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Innovation in the energy sector: advancing or frustrating climate policy goals?

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Abstract:

The energy sector is well known for the relatively modest level of resource that it devotes to research and development (R&D). However, the incremental pace of energy innovation has speeded up in the last decade as measured by public sector R&D budgets, deployment of alternative technologies and novel institutional arrangements. While much of this effort has been targeted at technologies that promise to reduce carbon dioxide (CO_2) emissions, there have also been major innovations that extend the fossil fuel resource base and reduce the cost of extraction. The last decade's developments can be seen in terms of a challenge to the existing energy paradigm in parallel with a renewed innovative response focusing on conventional fuels and technologies.

This paper examines this tension, by exploring the expectations of a variety of organisations in both the public and private sector regarding energy sector developments and by analysing private sector expenditure on energy research and development (R&D) and public sector budgets for energy R&D and demonstration (RD&D).

Scenarios and outlook exercises that have been published since 2013 reveal a wide range of beliefs about the future development of the energy system. The contrasting views underpinning the different scenarios are reflected in divergent patterns of R&D investment between the private and public sectors. There appears to be a tension between the drive to transform energy systems, on the part of public bodies, mainly motivated by the need to combat global climate change, and private sector activity, which tends to reinforce and extend existing patterns of energy provision. The paper addresses, but not answer definitively, the key question as to whether technological change is enabling or frustrating ambitious carbon goals.

Keywords: energy policy; energy scenarios; innovation; research and development

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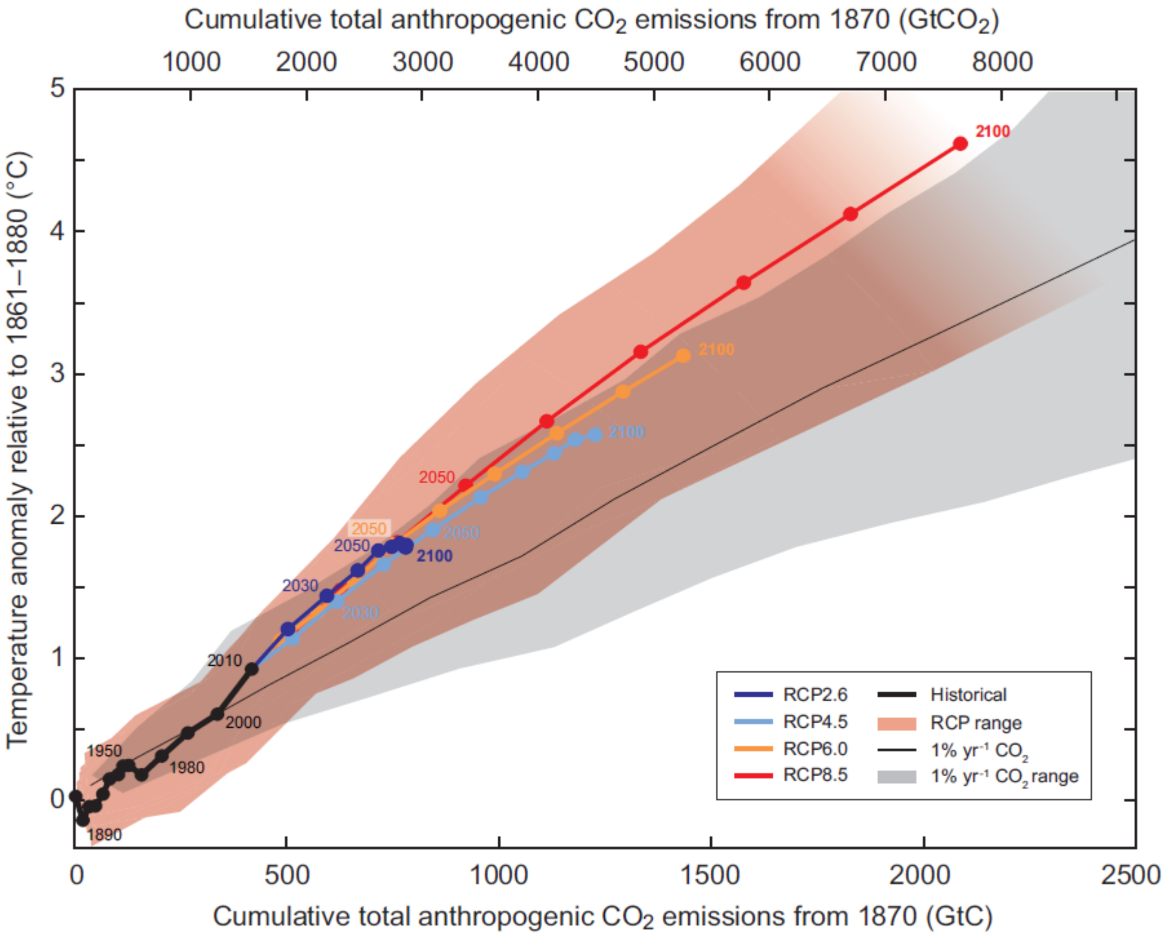
1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded in its Fifth Assessment Report that, if global temperature increases are to be likely to remain lower than 2°C above pre-industrial levels, a limited carbon budget of approximately 1 trillion tonnes carbon dioxide (CO_2) equivalent (Figure 1) is available for fossil fuels (Intergovernmental Panel on Climate Change 2013). Global emissions would need to be 40-70% lower in 2050 than in 2010 in order for this goal to be met (Intergovernmental Panel on Climate Change 2014). Meeting this goal would require a wholesale transformation of the global energy system and a radical change from current energy trends. However, the International Energy Agency (IEA) has concluded that the energy technologies currently available to the market at scale are not capable of reducing CO_2 levels to the required level (International Energy Agency 2012) . It has argued for a 'technological transformation' of the energy system, including significantly increased RD&D budgets over a sustained period of time, in order to support the technological advances needed to meet the 2°C target. The IEA estimates that the investment costs needed between now and 2050 to meet the 2°C target are over $36 trillion higher than would be the case in a scenario with no further CO_2 emission reduction policies (International Energy Agency 2008). This would entail more than a doubling of RD&D expenditure, with the decarbonisation of the electricity sector absorbing a great deal of this resource.

Figure 1: Cumulative and projected CO_2 emissions from 1870-2100



Source: Intergovernmental Panel on Climate Change (2014)

The energy system has traditionally been characterised as a 'mature' sector, displaying small, incremental technological improvements and low levels of research intensity, and dominated by large vertically-integrated firms competing on cost to provide largely undifferentiated products. For instance, in the private sector, the EU Industrial R&D scoreboard (EU IRI 2013) shows the average research intensity[2]of oil and gas producers and electricity producers to be 0.3 % and 0.5% respectively. This compares with an industrial average of 3.2% across all sectors and R&D intensities as high as 14% in sectors such as pharmaceuticals and biotechnology and 10% in software and computer services.

Over the past decade this situation has begun to change and innovative activity in the energy sector has expanded in many countries. This is indicated by both an growing share for new energy technologies and by a marked increase in public R&D expenditure (International Energy Agency 2013) focused largely on renewable technologies, infrastructure and energy efficiency. In parallel , there has been a surge in private sector RD&D investment (EU IRI 2013) concentrating mostly on driving improvements to deliver performance gains and cost reductions in conventional oil and gas technologies. As support grows for energy innovation so too does the need to understand how and why these trends in public and private energy R&D/RD&D expenditure are taking place and whether these are consistent with meeting climate policy goals.

This paper examines how different organisations from both the public and private sectors anticipate the global energy market will develop over the coming decades. It then explores how these perspectives have been translated into patterns of public and private sector energy research, development and demonstration (RD&D). To examine these trends we utilise datasets compiled by international organisations such as the OECD, IEA and World Bank. However, it is important that the limitations of these datasets are kept in mind. They rely on the quality of submissions from member countries which may, for example, be missing for particular countries/years, and may not always use precisely the same definitions. However, these still represent the best data available and, if approached critically, can be used to identify major trends and formulate working hypotheses. The different patterns of R&D effort highlighted by this analysis suggest a tension between innovation primarily supported by the public sector that is aimed at transforming the energy system and innovation driven by the private sector, which principally aims to extend the resource base and improve the efficiency of the current fossil fuel-based paradigm.

The paper is structured as follows. Section 2 examines the way that different organisations anticipate that economic and social trends, policy-influenced demand pull and science and technology push could play out in the energy sector at the global level. This is done by analysing published scenarios and outlooks exploring the time horizon to 2040. Section 3 examines past and current trends in both public and private expenditure on energy RD&D. Section 4 provides some overall conclusions and points the way towards future research into energy innovation.

2 Global Projections

Today's global energy system is in flux, shaped by a multitude of drivers and global priorities interacting with each other in often unpredictable ways. This complexity has led to key energy stakeholders developing divergent views about both the feasibility and the desirability of radical energy system change, particularly in response to addressing the climate change challenge. These tensions and differences are reflected in the views taken by

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[2] R&D expenditure divided by total sales

different organisations regarding the development of the energy system. In turn it is these views that inform the design of the contrasting R&D strategies that different organisations in both the private and public sectors follow, which we explore in Section 3. These scenarios fall into three broad categories: *outlooks, normative scenarios* and *exploratory scenarios*.

Outlooks are scenarios that project current trends in the energy system along a path defined by foreseeable policy, economic and technological changes, often referred to as ‘business-as-usual’ scenarios. By their very nature they are generally incompatible with the 2^{o}C target because they extrapolate current trends in the energy system which is currently dominated by fossil fuels. Outlooks tend to be produced by public national and supranational organisations, most notable being the US Energy Information Administration (EIA) (U.S. Energy Information Administration 2014), the Organisation of the Petroleum Exporting Countries (OPEC) (Organisation of the Petroleum Exporting Countries (OPEC) 2013) and the IEA with its 4DS and 6DS scenarios (International Energy Agency 2012). Some large private sector corporations, such as ExxonMobil (ExxonMobil 2014) and BP (BP 2014a), also produce outlooks which act as decision making guides for managers and investors. The majority of the most recent outlooks stretch out to 2035-40, whilst the IEA scenarios look to 2050.

Normative scenarios start from an endpoint, often the goal of holding global temperatures below 2^{o}C above pre-industrial temperatures, and ‘backcast’, modelling the policy and technology options for meeting this goal at the lowest cost. The IEA’s two degrees (2DS) scenario, developed for its Energy Technology Perspectives publication, constitutes such a normative scenario (International Energy Agency 2012). Over 900 scenarios of this type have been collected and assessed by the Intergovernmental Panel on Climate Change (IPCC) as part of the Fifth Assessment Report. (Intergovernmental Panel on Climate Change 2014)

Shell’s New Lens scenarios (Shell Scenarios Team 2013) provide an example of *exploratory scenarios.* The Shell scenarios are underpinned by two alternative qualitative ‘storylines’, focusing on different visions of the next fifty years. Their primary purpose is to help inform Shell’s business strategy so that it is robust against a range of plausible futures. Shell’s scenarios extend beyond the other scenarios mentioned to 2060.

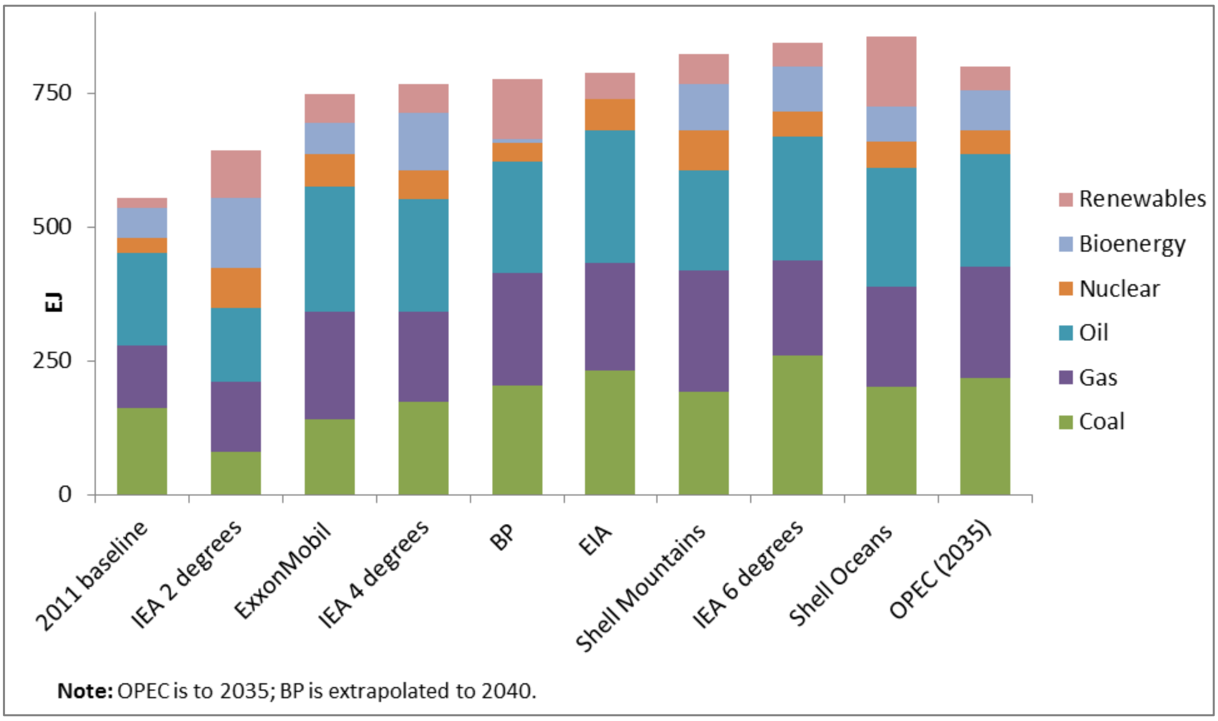
The six scenario sets referenced above are compared in Table 1 and Figure 2 for the year 2040 to illustrate the contrasting futures they envisage and in turn the lack of certainty around how the energy system will develop over the coming years.

Table 1: Key scenario/projection indicators for 2040

Scenario/projection	Style	Final demand for electricity (EJ)	Energy-related CO_2 emissions (bn t)
2011 baseline	-	66	31
IEA 2 degrees	Normative	108	20
IEA 4 degrees	Adopts Cancún pledges	120	40
IEA 6 degrees	BAU projection	131	52
EIA International Energy Outlook	Outlook	127	45
ExxonMobil Outlook for Energy	Outlook	124	36
Shell Mountains scenario	Exploratory	131	37
Shell Oceans scenario	Exploratory	159	41

Source: International Energy Agency (2012); Organisation of the Petroleum Exporting Countries (OPEC) (2013); ExxonMobil (2014); BP (2014a); Shell Scenarios Team (2013)

Figure 2: Primary energy demand in different global energy scenarios/projections for 2040.



Source: International Energy Agency (2012); Organisation of the Petroleum Exporting Countries (OPEC) (2013); ExxonMobil (2014); BP (2014a); Shell Scenarios Team (2013)

Some common themes emerge from the comparison of the scenarios. A significant rise in energy demand from the 2011 baseline is expected across all scenarios. However, this is significantly less pronounced in the IEA 2DS scenario. With respect to the technology mix, several energy technologies are common across all scenarios. For example, 'new' energy technologies, like electric vehicles and renewables, play a role in all the scenarios, albeit with slower rollouts and reduced market share in the 'business-as-usual' outlooks. Whilst renewable energy supply grows in all scenarios, it still meets only a small proportion of total energy demand. The renewables share is greatest in the Shell Oceans scenario, which features a substantial growth in solar PV driven by large-scale cost reductions.

In terms of fossil fuels, all of the scenarios envisage a large expansion in the role of natural gas, with most of the outlooks also entailing substantive increases in the roles of coal and oil. Combined with the increase in overall energy demand, this leads to a significant growth in energy related CO_2 emissions. The only exception to this trend is the IEA 2DS scenario, which is normative and constrained by the 2^oC climate change target[3]. Instead, the 2DS scenario projects a rapid expansion of all forms of renewable energy generation, nuclear power, carbon capture and storage (CCS) and energy efficiency measures. Oil and coal usage drops substantially from the 2011 baseline, and energy demand is substantially lower than the other scenarios.

There is a range of other differences between the scenarios, not least the role that bioenergy plays. Whilst expansions in the use of bioenergy can be seen in both the IEA scenarios and Shell Mountains, there are reductions in the ExxonMobil, BP and EIA outlooks. Additionally, the growth of energy related CO_2 emissions is lower in the ExxonMobil and Shell Mountains scenarios than the other scenarios. Finally, the two other differences are that ExxonMobil foresees greater energy efficiency savings than the other bodies and the Shell Mountains scenario includes larger-scale investments in CCS technology.

In the next section, we explore how the contrasting philosophies that underpin these public and private sector energy scenarios are reflected in patterns of public (Section 3.1) and private (Section 3.2) sector energy R&D investment, across a range of countries.

3 RD&D patterns

3.1 Public R&D trends

As discussed in the introduction, policymakers have developed a keen interest in energy innovation over the last decade due to the potential contribution it could make to addressing global climate goals. This resurgence follows a twenty-year slump in energy R&D following the end of the 1970s energy crises. In order to illustrate this trend in public energy R&D support, we draw upon annual data collected by IEA on public sector energy RD&D budgets from its member countries. It collects data as part of an annual survey sent to relevant government departments, which is collated to compile a time series database of historical RD&D expenditure. However, it should be noted from the outset that, due to potential differences in the scope and categorisation of data, budget levels should be considered indicative.

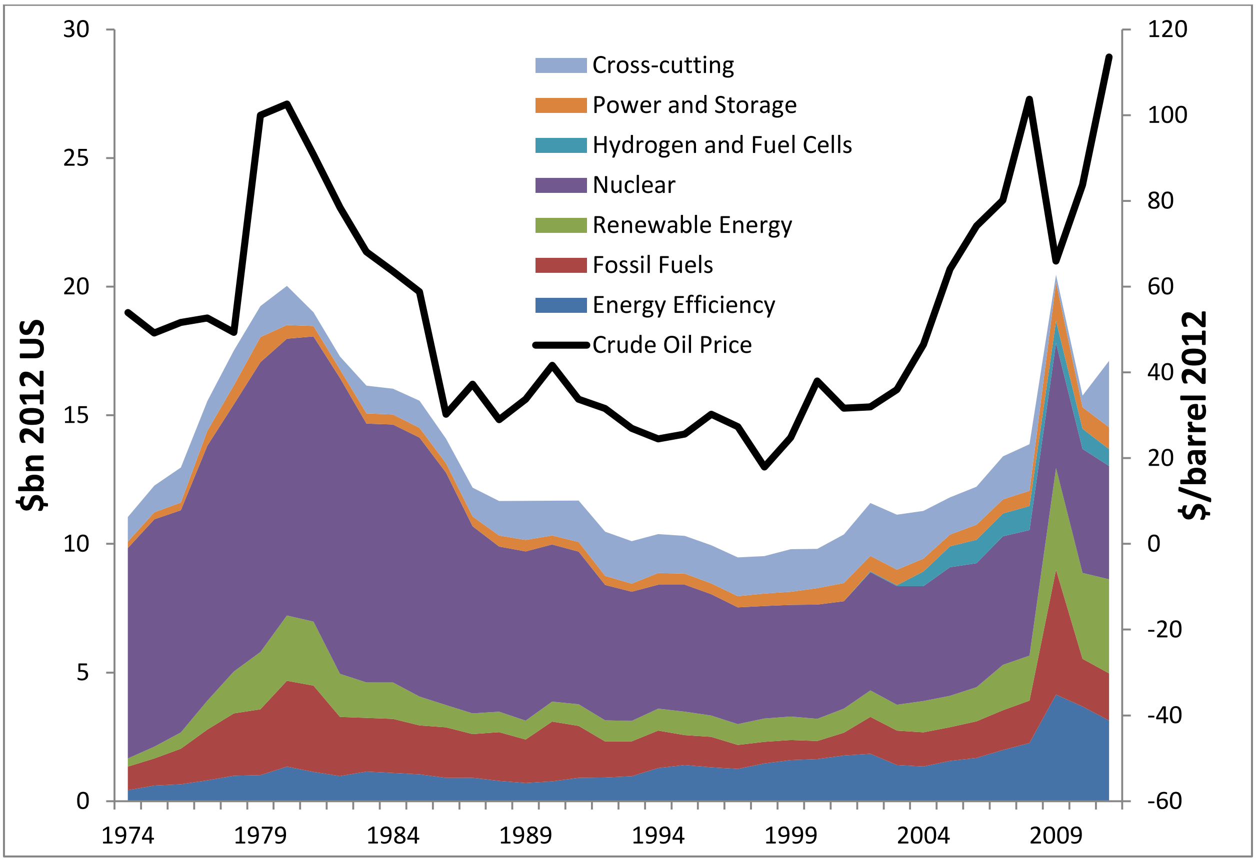
Figure 3 shows the total investment in RD&D in 2012 USD adjusted for purchasing power parity (PPP) across IEA countries 1974-2011 and

[3] The IEA 4DS scenario does take into account the pledges made at the Cancun agreement

Table 2 provides a breakdown of the total spend for 2011 (International Energy Agency 2013). The average annual price of oil is superimposed on the graph (BP 2014b) to illustrate the correlation between the price of oil and the quantity of global public RD&D activity, with the caveat that no direct causal relationship should necessarily be inferred. However, the high and volatile oil prices witnessed over the last decade have undoubtedly had some influence on policymakers.

Of further interest is the shift between nuclear (both fission and fusion) and renewables RD&D activity which has occurred over the last few decades. While making up the bulk of energy RD&D activities in the late 1970s and early 1980s, rising to a peak of $11 billion in 1981, the nuclear share of the total has decreased to roughly 30%, $4.4 billion, in 2011, driven by a shift away from nuclear fission in several European countries. A large share of public nuclear research resources is currently being spent on fusion development, much of it on the internationally-funded experimental ITER[4] reactor located in France. The shares of renewables, hydrogen and fuel cells, energy efficiency, cross-cutting research and basic science have increased sharply since the 2008 financial crisis, driven by stimulus packages in the US and increasing commercialisation and deployment of 'new' and renewable energy sources.

Figure 3: Investment in energy RD&D in IEA countries and average price of crude oil 1974-2011



Source: International Energy Agency (2013); BP (2014b)

[4] The acronym ITER once stood for International Thermonuclear Experimental Reactor

Table 2: Public sector RD&D spend in IEA countries 2011

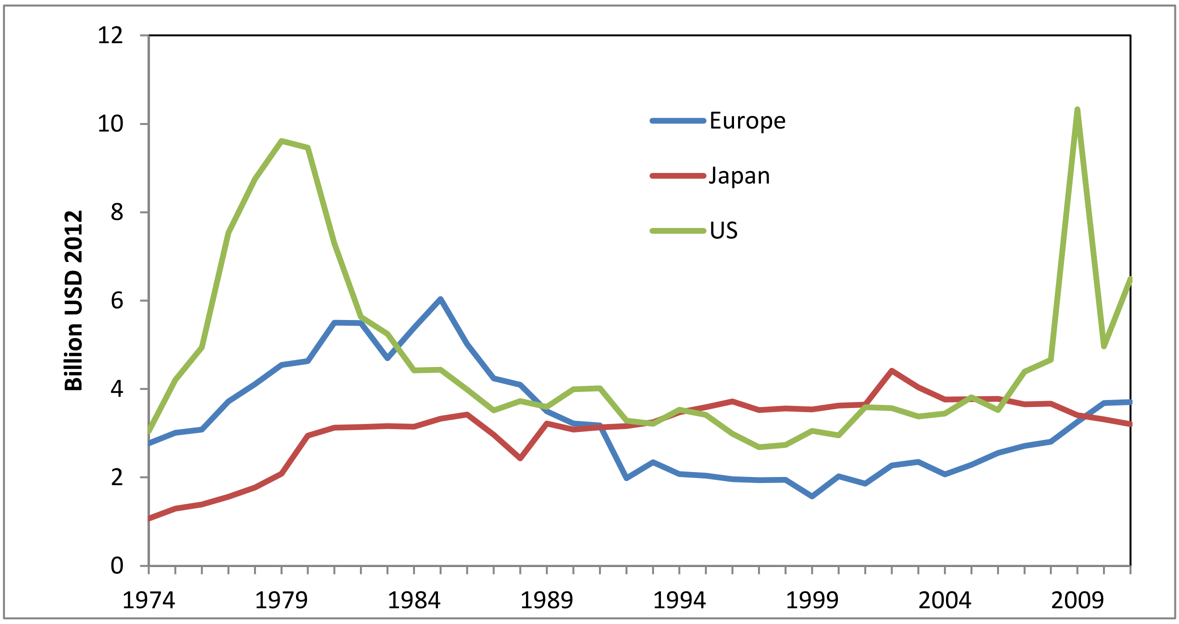
Area	Spend
Energy Efficiency	3.1
Fossil Fuels	1.8
Renewable Energy	3.7
Nuclear	4.4
Hydrogen and Fuel Cells	0.7
Power and Storage	0.9
Cross-cutting	2.6
TOTAL	**17.2**

Source: International Energy Agency (2013)

IEA member state expenditure on public energy RD&D has historically been concentrated in three geographical areas: the US, Europe and Japan.

Figure 4[5] compares expenditure between 1974-2011 in each area, complemented by individual figures (Figures 5, 6 and 7) for each of the three areas by IEA technology grouping. Much of the 'Other' spend seen in Figure 5 for the US can be accounted for by the large quantity of funding the US Department of Energy (DOE) commits to basic science and scientific facilities (International Energy Agency 2007).

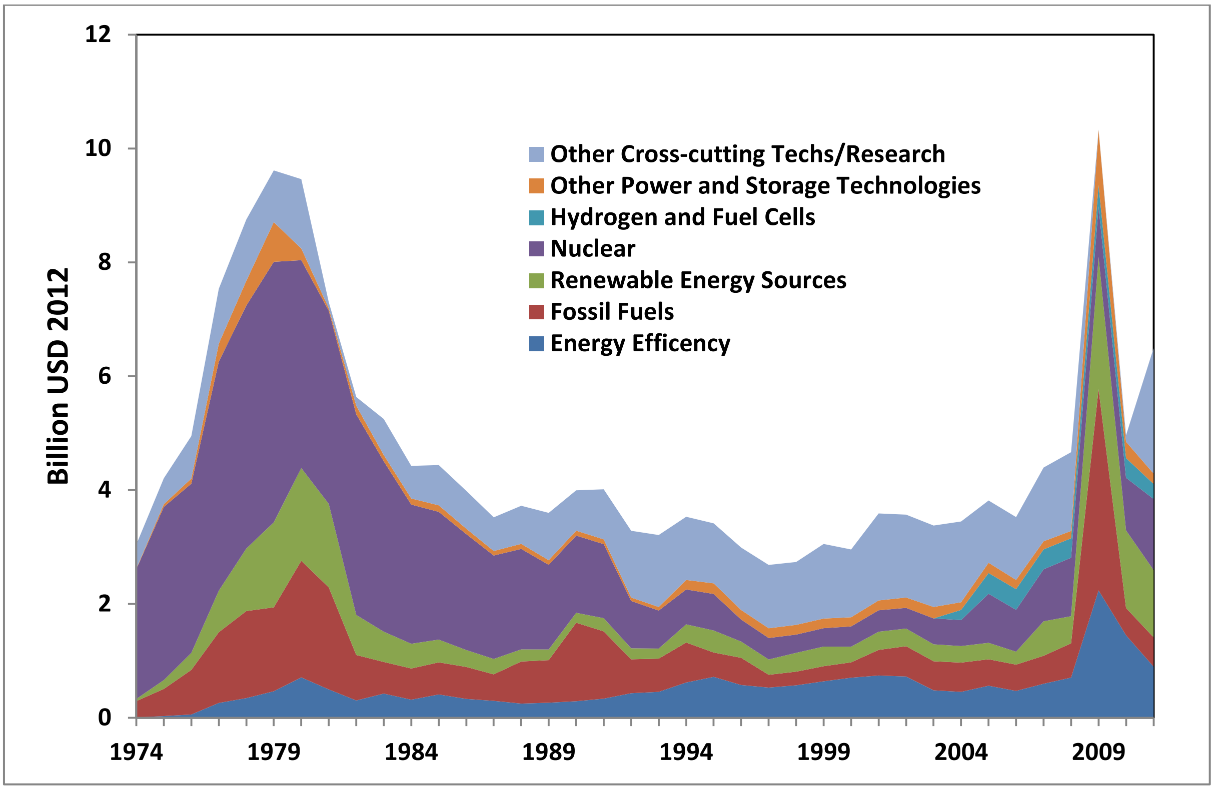
Figure 4: Historic Public Energy RD&D Spend in the US, Japan and major European economies 1974-2011.



[5] European data covers the six largest energy research funders: Germany, France, UK, Italy, Spain and the Netherlands. These were selected for the quality and continuity of their RD&D data. In 2011 these six countries covered 68% of EU/energy RD&D.

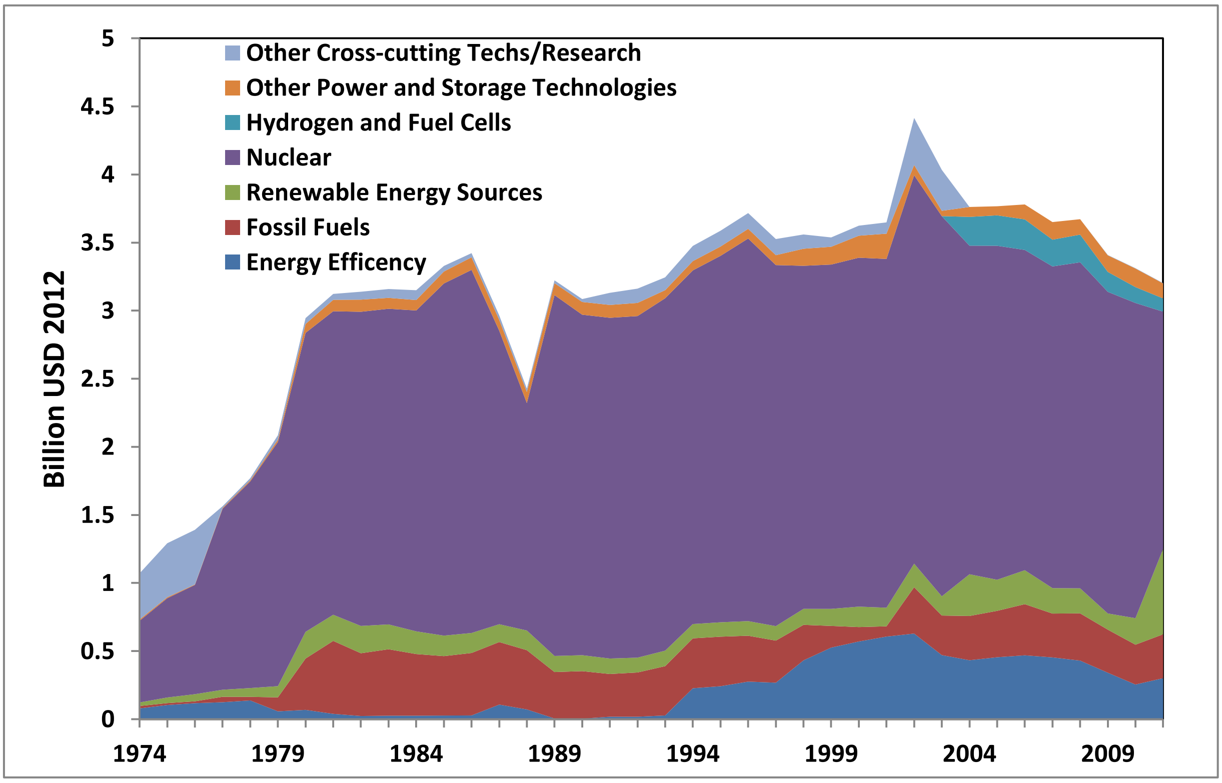
Source: International Energy Agency (2013)

Figure 5: Historic Public Energy Spend by Sector for the US 1974-2011



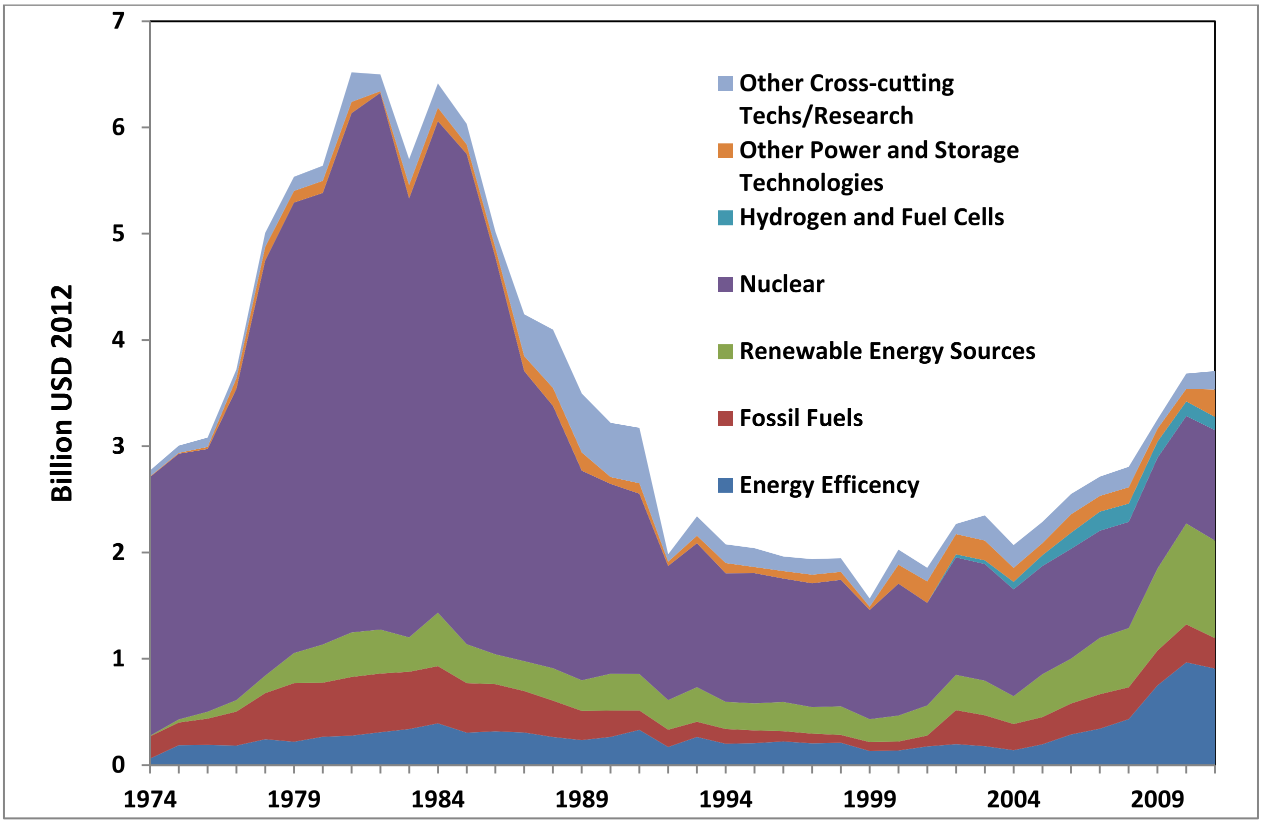
Source: International Energy Agency (2013)

Figure 6: Historic Public Energy Spend by Sector for Japan 1974-2011



Source: International Energy Agency (2013)

Figure 7: Historic Public Energy Spend by Sector for the major European economies 1974-2011



Source: International Energy Agency (2013)

We firstly compare the total energy spend in these three areas before comparing the make-up of their energy R&D portfolios.

Following high budgetary points in the late 1970s/early 1980s (for the US $9.6 billion in 1979, for Europe $6.5 billion in 1981) as a response to the 1970s energy crises, budgets for energy RD&D decreased rapidly and substantially over the 1980s in both the US and Europe. By 1992 budgets had decreased to $3.2 billion in the US and $2 billion in Europe. These reductions in public spending should be seen in the context of sustained low oil prices, as shown in Figure 3, as well as the related processes of privatisation and liberalisation in the energy sector. Japan's budget for energy RD&D, on the contrary, remained fairly constant throughout this period at an average of approximately $3.2 billion

Turning to the mix of energy R&D activities for each of the areas, the US's portfolio has remained relatively diverse in recent years despite a very sharp increase in spend in 2009 due to the post-financial crisis stimulus package. Japan's budget has remained similarly consistent over time but has been much less balanced, dominated historically by nuclear R&D. This is largely due to Japan's heavy reliance on nuclear power and its lack of indigenous fossil fuel resources. Japan funds an extensive programme of public spending on reactor design, maintenance and fuel reprocessing, as well as a substantial fusion programme. In contrast to the two countries, Europe's profile has changed quite dramatically over the years, being dominated by nuclear in the 1980s but becoming more balanced between renewables, efficiency and nuclear in the 2000s. If we narrow our focus to how budget allocations for different research areas have changed over the last decade (2000-2011) (Table 3), we observe considerable increases and changes in the composition of the three areas' public energy RD&D budgets. This growth coincided with a 'step change' in the policy measures deployed to mitigate climate change, as well as steep rises in the price of oil driven by tightening supplies and increasing demand from developed nations. Global trends show a considerable increase across the board for budgets for renewable energy sources, fossil fuels, including carbon capture and storage (CCS) technology, and the hydrogen and fuel cell sector. There are also some interesting regional trends.

Table 3: RD&D Budgets ($ million 2012) and percentage changes for research areas 2000-2011

Research area	US			Japan			Major European economies		
	2000	2011	% Change	2000	2011	% Change	2000	2011	% Change
1: Energy Efficiency	702	898	**128**	570	301	**-47**	137	908	**664**
2: Fossil Fuels	270	514	**190**	106	323	**304**	84	286	**339**
3: Renewable Energy Sources	275	1182	**430**	150	627	**418**	244	918	**376**
4: Nuclear	356	1248	**351**	2563	1742	**-32**	1242	1039	**-16**
5: Hydrogen and Fuel Cells	0	265	**-**	0	97	**-**	0	124	**-**
6: Other Power and Storage Technologies	161	182	**113**	162	110	**-32**	178	258	**145**
7: Other Cross-cutting research	1190	2200	**185**	74	2	**-97**	142	174	**123**
TOTAL	2955	6489	**220**	3624	3203	**-12**	2021	3708	**183**

Source: International Energy Agency (2013)

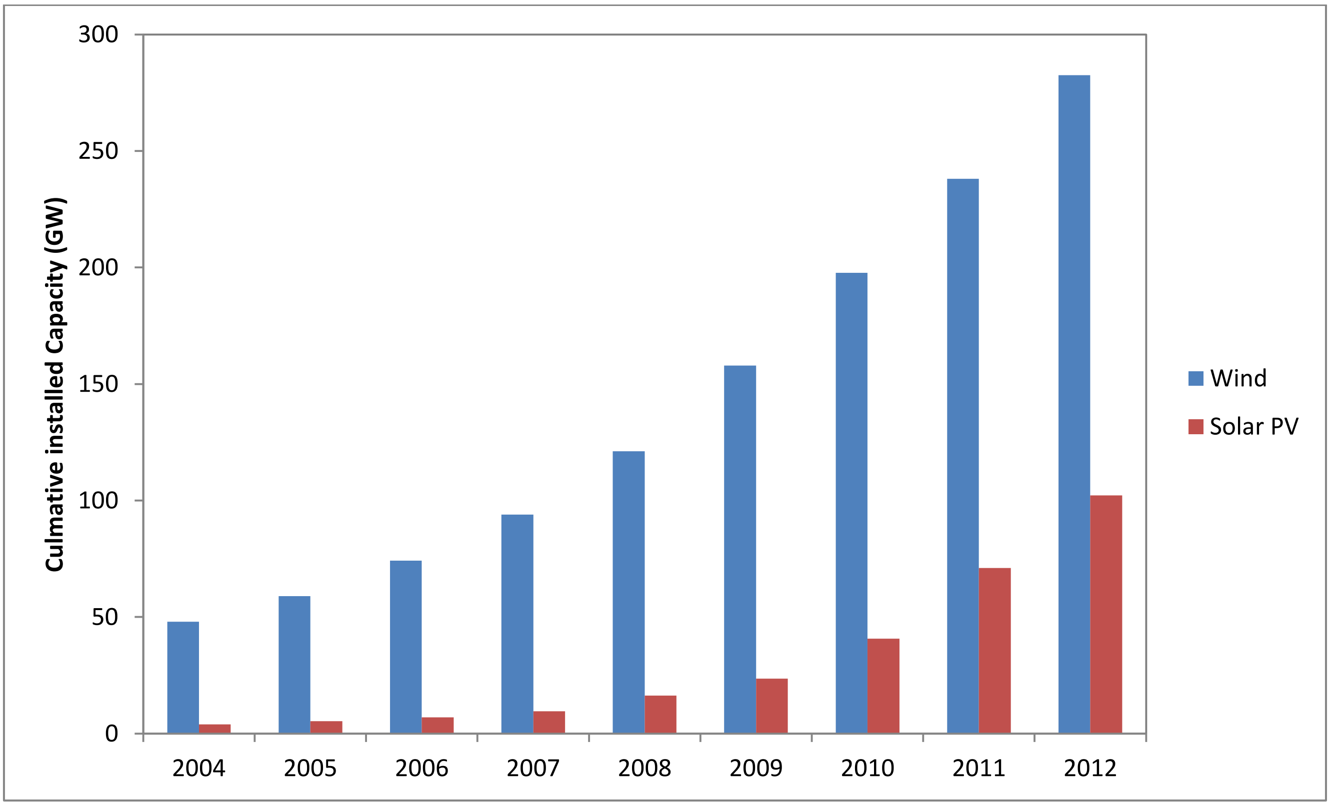
The US budget increased most during this period, with an increase of 220%. The figures for 2011 do not take into account the sharp temporary budgetary increase associated with the 2009 stimulus programme, during which the US energy RD&D budget totalled $10.3 billion. Japan witnessed a small decrease during this period of 12% in its total RD&D budget, whilst the total energy RD&D budgets for the major European economies rose from $2 billion to $3.7 billion

In all areas there was a significant increase in expenditure on renewable energy sources; RD&D in renewable energy during this period ranged between a 430% increase in the US and a 376% increase in Europe. Interestingly however, this trend was mirrored to a lesser extent by a major boost in fossil fuel RD&D, with the greatest increases seen in Europe (+339%) and Japan (+304%) and a more modest increase in the US (+190%). However, the total spend on renewable energy ($2.7 billion) in 2011 was almost three times as much as that on fossil fuels ($1.1 billion).

There were fewer consistent trends in other areas of energy RD&D. For example, whilst the US budget for nuclear energy RD&D increased by 351% between 2000 and 2011, Japan and Europe saw 32% and 16% decreases respectively. However, the nuclear sector still accounts for more than half of Japan's budget, with a total allocation of $1.7 billion in 2011. There was a similarly divergent trend in energy efficiency RD&D. Whilst there was a 664% increase in Europe from $137 million in 2000 to $907 million in 2011, there was a much more modest increase in the US (+128%) and a reduction of almost half in Japan (-47%). Finally, there is a similar divergence around spend in 'other power and storage technologies' and 'other cross-cutting research'. Whilst the US and Europe have more than doubled their spend on these RD&D activities, Japan has made drastic cuts, cutting 'other cross-cutting research' RD&D almost completely. Unfortunately, there is no data available for hydrogen and fuel cell spend in 2000, so we are unable to identify any meaningful trends. However, we do find that hydrogen and fuel cell research accounts for 3-4% of total energy RD&D in all three geographical areas.

These trends in RD&D spending, fuelled in part by policy responses to global climate goals, have been associated with an exponential growth in the deployment of renewable generation over the last decade, chiefly wind and solar PV. Between 2004 and 2012, global wind power capacity grew 660% from an installed capacity of 48GW in 2004 to 318GW in 2012. Solar PV grew more strongly from a lower base, increasing 2,600% from 3.9GW in 2004 to 102GW in 2012. Interestingly, capacity continued growing strongly throughout the financial crisis, as illustrated by Figure 8.

Figure 8: Global cumulative installed capacity of wind and solar PV generation 2004-2012



Source: Global Wind Energy Council (2014); EurObserv'er (2012)

Overall, the picture of global public RD&D budgets is one of substantial and transformative change. Significant increases in energy RD&D funding have been seen in all three geographical areas, with total public energy RD&D efforts having approximately doubled in the US and Europe, even during one of the most severe financial crises in living memory. Whilst there has undoubtedly been an increase in expenditure on fossil fuel RD&D, this is outweighed by the increase in spending on renewable generation technologies, energy efficiency and other alternative technologies like energy storage and fuel cells. These trends reflect a concerted public innovation effort, driven by a desire to shift the established paradigm of the energy system towards one epitomised by a diversified, low-carbon supply and high levels of efficiency.

3.2 Private sector energy R&D patterns

The availability of data on private sector energy R&D is less comprehensive than that for the public sector. One of the best R&D data resources is the EU Industrial R&D Scoreboard (EU IRI 2013), compiled from data in companies' annual reports and other corporate information accessible to the public. The Scoreboard examines annual energy R&D spend in 1,200 to 1,500 global companies, depending on the year. This section uses data from the Scoreboard to produce a snapshot of expenditure patterns in 2012 and to highlight some indicative trends for the period 2003-12. However, the dataset has its limitations:

a) The composition of the panel has evolved since it was first published in 2004, making it hard to infer trends in private sector R&D spending. Firstly, the number of companies covered rose from 1,000 in the 2003 survey published in 2004, to 2,000 in the 2009 survey published in 2010. Secondly, the scoreboard covered equal numbers of EU and non-EU companies until 2010. Since 2011, a single panel covering both EU and non-EU companies has been used. To account for this change we use a slightly smaller, but consistent, panel derived by including only companies spending more than $76m (2012 $) on R&D annually in both the EU and non-EU panels (Figures 9 and 10). While this neglects the possibility that the balance of R&D effort between larger and smaller companies may have been shifting, it does provide a broad indicator of trends.
b) It is difficult to ascertain exactly what proportion of relevant R&D activity relates specifically to energy, mainly due to the way in which energy-related R&D expenditure is categorised. The following energy-specific categories are used: oil and gas producers; oil equipment, services and distribution; electricity; gas, water and multi-utilities; and alternative energy. However, these categories do not capture energy-related R&D that takes place in other sectors. Most notable examples on the supply side are the electronic and electrical equipment sector and general industrials (e.g. Siemens, General Electric). On the demand side, R&D in the transport and construction industries is clearly relevant to energy but also reflects other priorities. Not including these types of companies in our analysis of private energy R&D will naturally skew the overall picture of innovation efforts. For example, Toyota is the world's largest investor in R&D at over $10bn in 2011, engaging in a mix of energy (e.g. alternative fuel vehicles) and non-energy explicit R&D (e.g. self-driving vehicles). Furthermore, manufacturers of appliances and electronic equipment are very R&D intensive (spending over 5% of revenue) and the total R&D expenditure of $50bn vastly exceeds the $3bn spent on energy efficiency RD&D by the public sector in IEA countries. These contributions are not included in this analysis because we do not know what proportion of the expenditure explicitly relates to energy.
c) Unlike the public sector data for countries' R&D budgets, the private sector R&D scoreboard data does not include demonstration activities. We therefore refer to R&D rather than RD&D in this section.

Despite these limitations, the data highlights some striking differences between patterns of research activity support in the public and private sectors. Table 4 provides a snapshot of private sector energy R&D spend among the 2000 top R&D companies for 2012, categorising this spend by the identifiable energy R&D categories.

Table 4: Industry Energy R&D Spend among the 2000 Top R&D Companies 2012 ($bn)

Sector	OECD	Non-OECD	TOTAL
Oil & gas producers	6.4	6.1	12.5
Oil equipment, services & distribution	2.6	0.3	2.9
Electricity	2.9	0.6	3.5
Gas, water & multi-utilities	1.4	0.1	1.5
Alternative energy	0.8	0.0	0.8

Source: EU IRI (2013)

One high level observation is that spend is concentrated in OECD countries, with $14.1bn of the total $21.6bn spend attributable to these. Turning to the balance of spend across the different sub-sectors of the energy industry, there is a sharp contrast with the public sector. Firstly there is a much greater emphasis on oil and gas R&D, with $15.8bn of private sector spend in 2012 committed to these activities. This support accounts for 0.3% of the companies' sales revenue and is a factor of five higher than all RD&D on fossil fuels in the public sector. $6.4bn of this spend is associated with OECD-based producers with $3.6bn of that associated with just four companies (BP, Chevron, ExxonMobil and Shell) based in the US or the UK. This OECD spend is matched by a group of oil and gas companies based in non-OECD economies, notably PetroChina, Brasiliero and Gazprom.

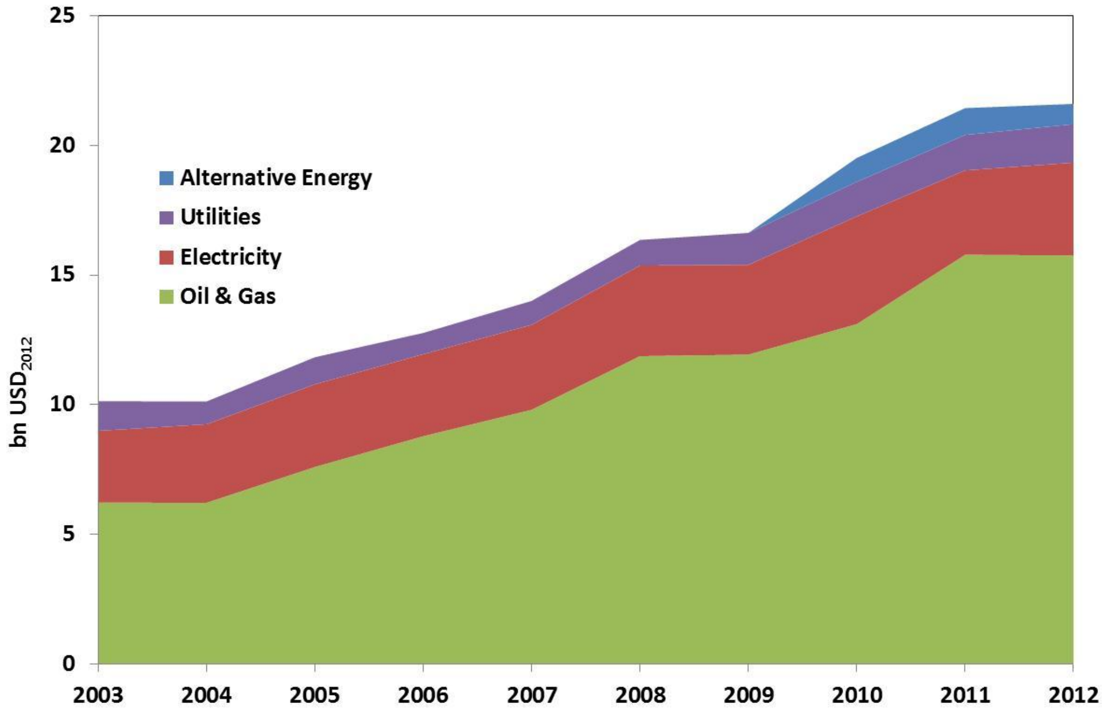
In the electricity sector, much of the $3.5bn spend is concentrated in a handful of companies, with EDF and AREVA (both French companies), plus Korea Electric Power, accounting for just under half the spend. It can be inferred that much of that was devoted to nuclear R&D, accounting for a similar spend on nuclear to the public sector. Electricity companies spend approximately 0.5% of their revenue on R&D.

'Alternative energy' R&D aligns fairly well with public RD&D on 'renewable energy' and 'hydrogen and fuel cells. Private sector R&D spend on alternative energy was $0.8bn in 2012, the majority of which came from specialised companies (e.g. Vestas) and diversified engineering companies rather than traditional energy companies. This is largely because many of these technologies are less mature and are not yet in a position to compete economically with traditional forms of energy on the open market. However, some alternative technologies (e.g. wind and PV) are more mature than others and have already achieved widespread deployment. They represent less of a risk to investors and have attracted greater support from business than other alternative energy technologies. However, their development was in large part driven by initial public sector support.

In the past, private sector energy R&D support has been, as it is today, closely associated with the role of oil within energy markets. However, during the 1970s, there was a strong drive to substitute oil with alternative fuels where this was technically and economically feasible due to a mixture of higher prices, market pressures and wider policy drivers to reduce import dependence. Consequently, nuclear and coal (and later natural gas) replaced oil in electricity generation while coal and gas substituted for oil in industry. Oil still dominates the transport sector due to its high energy density and ease of storage. In 2011, 77% of oil used for energy purposes in IEA countries went to transport compared to 45% in 1974.

Like the public sector, private sector energy R&D spending profile has not remained static over the past decade. This trend is presented in Figure 9 which breaks down spend over the 2003-2012 period by sector. Energy R&D spend almost doubled from $10.1bn in 2003 to $21.6bn in 2012 (Figure 9). Spend was static in the electricity and other utility sectors, whilst there was a very large increase in oil and gas R&D spend, rising from $6.2 billion in 2003 to $15.8 billion in 2012, an increase of 255%.

Figure 9: Industry energy R&D spend over the period 2003-2012, by sector

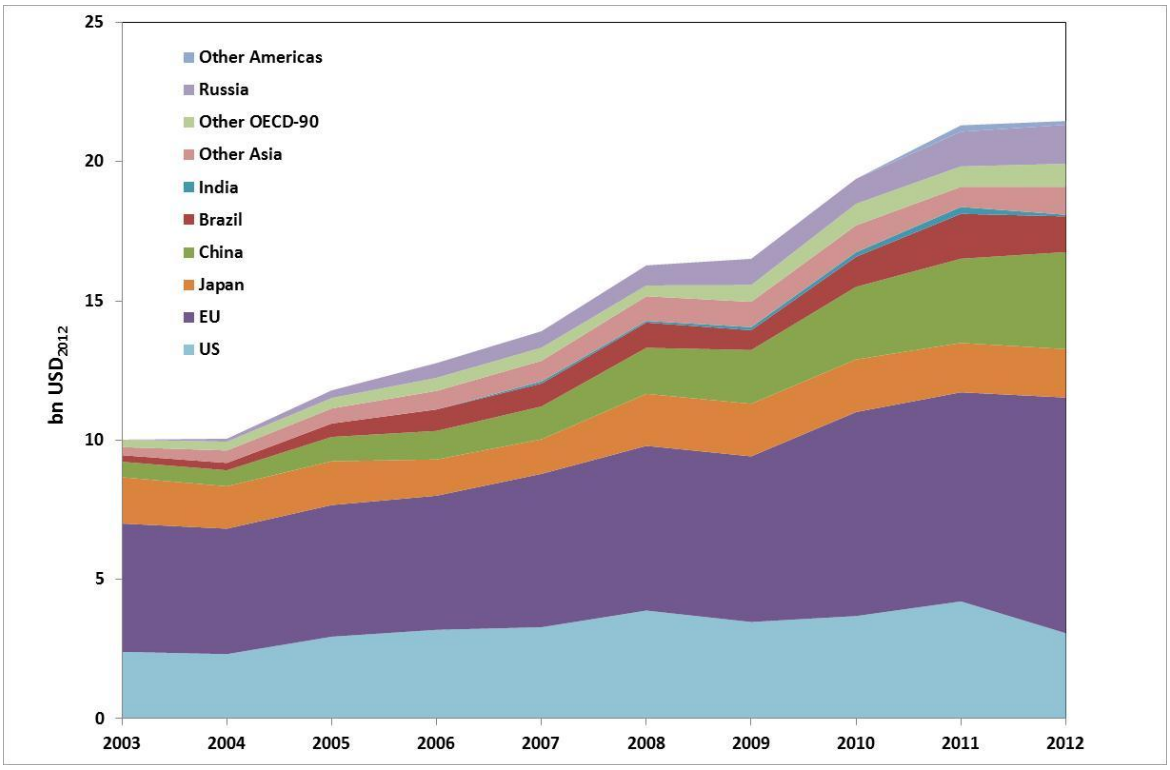


Note: includes only companies spending more than $76m_{2012}$ annually on R&D

Source: EU IRI (2013)

The spending profile of companies in different countries has also changed during this period (Figure 10). Private sector spend has been static in Japan but has grown in the other two areas. For example, the US spend grew from $2.4 billion in 2003 to $4.2 billion in 2011, constituting a 75% increase, before declining by more than a quarter in 2012 to approximately $3 billion. Spend in the EU grew from $4.6 billion in 2003 to $8.5 billion in 2012, an increase of 84%. However, the greatest increase by far was in China, which recorded a 527% increase from $0.6 billion in 2003 to $3.5 billion in 2012. On aggregate the 2008 financial crisis arrested growth in R&D expenditure in 2009, although spending profiles recovered in 2010 and 2011, before stabilising in 2012. During this period, reductions in the spend from some countries, like the US and Brazil, were compensated for increases in other countries, such as the EU and China.

Figure 10: Private sector energy R&D spend over the period 2003-2012, by country/region



Note: includes only companies spending more than $76m_{2012}$ annually on R&D

Source: EU IRI (2013)

The analysis of both patterns of public and private R&D spend provide a strong indication that the private sector focus is on extending the resource base and reinforcing the current energy paradigm, while the public sector focus is on technologies that will break the existing paradigm in response to wider policy drivers.

4 Conclusions and further work

Policymakers are seeking a major transformation of the energy system driven by mounting concerns about the effects of climate change and a growing desire to mitigate these. A critical part of the strategy to address these concerns is to promote the development and deployment of new energy technologies capable of reducing the CO_2 emissions associated with satisfying our energy needs. This move is reflected in a resurgence of energy innovation, unfolding at a pace last seen during the late 1970s. However, the directions in which public and private sector organisations are taking innovation are shaped by how they anticipate that global energy markets will develop and the degree to which policies and markets will respond to the challenges of climate change and other key drivers. The review of global energy scenarios reveals fundamental divergences between public and private organisations in their views of the future development of the global energy system. There are substantive differences in both anticipated levels of energy demand and GHG emissions, and the anticipated mix of primary energy sources. The contrast is largest between normative scenarios, such as IEA 2DS, which aim to meet the objective of keeping global temperature rises below 2^{o}C, and the energy company outlooks that broadly extrapolate current social and economic trends.

This tension regarding energy futures is reflected in patterns of public and private sector RD&D spend, in terms of dramatically different technological priorities and levels of resource spend. These patterns suggest that public policy concerns on energy security and climate change can be interpreted as driving investment into transformative low-carbon technologies, whereas private sector energy actors broadly conduct R&D that reinforces the existing energy paradigm by exploiting new and unconventional fossil fuel resources and reducing the costs of utilising existing sources. When a traditional technological regime is threatened by transformative innovations, actors invested in the original regime can respond by driving innovation efforts that improve and strengthen the existing paradigm (Geels 2005). For instance, sailing ship technology improved in response to the rise of steam-powered ships in the 19th century (Geels 2005). On balance it therefore appears that global energy innovation efforts are both enabling and frustrating ambitious climate change goals, depending on which sector is supporting these activities.

There is disagreement in the academic literature as how to develop the most optimal strategy for innovation in the energy sector. One view is that, due to the long lead times from basic research to deployment, high capital costs and long payback periods for investors of many new energy technologies, there is a significant ‘valley of death’ in the development of new energy technologies in which sufficient private finance to continue commercialisation is difficult to obtain, stifling innovation. Addressing this challenge would entail targeted support from the public sector to sustain the development of promising new technologies through this gap, allowing experience to be built up from ‘learning-by-doing’, and allowing economies of scale for new technologies to be more easily achieved (Gross 2012). The view that the public sector plays an essential role in providing long-term funding for new technologies, assuming much of the risk of developing new sectors, is gaining ground outside the energy innovation debate (Mazzucato 2013). The alternative view is that the public sector should not try to ‘pick winners’, and should therefore put in place policies designed to achieve government aims and targets in a technology-neutral way. A tax on carbon emissions is an example of a technology-neutral policy. Under this view, governments should provide greater funding for general early-stage R&D, with the private sector better placed to identify promising technologies and develop these further (Helm 2012).

The current state of the energy sector, with the tension between two diverging viewpoints of a public policy-led transformative effort and reinforcing efforts led by the private sector, presents a space for further research into how urgent public policy concerns can affect the development and commercialisation of new technological solutions. Within an overarching narrative about system transformation and reinforcement of the existing paradigm, there is scope to study, *inter alia*: innovation systems for different types of technology in terms of radical/incremental innovation; the engineering scale of technologies (from complex systems to commodity products); systemic technologies (e.g. smart grids); organisation and priority-setting processes for public sector innovation in different countries and jurisdictions; and the structure of transnational innovation systems characterised by the operations of global companies and the mobility of human capital. Further work could include the analysis of returns on investment in R&D in the private sector, both in a commercial sense and by utilising other metrics such as market penetration or energy efficiency improvements. This could provide indications as to whether these returns are increasing or decreasing with time. Data to answer this question would be very difficult to obtain but, if possible, it would be a rewarding avenue of study.

This paper has not discussed the role of the public sector in emerging economies such as China, India and Brazil, primarily due to the absence of relevant data. However, this is an important part of the debate given the large and increasing role these countries are playing in the global energy system. Further work in this area to assess the extent of the role these emerging economies are playing in the innovation process would be of considerable interest.

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References

BP, 2014a. *BP Energy Outlook 2035*, Available at: www.bp.com.

BP, 2014b. *BP Statistical Review of World Energy*, Available at: http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf.

EU IRI, 2013. *EU Industrial R&D Investment Scoreboard 2013*, Available at: http://iri.jrc.ec.europa.eu/scoreboard13.html.

EurObserv'er, 2012. *PV Barometer 2012*,

ExxonMobil, 2014. *The Outlook for Energy: A View to 2040*, Available at: www.exxonmobil.com.

Geels, F.W., 2005. *Technological Transitions and System Innovations*, Edward Elgar Publishing.

Global Wind Energy Council, 2014. *Global Wind Statistics 2013*,

Gross, R., 2012. *On picking winners: The need for targeted support for renewable energy*, Available at: http://assets.wwf.org.uk/downloads/on_picking_winners_oct_2012.pdf.

Helm, D., 2012. *The Carbon Crunch: How We're Getting Climate Change Wrong - and How to Fix it*, Yale University Press, New Haven.

Intergovernmental Panel on Climate Change, 2014. *Climate Change 2014: Mitigation of Climate Change - Summary for Policymakers*, Geneva.

Intergovernmental Panel on Climate Change, 2013. Summary for Policymakers. In T. F. Stocker et al., eds. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

International Energy Agency, 2008. *Energy Technology Perspectives 2008*, Available at: http://www.iea.org/techno/etp/index.asp.

International Energy Agency, 2012. *Energy Technology Perspectives 2012 Pathways to a Clean Energy System*,

International Energy Agency, 2013. *Energy Technology Research and Development Database 2013*, Available at: http://www.oecd-ilibrary.org/energy/data/iea-energy-technology-r-d-statistics_enetech-data-en.

International Energy Agency, 2007. *Reviewing R&D Policies*, Available at: http://www.oecd-ilibrary.org/energy/data/iea-energy-technology-r-d-statistics_enetech-data-en.

Mazzucato, M., 2013. *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*, Anthem Press.

Organisation of the Petroleum Exporting Countries (OPEC), 2013. *World Oil Outlook 2013*, Available at: www.opec.org.

Shell Scenarios Team, 2013. *Shell New Lens Scenarios*, Available at: www.shell.com.

U.S. Energy Information Administration, 2014. *Annual Energy Outlook 2014*, Available at: www.eia.gov.