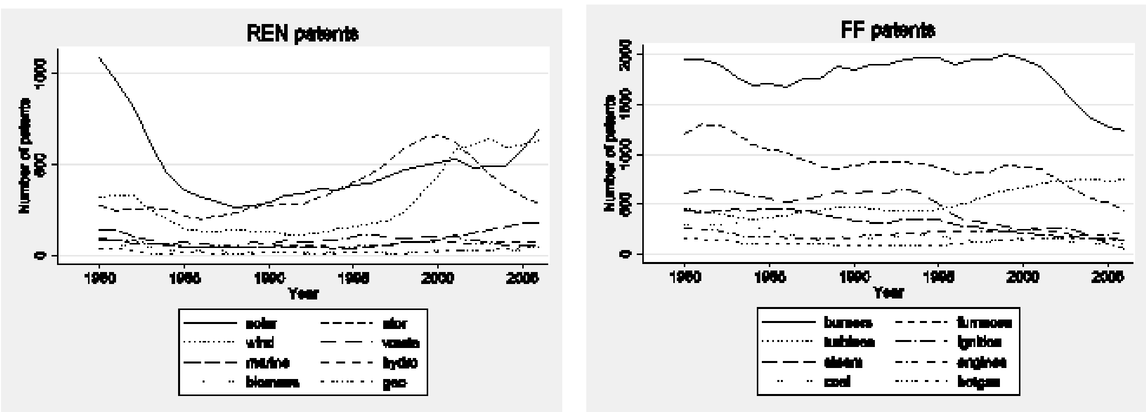
Figure 3.2 Total patent number per technology



Renewable technologies, in particular storage, solar and wind, have experienced a renewed interest in the mid-1990s as shown in Figure 3.3a, which gives the evolution of patenting activities in REN technologies over time for each specific technology. 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 storage technologies reach a peak at around 600 patents in 2000 and decrease afterwards.[11]

Comparing the patent numbers in REN technologies to those in FF technologies, shown in Figure 3.3b, we observe that 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 3.3 Evolution of patent numbers per technology: (a) REN technologies; (b) FF technologies



3.2 Citation data

We consider the *backward* and *forward* citations of our sample of 156,312 REN and FF patents. Backward citations are the citations *made* by our sample of patents to prior patents and, thus, reflect the past knowledge on which the patent builds on. We will use backward citations to answer our research question: on which technologies do renewable technologies build on? Forward citations are the citations subsequently *received* by our sample of patents and, thus, reflect the knowledge from these patents to follow-on inventions. Since relatively many patents in our sample of European energy patents cite other patents of the same

[11] Note that our classification codes for storage technologies 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. See definitions of different storage types in Appendix 1.

sample, results arising from forward citations and backward citations are to some extent overlapping. Therefore, forward citations can be used for the purpose of comparison and consistency checks.

As European patents also benefit from and contribute to the knowledge developing outside Europe, we also consider citations to and from patents filed at the US Patent Office[12] and at the Japanese Patent Office, as these two countries are the largest contributors to the world patents. Furthermore, following the earlier literature, we excluded intra-family citations, for which both cited and citing patents were referring to the same invention. The share of patents including such citations, however, is negligible (about 1%) and leaving them in the dataset would not significantly affect the result. Further issues with citation data are self-citations and unavoidable truncation problems. In particular, 7% of patents in our dataset include such self-citations (about 2% of all citation records in total).[13] Some studies suggest that self-citations (citations to patents of the prior patents of same applicant) may inflate the estimate of spillovers and need to be excluded. The result of Hall et al. (2005)[14] implies that self-citations reflect a high-patent value, which may be due to strategic interaction but may be also due to intra-firm knowledge spillover. Since we expect that research applicants specialize in certain areas, the inclusion of self-citations may bias the share of intra-technology citations upward. Therefore, following earlier studies (see footnote 5), we will exclude self-citations. Finally, data on forward citations are always truncated because recent patents have not had yet the opportunity to be cited. We do not make explicit corrections for this in the current analysis, but only take this into account when interpreting the results, leaving a more detailed analysis for future research.

Out of our sample of 156,312 patents, 58% of patents do not cite anything (hereafter: *non-citing patents*), while the other patents cite at least one patent (*citing patents*). The maximum number of backward citations is 113, as there is one patent in solar energy that refers to 113 older patents. Turning to forward citations, we find that 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.

Table 3.2 summarizes descriptive statistics for both REN and FF technology types. REN patents are on average 2 years younger than FF patents (since the respective average application years are 1993 and 1991). We observe that, on average, *citing patents* of both

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[12]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. Thus, these citations do not carry correct information on knowledge spillovers. Since only European patents have been included as citing patents in the analysis of backward citations, this problem does not arise there. However, it may arise for the dataset on forward citations of EU patents. Yet, since we focus on shares of citations, rather than on their numbers, 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. As a robustness check, we can however repeat the analysis without the US.

[13] These are the numbers on backward citations. In addition, 10% of patents will receive a forward citation by the same applicant, which corresponds to 4% of all citing-cited pairs in our dataset.

[14] Hall et al. (2005) find that highly cited patents (i.e. patents with more forward citations) generally have a higher market value; and self-citations are more valuable than external citations.

patent types have made roughly the same number of citations (4.8 and 4.4 for REN and FF respectively), and received approximately the same average number of subsequent citations (3.4 for both types). Furthermore, Table 3.2 presents statistics on citation lags. Looking at the backward citation lag, we find that REN technologies cite patents which are on average 12.7 years older than the patent itself, while FF technologies cite patents that are on average 15.1 years older. Shorter citation lags for backward citations in REN patents reflect the shorter development history of REN technologies. 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. As expected, the lag is shorter for forward citations, since they cover only the period 1978-2006, while backward citations are tracked back to the 1900s.

Table 3.2 Descriptive statistics on citations

REN technologies	Obs.	Mean	Std. Dev.	Min	Max
Application year	41491	1993.0	9.2	1978	2006
Number of backward cit. (citing patents)	17313	4.8	3.1	1	113
Number of forward cit. (cited patents)	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
Number of backward cit. (citing patents)	49393	4.4	2.6	1	44
Number of forward cit. (cited patents)	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

4 On which technologies do renewable energy innovations build on?

In this section, we describe knowledge spillovers as measured by backward citations. The question we aim to answer is: On which technologies do renewable energy patents build on? Using backward citations, we aim to identify the contribution of the four sources of knowledge spillovers to these technologies, namely:

- *Within-technology* spillovers, e.g. a solar patent refers (*includes at least one citation*[15]) to prior art in solar technologies;
- *Within-type* spillovers, e.g. a solar patent refers to prior art in other renewable technologies (wind, waste, biomass, hydro, geothermal, marine, storage, but excluding solar);
- *Across-type* spillovers, e.g. a solar patent refers to prior art in fossil-fuel technologies;

[15] The main text focuses on this measure of spillovers effects for the sake of clarity. An alternative measure, based on total citation records and discussed in Appendix 2, shows a similar picture of spillovers effects. That alternative measure is used in a companion paper of the current paper (Noailly and Shestalova, 2013). That companion paper considers forward citations to analyze the knowledge spillovers from REN-technologies to other technologies.

- *Other* spillovers, e.g. a solar patent refers to prior art outside REN or FF power generation technologies ('external' knowledge).

We focus on the sub sample of 65,834 patents (42% of the total sample) that do cite prior art (hereafter: *citing patents*) and thus exclude the non-citing patents. For each technology group, we compute the share of patents that cite at least one patent in each of the above-mentioned four citation categories. Both Figure 4.1 and Table 4.1 show the extent of spillovers for REN technologies. As the number of patents in geothermal, waste, hydro and biomass energy is relatively small (see Figure 3.2 in Section 3), the shares of patents citing different knowledge should be interpreted with caution. Most of our interpretation will therefore focus on the three main categories, namely solar, wind, and storage and to some extent waste and marine technologies.

Our analysis of citations is mainly descriptive, thus, we do not conduct econometric estimation to correct for the likelihood of citations. As mentioned in the literature, several factors might affect the citations patterns. For instance, if we find that solar patents cite more patents in engine technologies than in wind technologies, this is likely to reflect larger knowledge spillovers from engines to solar, than from wind to solar; but this outcome could also have been affected by the fact that engines patents tend to be older than wind patents and have thus a larger chance of being cited. We intend to correct for the likelihood of citations in future work.

As an illustration, in Figure 4.1 and Table 4.1 (row 'solar'), we find that 84% of *citing* solar patents cite at least one other patent in solar technologies, 55% of solar patents also refer to technology outside REN and FF power generation technologies, 2% of solar patents cite patents in other REN technologies (mainly wind according to Table 4.2) and 5% cite patents in FF technologies (see Table 4.2 for the distribution across FF technologies: 1% burners, 1% furnaces, 1% turbines, 1% steam, 2% engines, 1% hot gas).

Figure 4.1 Backward citation categories per REN technology

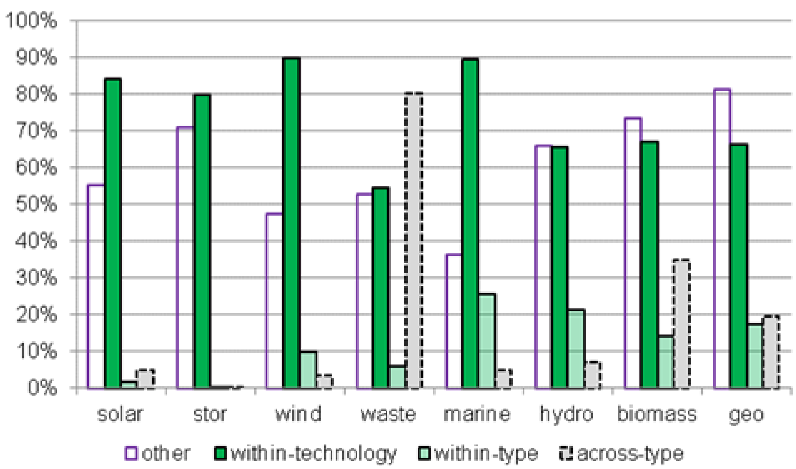


Table 4.1 Backward citation categories per REN technology (%)

	Within-technology	Within-type	Across-type	Other
	%			
Solar	84	2	5	55
Stor	80	0	0	71
Wind	90	10	3	47
Waste	54	6	80	53
Marine	89	26	5	36
Hydro	66	21	7	66
Biomass	67	14	35	73
Geo	66	17	20	81

Overall, Figure 4.1 and Table 4.1 show that there are large within-technology spillovers for REN technologies. On average, 83% of *citing* REN patents cites at least one patent in the same technological field. The extent of within-technology spillovers vary greatly across technology, with wind and marine technologies building the most on their own technology specific knowledge (nearly 90% of patents cite a patent within the same field) and waste technologies building the least on their own specific knowledge (54%). Remarkably, the share of other spillovers, i.e. the share of patents citing external knowledge, is high for all REN technologies. On average, 58% of REN patents cite patents external to power generation technologies. Within-type, i.e. within-REN, spillovers are generally low ranging from 0% for storage to 26% for marine technologies (based on Table 4.2, marine technologies build mainly on wind and hydropower energy). This indicates that knowledge accumulated in one specific type of renewable technology does not benefit much from other types of renewables. The extent of across-type spillovers, i.e. from fossil-fuels to renewables, varies greatly from one technology to another. For two REN technologies - waste and biomass - we observe substantial spillovers from FF technologies. About 80% of waste patents cite patents in FF technologies, mainly burners (74%), steam (17%), coal (16%) and furnaces (9%), as seen in Table 4.2. This implies that these technologies rely on the same type of knowledge, as technologies developed to burn coal for instance can also be used to burn waste. 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 general, the large overlap in the knowledge base of these technologies is consistent with the fact that many waste and biomass patents fall into both REN and FF technology classes as stated in Section 3.1. In fact, we conducted an additional check and found that a half of the citations of waste patents to FF technologies are actually citations to these 'combined' patents that are classified as both FF and REN.[16]

[16] Recent studies, however, stress potential physical limits to the expansion of these technologies (because of indirect emissions that may arise when new land is taken into arable production). For example, the recent ECN/PBL (2011) for the Netherlands argues that, while biomass remains an important energy source for achieving the EU 80% Co2-reduction target in 2050, its preferable use is the production of liquid fuels and green gas for the transport, small industry, and construction - in which there are still little clean alternatives, rather than electricity generation - in which there are such alternatives.

Table 4.2 Spillover effects between technologies, based on backward citations

	solar	stor	wind	waste	marine	hydro	biomass	geo	burners	furnaces	turbines	ignition	steam	engines	coal	hotgas
solar	84%	0%	2%	0%	0%	0%	0%	0%	1%	1%	1%	0%	1%	2%	0%	1%
stor	0%	80%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
wind	5%	0%	90%	0%	4%	5%	0%	0%	1%	0%	2%	0%	0%	1%	0%	0%
waste	1%	0%	0%	54%	0%	0%	8%	0%	74%	9%	5%	2%	17%	8%	16%	2%
marine	3%	0%	20%	0%	89%	18%	0%	1%	0%	0%	2%	0%	0%	3%	0%	0%
hydro	1%	0%	16%	0%	20%	66%	0%	0%	1%	0%	4%	0%	0%	2%	0%	0%
biomass	0%	0%	0%	23%	0%	0%	67%	0%	17%	1%	2%	5%	0%	4%	16%	3%
geo	20%	0%	1%	0%	2%	1%	0%	66%	1%	0%	2%	0%	6%	16%	0%	1%
burners	0%	0%	0%	5%	0%	0%	0%	0%	86%	9%	10%	2%	8%	2%	4%	1%
furnaces	1%	0%	0%	1%	0%	0%	0%	0%	17%	73%	1%	0%	3%	0%	2%	0%
turbines	1%	0%	1%	0%	0%	1%	0%	0%	22%	1%	72%	2%	4%	15%	2%	3%
ignition	0%	0%	0%	0%	0%	0%	0%	0%	6%	0%	2%	55%	0%	1%	0%	2%
steam	2%	0%	0%	3%	0%	0%	0%	0%	26%	7%	7%	0%	79%	15%	4%	2%
engines	7%	0%	1%	3%	1%	1%	1%	2%	16%	2%	42%	4%	31%	81%	6%	14%
coal	0%	0%	0%	6%	0%	0%	1%	0%	38%	11%	7%	1%	8%	6%	81%	0%
hotgas	5%	0%	1%	1%	0%	0%	1%	0%	9%	1%	12%	16%	8%	24%	1%	74%

Comparing the citation shares obtained for REN technologies to those for FF technologies (Figure 4.2), we observe that the latter are also characterized by large spillovers within-technology and from other technology fields. On average, about 80 % of *citing* FF patents cites at least one patent in the same technological field and nearly 60% cite external knowledge. The field of ignition relies the most on external knowledge as 90% of ignition patents cite patents in fields of research external to REN and FF technologies. However, differently from REN technologies, within-type spillovers of FF technologies are significant, as overall about 20% of the FF patents cite patents in another FF technology. Engines, for instance, make use of the knowledge developed in turbines, steam engines and burners. This means that FF technologies rely quite significantly on knowledge developed in other FF technologies. At last, FF technologies experience only small spillovers from REN technologies, except for engines technologies, which mostly cite patents in solar technologies.

Figure 4.2 Backward citation categories per FF technology

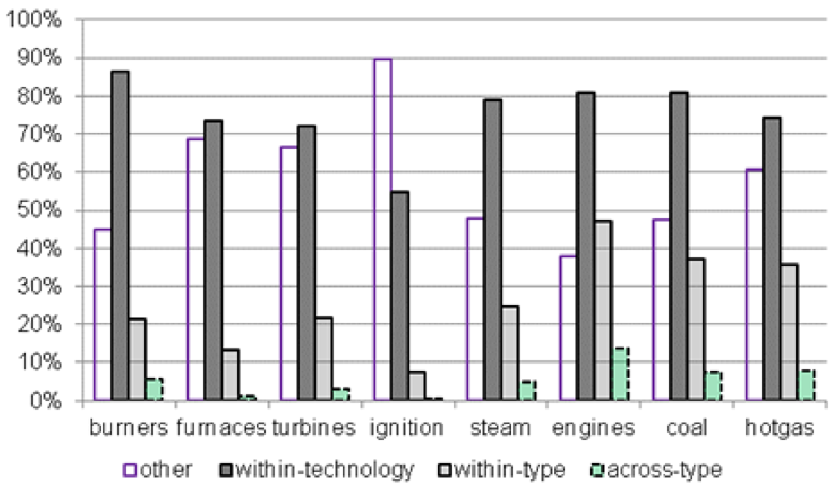


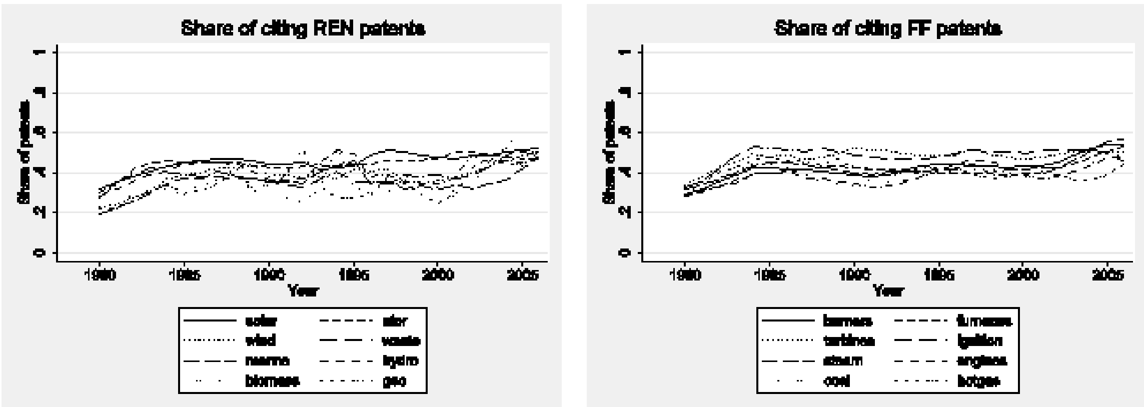
Table 4.3 Summary of the backward citation analysis on REN and FF technologies

	REN	FF
Knowledge stock	low [1/4 of all patents]	high [3/4 of all patents]
Within technology	high [55-90%]	high [55-85%]
Within type	low [<25%]	moderate [10-50%]
Across type	high for waste & bio [35-80%] low for the rest [mostly <10%]	low [<15%]
Other	high [55-80%]	high [40-90%]

Table 4.3 summarizes our main findings.[17] Most prominently, it stresses the difference in the size of knowledge stock accumulated in both areas, which disadvantages the REN patents. For both REN and FF technologies, within-technology spillovers are large, suggesting some form of path-dependency. REN technologies do not benefit from much within-type spillovers, i.e. spillovers from other REN technologies, while FF innovations do benefit from moderate spillovers from within-FF technologies. In general, across-type spillovers are low, i.e., REN technologies do not make use of much knowledge developed in FF and inversely. Important exceptions are the fields of waste and biomass that appear to be largely interlinked with FF technologies, notably on burners. This finding underscores the presence of differences between REN technologies. Last but not least, REN and FF patents benefit from large spillovers from 'other' technologies that are external to power generation technologies.

To complete our descriptive analysis of patent citations, we also considered how the citation pattern varies over time. The share of citing patents (see Figure 4.3) has slightly increased over time from 20-30% to around 50%. This seems to suggest that innovations rely more and more on prior art over time. However, as mentioned in Section 2, the increase may also reflect the increasing use of computerized searchable databases.

Figure 4.3 Share of patents with backward citations for REN (on the left) and FF (on the right)



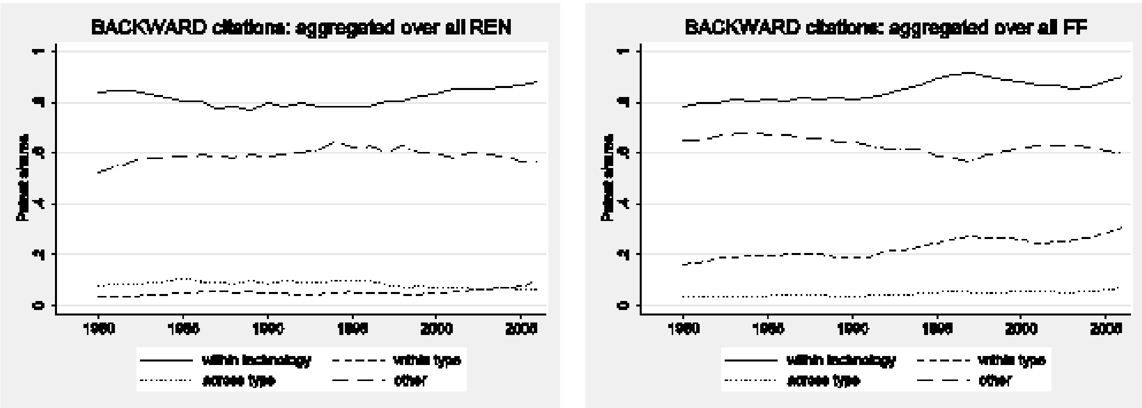
* 3-year moving average.

17 The numbers are rounded to fives.

Since patents increasingly cite prior art, the question arises whether this increase is primarily attributed to a certain knowledge category. Figure 4.4 (left panel) suggests no clear trend in the citing categories of REN patents over time, except a slight increase in within-technology citations in recent years. Overall, the shares of REN patents citing within the same technology and citing external knowledge seem stable over time. As REN patents cite more over time, they cite more both within and outside their own technology type. The slight increase in within-technology citations in the last years, marked by the rapid development of renewables, may be due to a shorter citations lags of within-technology citations, in comparison to other-technology citations (12.3 and 13.3 years, respectively), suggesting that it takes indeed longer to cite external knowledge.

For FF technologies (Figure 4.4, right panel), the shares are also stable, with some increasing trend in within-technology and within-type citations until the mid 1990s, and a less clear trend after that.[18]

Figure 4.4 Evolution of backward citation categories for REN (on the left) and FF (on the right)



* 3-year moving average

5 Discussion and conclusions

This document provides a descriptive analysis of various knowledge flows that contribute to renewable energy. Our main results suggest that path-dependency in knowledge creation (i.e. the fact that current innovation builds on its technology-specific knowledge stock) is an intrinsic phenomenon of technology development. In particular, using backward citations analysis, we find that renewable energy technologies build to a large extent on their own knowledge stock, as 83% of the renewable patents citing prior art cite at least one patent in the same technological field. The three main groups of renewable energy, namely solar, wind and storage technologies, exhibit high levels of within-technology spillovers, while waste technologies benefit the least from past knowledge developed in the same field. A brief

[18] For FF technologies, the citation lags of within- and other-technology citations are 14.7 and 15.4 years.

analysis of forward citations (in Appendix 2) confirms that renewable patents show high within-technology spillovers in the energy field.

Overall, the presence of large within-technology spillovers is consistent with the presence of path-dependency in the technology-specific knowledge accumulation process. Therefore, given that the patent stock in renewable technologies is still much smaller than that in fossil-fuel-technologies, providing R&D support to renewables could help to further enhance their technology-specific knowledge base, thus, spurring innovation in renewable energy (Aalbers et al., 2013).

We also find that innovations in a specific renewable energy field do not benefit much from the knowledge base of other renewable technologies (within-type spillovers) or from FF technologies (across-type spillovers), with the notable exception of waste technologies. In Aalbers et al. (2013), we explain that the strength of the argument for technology-specific R&D support depends (among other things) on the size of spillover effects between technologies. In particular, this argument is weaker for renewable technologies characterized by larger knowledge spillovers from fossil fuel technologies, and thus by lower levels of path-dependencies. Waste and biomass technologies for electricity production may belong to this category.

More work needs to be done to inform future policies in this area. In particular, the results of the current descriptive study can be further refined. We highlighted in the text that the interpretation of our descriptive results can be affected by issues such as truncation effects or time and technology effects affecting the likelihood of citations, which can be explored in future work. Other potential extensions concern the determinants of the size and the broadness of knowledge spillovers from innovations in the power sector, and policy effects on the value of these innovations. Furthermore, learning more detail about the composition of the external knowledge contributing to renewable innovation may provide additional policy insights.

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Appendix 1: Technology classes by IPC

Table A1.1 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 bas ed 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 Hascic (2010) for storage technologies.

Table A1.2 Classification into IPC classes for Fossil-Fuel Energy Generation Technologies (PM)

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
HOT GAS	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
COAL	Production of fuel gases by carburetting air or other gases without pyrolysis	C10J

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

Appendix 2: Discussion of alternative measures

In the main text we measure spillover effects by counting patents that have at least one citation in a certain category. However, one can also consider alternative definitions of spillovers. Here we compare the measure used in this study (hereafter: *patent counts*) to an alternative measure of spillovers (hereafter: *record counts*).

The patent-based measure, which was used in the main text, focuses at the level of patents: as long as a patent cites at least one patent in a certain technology we say that this patent has benefited from that technology. The record-based measure, which we introduce here, focuses on separate citation records, i.e., on pairs of a citing patent and a cited patent (or a missing value, if there was no backward citations). The same patent may cite several patents from different technology classes. Therefore, the four citation categories that we distinguish in our analysis may overlap. For instance, suppose a solar patent cites a solar patent, a burner patent and an 'other patent'. Then, the patent-based measure will allocate it into each of these three categories. Therefore, the shares of the four categories will not sum up to one. This problem will be less if we consider the record-based measure, because the allocation into categories will then occur at the level of citation records, and most cited patents fall under a single technology. Furthermore, our patent-based measure biases the estimate of spillovers towards technologies, on which a smaller number of patents is typically cited. For example, when a patent cites one patent in wind and 10 patents in burners, this measure says that this patent cites wind and burners, ignoring that more patents on burners were cited. The record-based measure takes this into account. However, it now attaches the same weight to each citation in a patent; hence, it is also subject to some bias, because the citations included in one patent may have different contributions to the patent. An important advantage of the patent-based measure is its straightforward interpretation in the context of our research question, because of which we have chosen to focus on it in the main text. However, it is instructive to compare both measures to each other as a robustness check.

Figure A.2.1 and Figure A.2.2 show, per technology, the four citation categories for both measures. On the left, we use the patent-based definition of knowledge spillovers; and on the right, we use record-based definition. It can be seen from these figures that both measures show qualitatively the same relative pattern of spillovers: large spillovers within technologies and from outside the electricity field; typically smaller within-type spillovers for REN and somewhat larger for FF; and high across-type spillovers for waste and biomass, while low for other technologies. For completeness, we report the record-based results on forward citations inFigure A.2.3. Also these two patterns have turned out to be qualitatively similar to their countreparts reported in section 4, justifying our focus on one measure only.

Figure A2.1 Backward citations for REN: patent counts (on the left) vs. record counts (on the right)

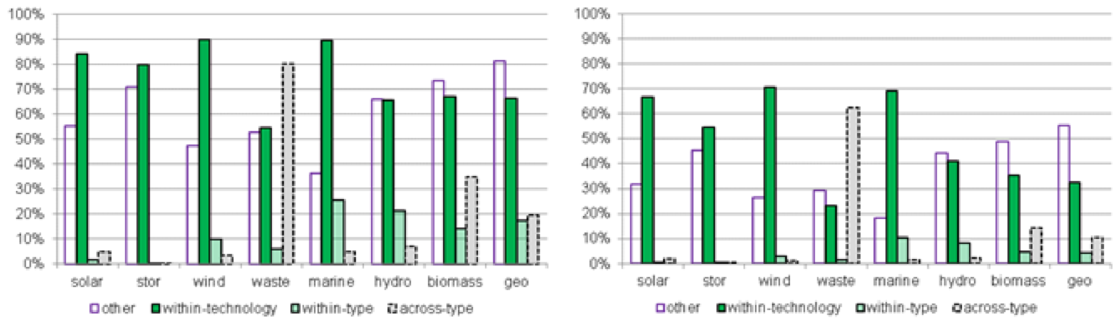


Figure A2.2 Backward citations for FF: patent counts (on the left) vs. record counts (on the right)

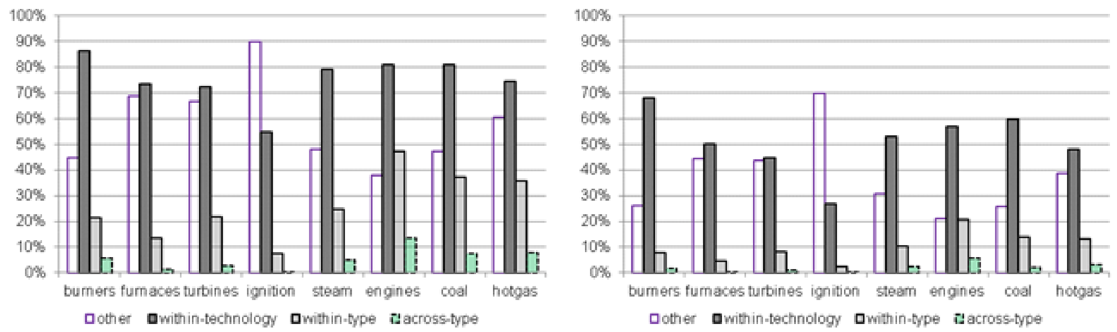
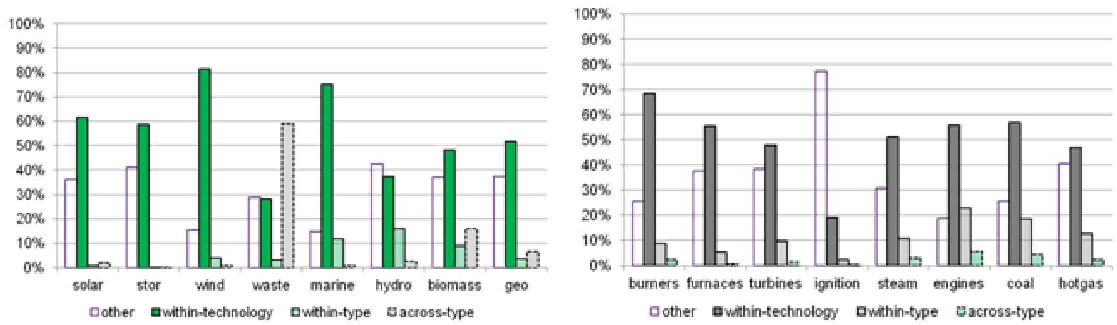


Figure A2.3 Forward citations: record counts for REN and FF technologies



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