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The role of private and public actors in power sector innovation

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SUMMARY This paper makes an effort to collect, harmonize, and describe data on power-related R&D and innovation for a sample of 16 countries over the years 1995-2007. We focus on the upstream energy sector (power) due to its relevance for energy security concerns both in developed and in developing countries and its importance with respect to climate policy. A novel contribution of the paper is a methodology based on inter-sectoral trade flows to estimate an upper bound of private power-related R&D in a given country. This allows gauging the extent to which energy R&D investments are embedded in intermediate inputs. We compare our estimates of private and public R&D with those available in the literature, which often refer to shorter time frames and fewer countries, as well as with data coming from top innovators in the energy sector and venture capital (VC). Finally, we combine the resulting R&D time series with trends in patent statistics to provide a qualitative assessment of R&D effectiveness.

Keywords: Public Energy R&D, Private Energy R&D, Power Sector

JEL: O32, Q50, Q55

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1. INTRODUCTION

Innovation on efficient and eco-friendly technologies is often cited as one of the most important policy tools to address energy challenges and the resulting environmental concerns (IEA 2012). The EU, for example, endorsed the European Strategic Energy Technology Plan (SET-Plan), a framework to promote and coordinate research, development and deployment of key low carbon technology options among member countries to support the achievement of the EU's ambitious climate and energy targets for 2020, namely a 20% reduction in EU greenhouse gas emissions from 1990 levels, raising the share of EU energy consumption produced from renewable resources to 20% and a 20% improvement in the EU's energy efficiency. For this to happen, significant investments in research and development (R&D) for low carbon and high efficiency technologies need to be fuelled into the system.

Given that technological change is on top of the agenda of developed and developing countries, insights on past trends are essential to set the basis for both climate and energy policy in the coming years. The International Energy Agency's Energy Technology Perspectives (ETP) posits that with appropriate policy support the power sector could account for up to one-third of potential CO2 emissions reduction worldwide by 2020 under the 2°C scenario, and almost 40% of 2050 emissions savings (IEA 2012). However, assessing the impact and effectiveness of past R&D investments and programs to guide future policy making proves difficult. Energy-related R&D is a very elusive concept and for this reason extremely hard to quantify. For a start, it is unclear which R&D can be classified under the "energy" category (Gallagher et al 2011). Energy is a key input for almost all sectors and R&D aimed at reducing energy-related costs is pervasive. However, due to the nature of national accounting procedures, such expenditures are hardly ever collected as a separate category and cannot be attributed to a single sector.

The difficulty in collecting comparable cross-country data in energy investment is apparent given the limited contributions available on this subject , which are limited and largely confined the energy sector in the USA. Nemet and

Kammen (2007) isolate and quantify energy-related R&D spending for the USA between 1975 and 2005. Popp and Newell (2012) focus on the dynamics of energy and non-energy R&D. They study whether energy-related R&D investments come at the expense of overall R&D in other sectors. Using industry-level data, they show that increased economy-wide energy R&D efforts do not come at the expense of R&D investments in other sectors. Using firm-level data they provide some evidence that within the alternative energy industry, one new alternative energy patent results in one less non-alternative energy patent. Moreover, research efforts by firms in this industry appear to be financially-constrained, as increased sales revenue also leads to more patenting activity. In contrast, crowding out does not appear to be a problem within the automotive industry. Recently, Gallagher et al (2011) enlarge the focus of the analysis by looking at the USA, Mexico and the BRIC countries, but are able to provide only statistics on public investments and over a limited time period.

To our knowledge, only a few contributions focus on energy R&D spending in the EU. The EC (2009), which is based on data estimated and presented by Wiesenthal et al. (2008), provides a snapshot of estimate private investment in SET-Plan technologies within European Member states for the year 2007. It provides a snapshot of public and private investment in energy-relevant sectors, including transport, but statistics of private investments do not include time series data. They show that the contribution of the private sector to energy-related R&D is significant in all SET Plan technologies and accounts for the majority of funding, with the exception of nuclear. The Global Gaps in Clean Energy Research, Development, and Demonstration of the IEA (2009) also provides a snapshot of current expenditures and future challenges, but also in this case time series data is not available in an organized fashion. More recently, Buchner et al. (2011, 2012, 2013) provide an overview of energy financing, including information on venture capital, private equity by drawing on a few recent databases, including the Bloomberg New Energy Finance.

The resulting pervasive lack of comparable statistics in energy-related R&D over time and across countries makes it hard to provide well-grounded empirical insights on the outcomes of energy-related R&D processes, on how successfully countries translate R&D investment into technology improvements, or on the relationship between private and public investment in the creation of more efficient and less polluting technological options.

This paper makes an attempt to fill this gap by collecting, harmonizing, and describing data on power-related R&D and innovation. We focus our analysis on the upstream energy sector (power) due to its relevance for energy security concerns both in developed and in developing countries and its importance with respect to climate policy. Public energy R&D is to some extent available for a broad number of countries, including emerging economies (Kempener et al. 2010), with good time coverage. Conversely, private R&D is more difficult to measure and available data is scattered and difficult to collect. First, we identify and describe a lower bound for private power R&D expenditure by focusing on the investment statistics of the electricity sector. Second, we present a methodology based on inter-sectoral trade flows to estimate an upper bound of private power-related R&D in a given country. This allows gauging the extent to which energy R&D investments are embedded in intermediate inputs. Third, we compare our estimates of private and public R&D with those available in the literature, which often refer to shorter time frames and fewer countries, as well as with data coming from top innovators in the energy sector and venture capital (VC). VC in particular is an increasingly important channel of private financing in energy both in developed and developing countries (Nemet and Kammen 2007). Finally, we combine the resulting R&D time series with trends in patent statistics to provide a qualitative assessment of R&D effectiveness. Our sample includes 16 countries (DNK, PRT, BEL, FIN, NLD, AUS, SWE, ITA, ESP, GBR, DEU, CAN, KOR, USA, FRA, JPN) and it spans the time frame from 1995 to 2007.

We contribute to the aforementioned literature by providing comparable times series of different R&D expenditure indicators and by expanding the spatial scale beyond Europe. Moreover, we jointly analyze the dynamics of R&D and patents, setting the ground for a more systematic analysis of R&D effectiveness and for the development of quality indicators of R&D spending. The remainder of paper is organized as follows. Section 2 presents statistics about government spending in power technologies, comparing two different but widely used data sources. Section 3 presents the lower and upper bound estimates of private energy R&D investment, while Section 4 compares these estimates with the available literature and with data on venture capital investments. Section 5 relates public and private investments to patent statistics. Section 6 concludes by summarizing the key messages emerging from our analysis.

2. AN OVERVIEW OF PUBLIC R&D INVESTMENTS

The two most widely known sources of data on public R&D include the OECD government budget appropriations or outlays for R&D (GBAORD 2012) and International Energy Agency (IEA) Energy R&D database (IEA 2012). We consider both data sources in order to check the consistency of different statistics in terms of both magnitude and country rankings. The main shortcoming of both data sources is that they are based on budget appropriations and outlays and therefore they do not represent the actual expenditure by the public sector, but only planned expenditure.[1]

GBAORD data is organized by socio-economic objective (SEO) using the Nomenclature for the Analysis and comparison of Scientific programs and Budget (NABS) 2007 classification. One of the 13 objectives is the Production, Distribution and Rational Utilization of Energy, which we refer to hereafter as “Energy”. This item refers to the research aimed at improving the production, storage, transportation, distribution and rational use of all forms of energy. It also includes

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[1] There are two approaches to measuring government expenditure on R&D: surveying actual expenditures ex-post and collecting information on budget allocations. Survey data on expenditures are carried out in firms performing the R&D activity and the sum of the R&D spending in a national territory is reported as “government-financed gross domestic expenditure on R&D” (government-financed GERD). In these surveys, member states can indicate whether the government-financed research was carried by one of four sectors: government, higher education, business enterprise, and private non-profit. However, providing this level of detail is optional, and most major EU economies are missing the necessary level of detail in this respect. In addition, GERD data do not become available until between one and two years after the R&D has been carried out, since it includes actual expenditures.

research on processes designed to increase the efficiency of energy production and distribution, and the study of energy conservation.[2] Conversely, IEA Energy R&D data includes budget allocation for R&D, deployment and demonstration related to energy efficiency, fossil fuels, renewable and biofuels, nuclear, hydrogen and fuel cells, other power and storage techniques, other cross-cutting technologies or research.[3]

Table 1 compares GBAORD Energy R&D with General Knowledge, which takes the largest share of a the public budget, and Industry R&D.[4] Leading the Energy R&D average statistics is Japan, with investments more than 3 times those of the second forerunner, the USA. Germany follows, but in absolute amount investments are less than half the expenditure of the USA. The public sector in Spain, Canada, Italy, and South Korea can be considered a medium investor in energy R&D, with a budget between 100 and 500 million US$. The remaining countries allocated less than 100 million US$. Excluding the General Knowledge sector, which attracts most resources in all countries, in certain countries R&D is homogenously distributed across the other sectors. The public budget allocated to

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[2] The different SEOs in NABS 2007 are: Exploration and exploitation of the earth, Infrastructure and general planning of land-use, Control and care of the environment, Protection and improvement of human health, Production, distribution and rational utilization of energy, Agricultural production and technology, Industrial production and technology, Social structures and relationships, Exploration and exploitation of space, Research financed from GUF, Non-oriented research, Other civil research, Defense.

[3] The IEA R&D data includes state-owned companies. EUROSTAT also collects information on energy related R&D investment. The differences between the nature of the data collected by the IEA and EUROSTAT, the collection methods, and inconsistencies between databases are presented in EC (2005). EUROSTAT data is however not very useful to isolate energy statistics. Main differences between the IEA and EUROSTAT data are: IEA collected energy statistics from public sector with a very rigid and detailed scientific and technological nomenclature, and includes both budgets and expenditure data. EUROSTAT collects investment in all areas of R&D in GBAORD and GERD. Budget data is collected in GBAORD while expenditure data is collected in GERD. GBAORD uses socioeconomic objectives while GERD attributes expenditures to one of four sectors (government, higher education, business enterprise, and private non-profit). As a result, EUROSTAT data cannot be used to isolate "energy" R&D investment, while IEA data can't be attributed to a given sector in the economy.

[4] The three sectors shown in Table 1 account for between 48% (Portugal) and 93% (United States) of the total R&D budget.

power is comparable to the budget for health in Canada and South Korea, or to the outlay for space in France and South Korea.

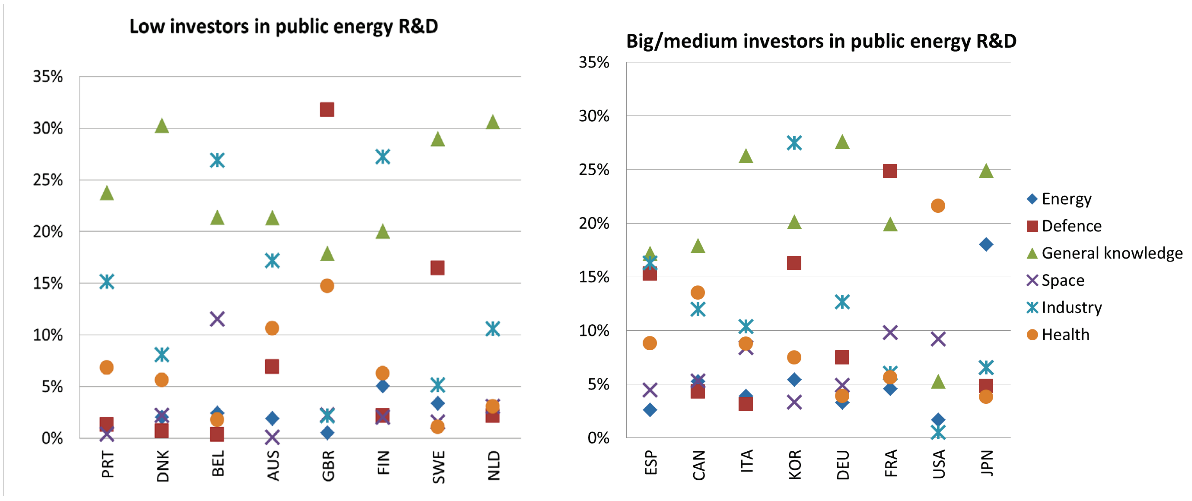
Table 1 also shows the variability of government R&D budget over time across socio-economic objectives in different countries, which is measured by the coefficient of variation. There seems to be no relationship between budget size and variability. There are big investor countries where energy budget shows a higher variability than other sectors, such as the US, but also opposite situations in which government R&D has been stable through time, such as Japan. Within the energy sector, the largest variability is seen in the US, Spain, Portugal, and Finland, the lowest in Japan.[5] Focusing on the level of R&D expenditures does not however inform on the relative importance of energy R&D with respect to other socio-economic objective. The ranking of countries varies when considering the share of total R&D budget that goes to energy R&D, as shown in Figure 1. When using this metric, the top investors are France, Canada, South Korea, Finland, Japan, with a share of approximately 5% (Japan reaches 18%). The shares in USA and Germany are 1.7% and 3.3%, respectively. Finland and Sweden, which have a low energy R&D budget, are comparable to top investor countries in terms of shares over total public R&D. Figure 1 also gives insights on the ranking of socio-economic objectives across countries. General knowledge is on top in most countries, with the exception of a few places that allocate more resources to Defense (United States, France, and Great Britain) and of another few that allocate more budget to industry R&D (South Korea, Belgium Finland).

[5] This evidence should be interpreted with caution given that GBAORD refer to budgeted allocations, not actual expenditures. Hence we could also interpret these statistics as different ways of planning.

Table 1: Government R&D Budget Appropriations or Outlays - GBAORD (1995-2007). Mean values (1995USD million) and standard deviation.

	Mean				Coefficient of variation			
	Energy	General knowledge	Industry	Total	Energy	General knowledge	Industry	Total
PRT	7	169	108	712	0.43	0.69	0.39	0.32
DNK	27	399	107	1320	0.39	0.41	0.23	0.18
BEL	39	341	429	1596	0.09	0.23	0.42	0.20
AUS	47	527	424	2473	0.36	0.63	0.21	0.18
GBR	54	1832	220	10251	0.31	0.37	0.76	0.17
FIN	72	285	388	1424	0.43	0.41	0.16	0.21
SWE	81	697	123	2406	0.23	0.61	0.42	0.23
NLD	94	1050	363	3431	0.15	0.70	0.12	0.17
ESP	102	675	642	3938	0.44	0.67	0.33	0.34
CAN	222	756	506	4229	0.28	0.68	0.33	0.27
ITA	277	1887	743	7179	0.19	0.68	0.36	0.20
KOR	321	1193	1632	5938	0.41	0.34	0.39	0.34
DEU	611	5157	2362	18689	0.19	0.45	0.17	0.15
FRA	687	2986	901	14991	0.17	0.28	0.20	0.13
USA	1444	4558	418	86649	0.45	0.41	0.12	0.20
JPN	5446	7538	1984	30267	0.09	0.47	0.29	0.14

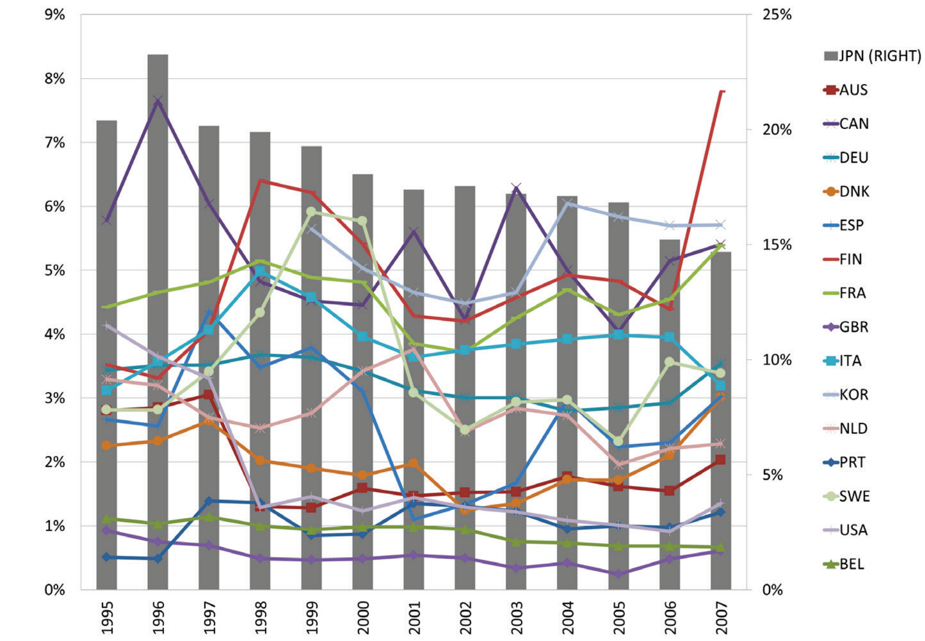
Figure 1: Government R&D Budget Appropriations or Outlays - GBAORD (1995-2007) – Average share to total budget[6]. Countries from left to right ordered according to increasing Energy R&D outlay as in Table 1.



The budget allocated to energy R&D as share of total R&D declined between 1995 and 2007 in the top energy/power R&D countries. Figure 2 shows the share of GBAORD energy over total GBAORD R&D. Energy R&D fell significantly in Japan, Canada, United States and Australia. This tendency is weaker in most European countries, and inverted in France, Denmark, and Sweden. South Korea stands out as a country increasing the public R&D budget to the energy sector. However, South Korea starts from a low value compared to the other countries.

[6] Actual value for Defense GBAORD R&D is 55% in the USA.

Figure 2: Share of government Energy R&D Budget Appropriations or Outlays over the total R&D GBAORD budget.



The International Energy Agency (IEA) Database focuses on the power sector. We isolate data for fossil fuels, renewable excluding biofuels, nuclear, hydrogen and fuel cells, other power and storage techniques. Since it is not clear whether fossil R&D can be classified as power or not, Figure 3 separates this component. Figure 3 compares the mean values of GBAORD energy R&D with the IEA average. When considering total IEA R&D, the two indicators are comparable in most countries. Exceptions are Germany, Japan, Spain, and South Korea where GBAORD is 95, 71, 58, and 31% and greater. In BEL, DNK, FIN, ESP, GBR, NLD, AUS, KOR, CAN, ITA, DEU, FRA the two indicators give close estimates[7].

Table 2 shows the coefficient of variation of power R&D in IEA (including fossil), total IEA R&D and GBAORD. The correlation between the coefficient of variation of total IEA R&D and of GBAORD energy is close to 0.5. The correlation between the coefficient of variation of power IEA R&D and of GBAORD energy is greater than 0.5 only when considering the six top investing countries.

[7] The inclusion of energy efficiency in the IEA definition of power R&D would not significantly alter the results shown in Figure 3.

Figure 3: Public energy R&D budget. A comparison of IEA and OECD databases. Mean values 1995-2007. Other IEA refers to categories such as other cross-cutting technologies and research which is reported by IEA but excluded from the power definition used in this paper.

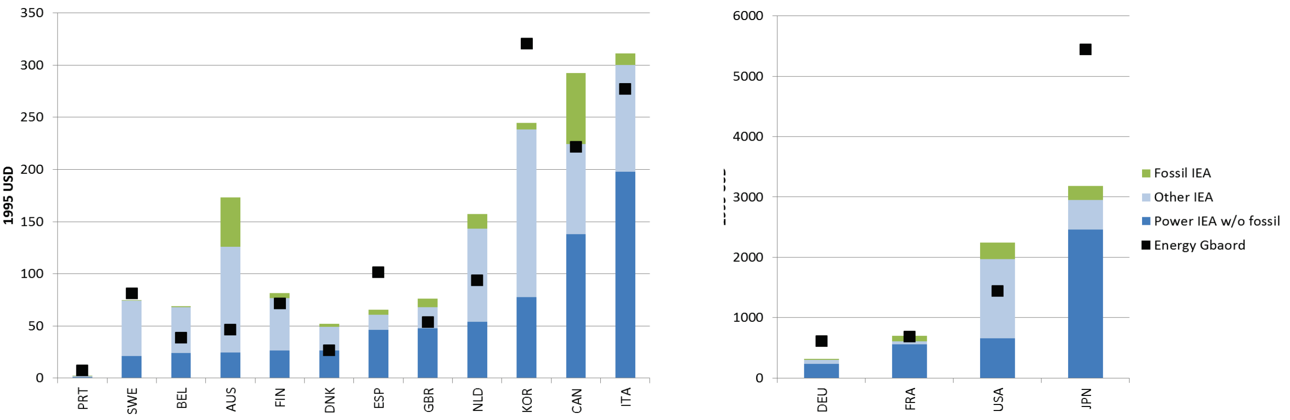
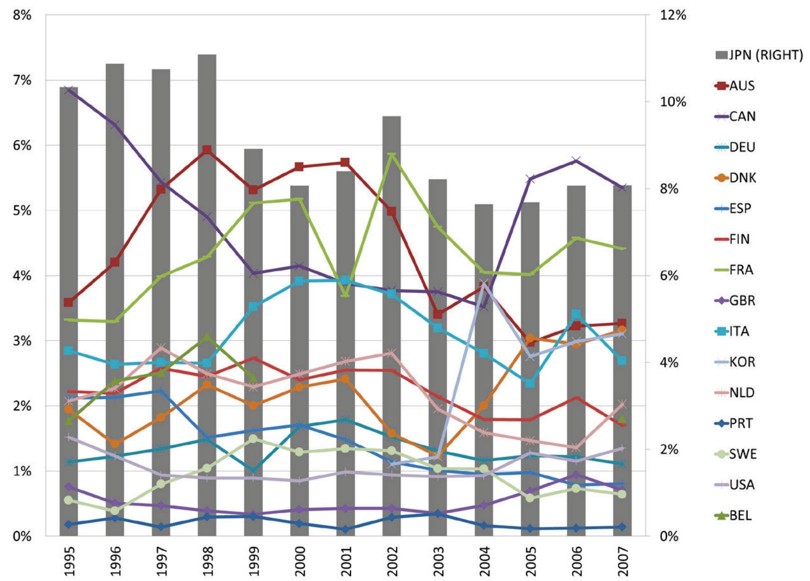


Table 2: Public energy R&D budget. A comparison of IEA and GBAOARD databases (1995-2007). Mean values (1995USD million) and standard deviation.

	Mean			Coefficient of variation		
	Power IEA including fossil	Total IEA	Energy GBAORD	Power IEA including fossil	Total IEA	Energy GBAORD
PRT	1.4	2.1	7.5	0.38	0.28	0.43
SWE	21.2	74.3	81.3	0.24	0.25	0.23
BEL	24.6	68.8	38.6	1.15	0.22	0.09
DNK	29.4	52.1	26.9	0.45	0.41	0.39
FIN	31.3	81.5	71.5	0.12	0.26	0.43
ESP	50.6	65.4	101.7	0.14	0.19	0.44
GBR	56.0	76.3	53.5	0.48	0.49	0.31
NLD	68.0	157.3	93.7	0.34	0.15	0.15
AUS	71.3	173.0	46.5	0.71	0.28	0.36
KOR	84.2	244.6	320.7	1.36	0.43	0.41
CAN	205.7	292.1	221.7	0.37	0.28	0.28
ITA	208.4	311.0	277.4	0.36	0.10	0.19
DEU	242.8	312.8	610.5	0.10	0.20	0.19
FRA	644.7	694.6	686.5	0.15	0.19	0.17
USA	930.5	2246.7	1443.9	0.30	0.14	0.45
JPN	2694.6	3184.9	5446.3	0.05	0.07	0.09

The budget allocated to power R&D as share of total R&D declined between 1995 and 2007 in the top energy/power R&D countries. Figure 3 shows the share of power IEA R&D (with fossil) over total GBAORD R&D. Compared to 1995, power R&D fell in Japan, Canada, and United States. This tendency is weaker in most European countries, and inverted in France and Denmark. South Korea IEA power R&D shows a jump between 2003 and 2004, as in the GBAORD database (see Figure 2). Major differences between the two databases stand out for Australia, Finland.

Figure 3: Share of power R&D with fossil (IEA) over the total R&D GBAORD budget.



3. AN OVERVIEW OF PRIVATE R&D INVESTMENTS

In comparison to public R&D statistics, data on private investment in energy innovation are less readily available.[8] The main source of information on R&D expenditure performed by the different industrial sectors is the OECD ANBERD Database (BERD).[9] We focus on the "Electricity, water and gas distribution industry" sector, which includes all activities related to the production, transmission and distribution of electricity, manufacture of gas, distribution of gaseous fuels, and steam and hot water supply.

There are two main challenges in using the ANBERD data. First, the statistics are presented by sector of performance expenditures regardless of whether funding was sourced from private or public spending. Second, the sector "Electricity, water and gas distribution industry" is clearly not capturing in a

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[8] Different countries rely on different forms of financing private R&D expenditure and data are not always comparable. There are important differences in the way in which data is collected across countries and databases. We briefly highlight here the most important ones, which will help highlight the strength and weaknesses of the data assembled in this paper. Data on R&D investment can be collected either by sector of performance or by sector of funding. The OECD collects R&D expenditure statistics performed in the business enterprise sector by industry according to the International Standard Industrial Classification (ISIC) revision 3.1. and by source of funds (business enterprise, government, other national funds, and funds from abroad) . However, the time and country coverage is not good enough for international comparison (see Section 3.2). Moreover, data can be classified according to the territorial principle territorial principle, which allocates the private expenditure to the country where the money is spent, or by attributing it to the corporate entity which supports the research activity (for example, the case of multi-nationals, by attributing all the investment to the country where the parent company is based. This clearly complicates the comparison of statistics coming from different data sources

[9] The Frascati Manual (OECD 2002) defines the business enterprise sector as "All firms, organisations and institutions whose primary activity is the market production of goods or services (other than higher education) for sale to the general public at an economically significant price. The private non-profit institutions mainly serving them." ANBERD provides information on 60 manufacturing and services sectors in the OECD member countries according to the industrial classification ISIC Rev. 3, http://unstats.un.org/unsd/cr/registry/regcst.asp?Cl=17. The database also includes limited time-series data for selected non-members economies (China, Romania, the Russian Federation, Singapore, South Africa, and Chinese Taipei). The data collected in ANBERD refers to actual R&D expenses by business. The information is collected though performer-based surveys at the enterprise level. Each enterprise is then allocated to the industrial class of its principal activity. The ANBERD data is classified using a territorial principle, namely expenditures are assigned to the country where the money is spent (Azagra Caro and Grablowitz 2008).

satisfactory way the R&D expenditure related to power production and distribution, as much of it is carried out in other sectors such as mining and machinery which provide capital and material inputs to energy production. We address this second issue by providing lower and upper estimates to private spending in power R&D. The R&D expenditure in the power sector (ISIC Rev. 3 sectors 40-41) represents a lower estimate of energy-related R&D expenditures. An upper estimate of power-related R&D can be derived by estimating how much R&D spending is embedded in the inputs used in the power sector, but produced by other sectors of the economy. Using data on inter-sectoral, inter-country trade flows, we develop a methodology to produce such an estimate, see Section 3.2.

3.1 LOWER-BOUND ESTIMATES OF PRIVATE POWER R&D INVESTMENTS

In this subsection we present lower bound estimates of private investments in energy by relying solely on information on R&D investments for the sector of energy. In the following subsection (3.2), conversely, we explain the methodology that uses data on sectoral input-output flows to provide an upper bound estimate of the same statistics.

Table 3 shows mean values and coefficient of variation over our sample period for R&D expenditures in the power sector from the ANBERD database. It also compares them to those of the upstream sector of mining and quarrying as well as those of the most R&D-intensive industry, namely electronic and optical equipment. In particular, a focus on the mining and quarrying is justified here because it represents the sector which provides material inputs to power production, as most of the electricity worldwide is produced using coal and gas.

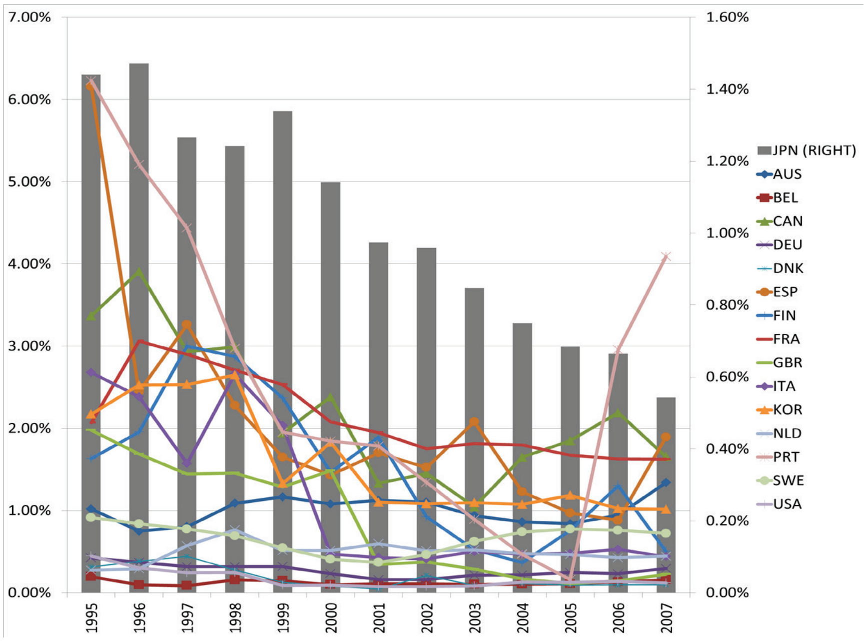
Power R&D is two orders of magnitude less than Electrical and Optimal Equipment. In absolute amounts, the top investors are Japan, France, United States, followed by South Korea and Canada, which together account for the 78% of the average business power R&D, approximately 2.5 billion US$ 1995 dollars per year. Although power R&D investments correlate well with total business R&D, some countries that are top innovators in terms of total or electronic and optical equipment R&D, are not in the same ranking when considering power R&D. As a consequence, there are countries that invest in power R&D a comparable amount to Germany and USA, but invest much less in the other sectors, thus showing a relatively specialization toward power R&D. For example, consider Portugal. Although it is at the bottom of the ranking when considering the amount invested (Table 3), the average share of power R&D over total private R&D is about 2%, ten times greater than that of the United States (see also Figure 4). The coefficient of variation indicates that on average power R&D varies more than total R&D, with the exception of Japan and South Korea, and Canada.

Table 3: ANBERD – Power, Mining, R&D Intensive industries and Total private R&D (ANBERD). Mean values (1995USD million) and standard deviation.

	Electricity, Gas And Water Supply	Mining and Quarrying	Electrical And Optical Equipment	Total	Electricity, Gas And Water Supply	Mining and Quarrying	Electrical And Optical Equipment	Total
	Mean				Coefficient of variation			
DNK	6	NA	415	3211	0.69		0.54	0.52
PRT	8	0	48	335	1.16	0.67	0.29	0.65
BEL	23	5	830	4287	0.91	0.63	0.16	0.11
FIN	23	7	NA	1665	0.50	0.31		0.21
NLD	25	112	1590	4976	0.26	0.29	0.07	0.08
AUS	41	783	404	4020	0.51	0.65	0.13	0.41
SWE	58	NA	2606	8988	0.24		0.20	0.17
ITA	71	42	1559	6478	0.76	1.21	0.11	0.09
ESP	73	21	501	3906	0.40	1.41	0.11	0.33
DEU	121	64	9711	45955	0.21	0.43	0.07	0.13
GBR	122	67	2394	15429	0.78	0.31	0.11	0.10
CAN	137	196	1665	6854	0.16	0.54	0.50	0.28
KOR	187	10	6258	13012	0.21	1.87	0.41	0.33
USA	209	NA	46400	135851	0.49		0.12	0.14
FRA	512	149	5991	24486	0.17	0.25	0.04	0.07
JPN	977	230	20181	100968	0.15	0.24	0.57	0.23

Between 1995 and 2000, private power R&D as share of total private R&D dropped in most countries. Figure 4 shows the share of power ANBERD R&D over total private R&D. After 2002, the share of private power R&D begun to rise again in Canada, Austria, Sweden, and later on it jumped also in Portugal.

Figure 4: Share of power R&D (ANBERD) over the total private R&D.



3.2 UPPER-BOUND ESTIMATES OF PRIVATE POWER R&D INVESTMENTS

The figures just discussed provide lower bound estimates of total private power R&D for two reasons. First, a large part of R&D which is essential for power production is actually embedded in capital and material input to this sector (machinery and fuels), depending on the type of technology used. Second, in some countries such as the United States venture capital is a major source for funding innovation. We deal with the first issue here, while we address the second one in the next Section.

The first source of approximation is particularly important when considering fossil fuel power generation. The R&D related to fossil fuel power generation mostly occurs in the mining and quarrying, coke and refined petroleum, machinery and equipment sectors, which are the main factors of production. Some of these sectors (e.g. machinery and equipment) are very R&D-intensive. Not accounting for this can lead to severe underestimation of power-related R&D. To compute a more inclusive indicator of private power R&D we resort to input-output data and bilateral trade flows included in the WIOD database.[10] Using this data, we calculate the share of exports to the electricity, gas, water sector from all other sectors/countries in each year (see Appendix for the detailed methodology). We then use these ratios to build an extended estimate of power-related R&D by weighting the R&D investments of all the sectors exporting to the electricity sector and summing them up by country and year. The main exporters to the power sector in any country are the sectors mining and quarrying, coke, refined petroleum and nuclear fuels, and the electricity sector itself. In some countries (Germany, China, Russia) other important exporters to the power sectors include machinery and equipment, electrical and optical equipment, transport, storage and communication (in the USA). The resulting extended definition of power R&D includes the R&D embedded in all inputs used in the power sector, independently of the country source.

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[10] www.wiod.org.

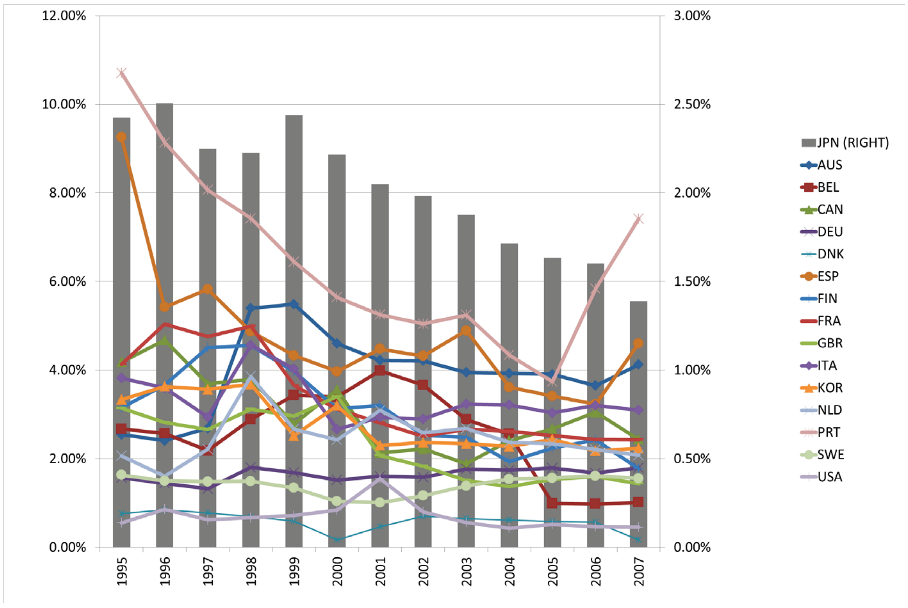
Table 4 compare the statistics for the resulting extended definition of power R&D with the restricted definition. The countries with the largest fraction of embedded power R&D tend to be the major R&D investors. When considering the extended definition of power R&D the R&D intensity of the power sector in some countries increase significantly and becomes comparable R&D intensive sectors. With the exception of France and the US, extended power R&D is more stable over time, as indicated by the lower coefficient of variation.

Table 4: ANBERD - Extended Power, Power and Total private R&D. Mean values (1995USD million) and standard deviation.

	Extended Electricity, Gas And Water Supply	Electricity, Gas And Water Supply	Total	Extended Electricity, Gas And Water Supply	Electricity, Gas And Water Supply	Total
	Mean			Coefficient of variation		
DNK	22	6	3211	0.36	0.69	0.52
PRT	30	8	335	0.97	1.16	0.65
BEL	101	23	4287	0.50	0.91	0.11
FIN	48	23	1665	0.19	0.5	0.21
NLD	124	25	4976	0.23	0.26	0.08
AUS	171	41	4020	0.48	0.51	0.41
SWE	126	58	8988	0.20	0.24	0.17
ITA	217	71	6478	0.15	0.76	0.09
ESP	191	73	3906	0.30	0.4	0.33
DEU	768	121	45955	0.18	0.21	0.13
GBR	325	122	15429	0.30	0.78	0.1
CAN	192	137	6854	0.13	0.16	0.28
KOR	368	187	13012	0.24	0.21	0.33
USA	963	209	135851	0.53	0.49	0.14
FRA	807	512	24486	0.23	0.17	0.07
JPN	2017	977	100968	0.07	0.15	0.23

Between 1995 and 2000, extended private power R&D as share of total private R&D dropped in most countries, though in a less sharp way compared to the dynamics of restricted power R&D. Figure 5 shows the share of extended power ANBERD R&D over total private R&D. After 2002, the share of extended private power R&D begun to rise again in Canada, Sweden, and later on it jumped also in Portugal.

Figure 5: Share of extended power R&D (ANBERD) over the total private R&D.



4. ROBUSTNESS CHECKS ON PRIVATE R&D ESTIMATES

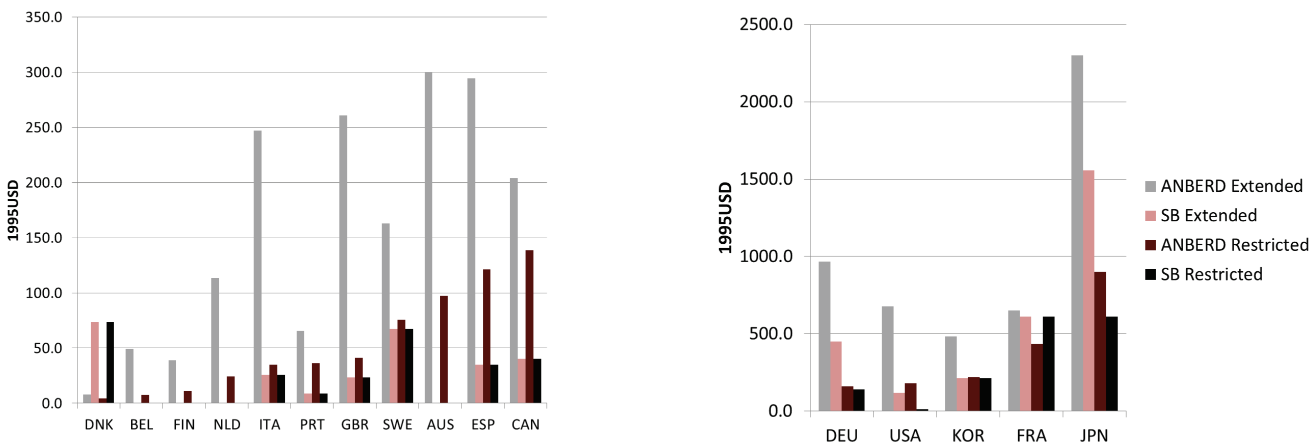
As mentioned previously, an first problem when defining power R&D is to appropriately account for energy R&D expenditures which are not included in the power sector. Our methodology to build lower and upper bound estimates is a first step in this direction. A second source of underestimation in the private power R&D figures depends on the fact that some countries actually use Venture Capital as the major way to finance RD&D rather than private investments in R&D (Jeng and Wells 2000, Hall and Lerner 2009). In this section we address these two issues, as well as provide a comparison with previous available estimates for the years in which the data overlaps. To address the first issue, our estimates of R&D expenditures for the energy sector from ANBERD can be compared with two other databases, whose level of detail is greater but whose time coverage is more limited.

First, we use data from the JRC-IPTS Scoreboard, which contains information on corporate R&D financed by the top 1400 EU and non EU firms. Unlike ANBERD, the Scoreboard allocates all R&D expenditures to the parent company, thus effectively assigning all the R&D investment to the country where the parent company is located, independently of where the actual R&D expenditure took place (Azagra and Grablowitz 2008). A focus on the power sector is available for the time period 2007- 2010. In particular, we define power R&D as the aggregate of R&D performed by firms grouped under the sectors Electricity, Gas, water & multi-utilities, and Alternative energy.

As in the case of ANBERD data, some firms reported in the Scoreboard and that perform R&D relevant to the power sector are classified elsewhere, as their main product segment is not power generation. For example, the Japanese Company Hitachi Kokusai Electric is classified under the Electronic equipment sector, but it sells most of its products (69% of total sales) to the power sector. General Electric, which according to the ICB classification standards falls under General Industries, perform research in many areas closely connected to power generation such as wind turbines and sells 9% of its products to the power sector. These figures suggest that the Electricity, gas and water sector underestimates power R&D, as other sectors perform R&D that is relevant to the power sector. Like in the ANBERD case, we compute narrow and extended estimates of corporate energy R&D investment, with a methodology similar to the one used for ANBERD data. To compute extended estimates of corporate power R&D for the Scoreboard data, we applied a similar methodology to the one we applied to the ANBERD data. Specifically, we used firm level information on the share of sales to the power sector in order to compute the R&D embedded in other sectors. By assuming that the same share will approximate the share of power R&D with respect to total R&D we can then include a fraction of the R&D effort undertaken by top innovative firms not directly listed under the power sector in the Scoreboard dataset. The Scoreboard database indicates a gap between restricted and extended power R&D for Germany, Japan, and United States (Figure 6). These are the top innovator countries, all characterized by a few large companies that perform a lot of R&D that is embedded in a lot the machinery and equipment used by the power sector.

Figure 6 compares ANBERD and Scoreboard estimates for the year 2007, which is the only year of overlapping with ANBERD[11]. In some countries the two statistics yield comparable estimates (e.g. Italy, Germany, South Korea, Sweden) when considering the restricted definition. In Japan, Spain, the United States, ANBERD power R&D points at higher values than Scoreboard, both for the upper and lower bound.

Figure 5: Power R&D investments in Scorebaord and ANBERD in 2007. Extended (upper-bound) and restricted (lower-bound) definitions. 1995 USD million.



The difference could be due to various reasons. R&D could be performed by the Business sector, but financed by non-business enterprises or non-Scoreboard companies. In fact, the ANBERD database reports the expenditure of the R&D carried out in industry sectors without specifying the source of funding. Adjusting the source of funding reduce the gap between Scoreboard and ANBERD, but it does not eliminate it but for a few countries, such as Germany. In France the Scoreboard R&D is about 200 million dollars greater than ANBERD R&D. As discussed in Azagra Caro and Grablowitz (2008), Scoreboard R&D overestimates ANBERD R&D

[11] We aggregate company data by sector of performance and country. We classify as power R&D the R&D performed by the firms in the sectors electricity, Gas, water & multi-utilities, and alternative energy. We are currently working on extending the comparison to the period 2007-2010.

when there are companies that performs a lot of R&D in subsidiaries located in a country different from the location where the company is registered .

Notwithstanding these differences, the two database point at the same ranking across countries. The EU Scoreboards also reports company' sales and therefore it allows computing an indicator of private R&D intensity by relating R&D investments and total sales[12]. Both indicators suggest that that the countries with the lowest R&D intensity in the power sector are Great Britain, Italy and the USA, while the ones with the highest R&D intensity are Sweden, Canada, Korea and France.

Having compared our estimates to other available ones in the literature, we now turn to the issue of venture capital investments. VC is another important source of R&D funds for the energy sector in some countries (Kortum and Lerner 2000). We therefore collect information on venture capital investment from the Bloomberg Energy Finance Database (BNEF, 2012) and Evca.[13] The BNEF collects information on private equity and venture capital investment in the renewable energy sector worldwide. The Evca Yearbook includes data on venture capital investment by industry in European countries[14] and specifically distinguishes investments in "Energy and the Environment". Data for the USA are provided by the

[12] As discussed in detail in Azagra Caro and Grablowitz (2008) there are conceptual differences that make the comparison between ANBERD and Scoreboard not appropriate. The share of R&D investments over total sales is an indicator of R&D productivity at the firm level, though it can be aggregated at the sectoral/country level, and it can inform about the performance of a firm. In contrast, the ratio of R&D expenditure to gross output can still be seen as an indicator of R&D efficiency, but it is less clear what is the unit of which the performance is evaluated (firms or government funds?) . Rather than comparing the two databases, we use them to evaluate whether cross-countries patterns and inter-temporal trends are consistent.

[13] Unfortunately, the most relevant sectors for our analysis are the sector "Energy and the Environment" for the EU and the sector "Industry/Energy" for the US. These sectors are much broader than what we have discussed so far, as we have focused our attention mainly on the power sector. A finer resolution dataset of Venture Capitals is provided by the Bloomberg New Energy and Finance Database BNEF. However, the database does not collect VC investments in traditional power technologies, rather the chief objective of the dataset is that of collecting information on carbon free technologies.

[14] Evca Yearbook 2011

US VC Database for the sector Industry/Energy,[15] which includes also environmental, agricultural, transportation, manufacturing, construction and utility-related products and services. As shown in Table 5, venture capital plays a large role in the USA and Great Britain, while in Japan R&D is internally financed by corporate funds. United States is the major investor in both R&D and VC, with the only exception of power R&D, which is dominated by Japan and France.

Table 5: Private investments in VC. Total and energy sectors for selected countries. 1995 USD million.

	VC Power Ren Average 2000-2010	VC Total Average 2000-2010	VC Energy Average 2000-2010
AUS			
CAN	30	na	na
DEU	24	819	88
DNK	4	140	8
ESP	1	300	52
FIN		11	111
FRA	22	942	68
GBR	91	1117	165
ITA	5	90	20
JPN	na	na	na
KOR			
NLD	na		
PRT		64	6
SWE	7	305	34
USA	1428	18675	2754

[15] Producers and suppliers of energy, chemicals, and materials, industrial automation companies and oil and gas exploration companies. Also included are environmental, agricultural, transportation, manufacturing, construction and utility-related products and services.

5. PATENTS IN POWER

This section presents general statistics on patents in energy, with the aim at providing a general overview of how this widely used indicator of the outcome of research activity is developing over time for this sector.

Patent statistics are taken from the OECD Patent Statistics Database, version 2013, accessed in November 2013. As customary in the innovation literature, we select patents by country of inventor and count them by priority date. Since patent statistics suffer from the shortcoming that patent values are highly heterogeneous, we select here data relative to PCT applications, namely those patents that are targeted to more than one market. This provides a quality threshold in our innovation indicator. To isolate patents which are related to power, we select the following technological categories (which are derived based on IPC classification codes):

- Energy generation from renewable and non-fossil sources, namely renewable energy generation (Wind energy, Solar thermal energy, Solar PV, Solar thermal-PV hybrids, Geothermal energy, Marine energy (excluding tidal), Hydro energy - tidal, stream or damless, Hydro energy – conventional) and energy generation from fuels of non-fossil origin, namely fuel from waste (e.g. methane)
- Combustion technologies with mitigation potential (e.g. using fossil fuels, biomass, waste, etc.), namely technologies for improved output efficiency (Combined combustion), Heat utilisation in combustion or incineration of waste, Combined heat and power (CHP), Combined cycles (incl. CCPP, CCGT, IGCC, IGCC+CCS) and technologies for improved input efficiency (Efficient combustion or heat usage)
- Technologies specific to climate change mitigation, namely CO_2 capture and storage (CCS), Capture and disposal of greenhouse gases other than carbon dioxide (incl. N_2O, CH_4, PFC, HFC, SF_6)

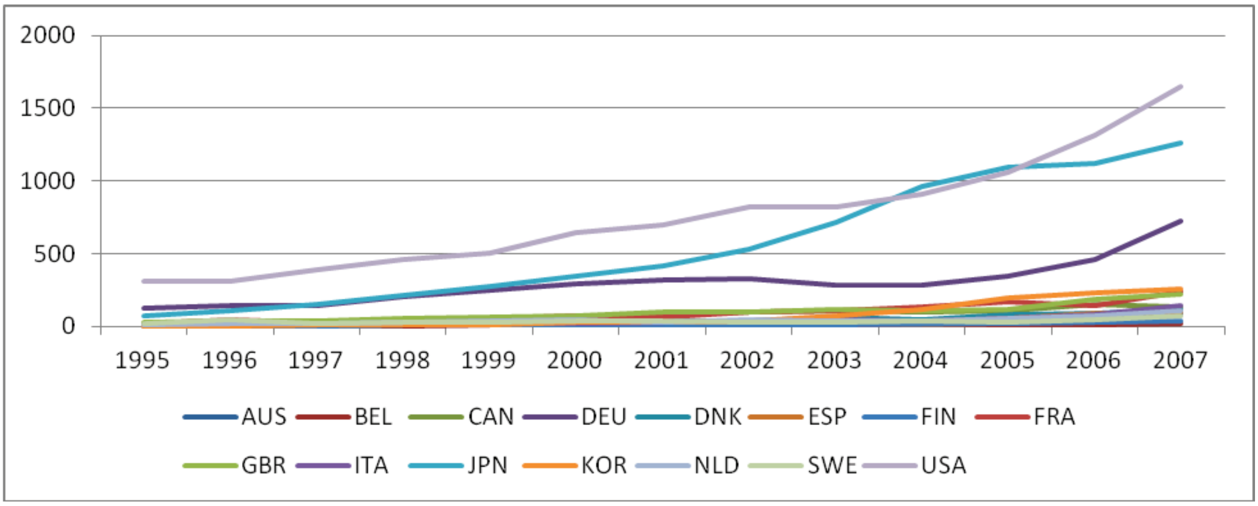
- Technologies with potential or indirect contribution to emissions mitigation, namely Energy storage, Hydrogen production (from non-carbon sources), distribution, and storage, Fuel cells
- Nuclear power technologies, which are selected from IPC classes G21B, G21C and G21D.

We observe a general increasing trend in patents, which has also been document by previous studies. Leading innovators in energy, as in many other sectors, are the USA, Japan and Germany. The number of power-related patents has been steadily increasing over time, both in top innovating countries and in countries characterized by mid innovation levels (Figure 6). This is in contrast with the trends observed for private power R&D, whereas it is more in line with the trends observed for public power R&D.

Private power R&D fell in all countries, but by a greater amount in Europe and Japan. The drop in Europe is driven by a significant reduction in United Kingdom, Italy, and Germany. Japan, UK, and the USA reduced power R&D by about 1995USD 200 millions, which is a significant amount but much lower than the reductions observed in the energy R&D in the US between 1994 and 2005. This pattern seems to be specific to the power sector, as the time series for total R&D in these countries do not show any inflection during the same time period. The trend reverted after 2004 in all countries considered and since that date power R&D begun to rise again. When considering the extended power R&D, there are no great variations between 1995 and 2007, and it shows the same tendency to pick up after 2004.

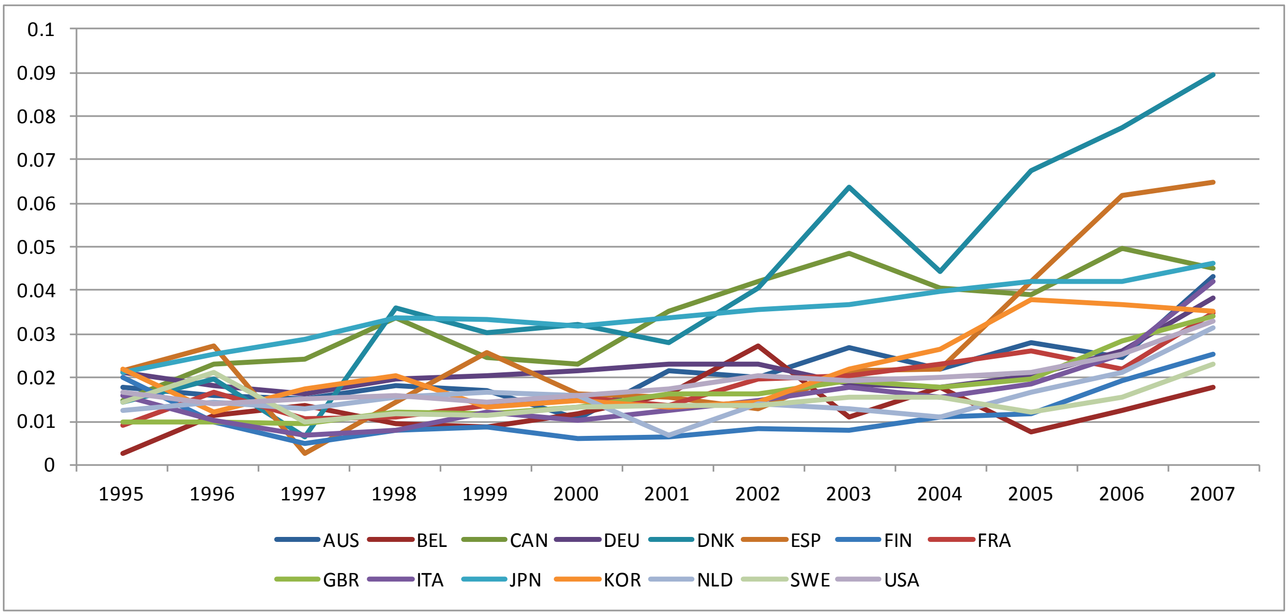
Public energy (GBAORD) and power (IEA) R&D trends have been quite stable throughout the time span considered in Japan. In the US, after a decline in the late nineties, it begun to rise again. In most countries the positive trend is mostly observed after 2000 and 2003.

Figure 6: Power PCT applications, 1995/2007. Patents are selected by country of inventor and sorted by priority date.



Looking at the absolute value of patent statistics does not however inform on the relative importance of energy versus non-energy patents. Figure 7 provides the same statistics as a share of total PCT applications. Energy patents are steadily rising in importance within the patent portfolio of each of the countries in our analysis. The average share of energy-related patents to total patents in PCT applications went from 1.6% in 1995 to roughly 3% in 2007. Results are very similar when considering other classifications of patent applications, such as Triadic patent families or applications to the EPO. It is interesting to note the clearly increasing trend in the share of power patents despite the pronounced decline in the share of power R&D observed in the private and public sector for the top innovators, USA and Japan, and also for the other countries especially in the private sector.

Figure 7: Share of power PCT applications in total PCT applications, 1995/2007. Patents are selected by country of inventor and sorted by priority date.



6. PRELIMINARY CONCLUSIONS AND NEXT STEPS

This paper describe the attempt to collect, harmonize, and describe data on power-related R&D and innovation. Energy-related R&D is a very elusive concept and for this reason extremely hard to quantify. We therefore introduce a methodology to define lower and upper bounds to power R&D and compare different sources. We do find that the most widely used sources for public R&D give different value and in some cases might also point at different trends over time. Despite these heterogeneities it is possible to identify a number of clear patterns and tendencies.

Top innovators in non–power other sectors are not necessarily top innovators in the power sector. The USA is leader in terms of total business R&D expenditure, but not in terms of power R&D. Major nuclear-oriented countries and top investors in power R&D, Japan and France, have reduced the R&D expenditure between 1995 and 2007, whereas significant increases have been observed in smaller countries such as Spain and Portugal, especially since 2004. Countries that stand out in terms of private power R&D, namely Japan, France, United States, also allocate to power R&D relatively more public funds. Despite the significant time variation observed in the share of power R&D over total R&D, both in the private and public sector, the share of power patents has been steadily increasing.

The next steps of this work include a systematic analysis of the relationship between private and public R&D in the power sector as well as elsewhere, an assessment of the efficiency of patent productions by country, looking at how country ranks in terms of innovation efficacy, the definition and comparison of quality indicators of R&D spending.

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APPENDIX

We computed the extended definition of ANBERD power private R&D using the input-output data and bilateral trade flows from the WIOD database.[16] Using this data, we calculate the share of exports to the electricity, gas, water sector from all other sectors/countries in each year:

$$sh_{i,j,t} = \frac{EX_{i,j,d,m=ely,t}}{\sum_i \sum_j EX_{i,j,d,m=ely,t}}$$

where $t = 1995 - 2009$; $i =$ exporter; $j =$ exporter sector; $d =$ importer country; $m =$ importer sector;

We then use these ratios to build an extended estimate of power-related R&D by weighting the R&D investments of all the sectors exporting to the electricity sector and summing them up by country and year.

The main exporters to the power sector in any country are the mining and quarrying sector and the coke, refined petroleum and nuclear fuels sectors, the electricity sector itself, and in some countries (Germany, China, Russia) machinery, and electrical and optical equipment, transport, storage and communication (in the USA). The resulting extended definition of power R&D includes the R&D embedded in all inputs used in the power sector, independently on the country source.

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[16] www.wiod.org.

Table A1: Sources for public and private R&D used in this studies and main characteristics

	Data Source	Monetary flow	Sector/technology	Type of data
Private Power R&D	OECD ANBERD Database http://stats.oecd.org/	BERD	Industry ISIC Rev 3	Expenditures / territorial principle
	JRC-IPTS Scoreboard http://iri.jrc.es/research/	Investments	Electricity, Gas, water & multi-utilities, and alternative energy	/parent company principle
	Bloomberg New Energy Finance http://bnef.org	Venture Capital Investments	Renewable power	/
	Evca Yearbook	Investments	Energy and the Environment	/
	US VC Database	Investments	Industry/Energy	
Public Power R&D	IEA (2011) Guide to Reporting Energy RD&D Budget/Expenditure Statistics (http://www.iea.org/stats/rd.asp)	Budget outlays	Fossil fuels, renewable minus biofuels, nuclear, hydrogen and fuel cells, other power and storage techniques	Budget
	OECD (2012), "Government budget appropriations or outlays for RD", OECD Science, Technology and R&D Statistics (database) doi: 10.1787/data-00194-en	GBAORD	SOE using NABS 2007 classification	Budget

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34

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