

State and Trends of Public Energy and Electricity R&D

A Transatlantic Perspective

Jan Martin Witte



global public policy institute

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Executive Summary

It is now widely accepted that carbon markets alone will not be sufficient to initiate large-scale greenhouse gas mitigation efforts that are needed in the short- and medium term to avoid catastrophic climate change. In response, policymakers have started to broaden their climate policy strategies. One of the policy tools that has received renewed attention in this context is public energy R&D.

Both researchers and policymakers are calling for significant increases in public energy R&D commitments to foster the development of low-carbon technologies in the power sector. Economic analysis indeed suggests that public funding has a crucial role to play in correcting market failures that are endemic to the market for innovation in general, and innovation in the power sector in particular. In that view, public support for basic research but also feasibility testing and in some cases also small-scale commercial testing is essential in order to move innovations along the technology development path. While policy instruments designed to foster broader market uptake of renewable energy technologies (such as measures for guaranteed market access, legislated rate increases, etc.) have found wide application on both sides of the Atlantic in recent years, a review of energy R&D funding trends shows that public spending for basic research, feasibility testing and early commercial viability exploration has dropped dramatically in the entire OECD world since the early 1980s.

More recent budget increases in both the US and also the European Union (EU) indicate a reversal of that situation. However, it is too early to tell whether these funding increases are likely to be sustained, and whether they will eventually result in budget levels for energy R&D that many climate change experts are calling for. In the past, public commitment to energy R&D – and notably R&D spending on electricity research – has vacillated significantly, influenced by shifting variables such as the price for oil. It also remains to be seen what impact the global economic crisis (and thus strained government coffers) may have on medium-term spending levels on energy R&D.

Yet, even if sustained spending increases can be realized, policymakers would do well to recognize the limits and pitfalls of publicly funded innovation programs. Experience with public energy R&D support suggests that spending programs need to be carefully designed to avoid investments into pie-in-the-sky programs and to reduce wasteful rent-seeking.

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1. Introduction

Climate change is commonly regarded as one of the most pressing challenges of our time. Almost four decades after scientific debates about global warming have started there is now almost universal agreement that the anthropogenic sources of the climate change phenomenon are significant, and demand urgent action. The last Assessment Report of the International Panel on Climate Change (IPCC) has laid out, in stark terms, the likely consequences of a “business as usual” approach to the climate change challenge and recommended rapid action on adaptation (i.e. measures to prepare societies to adapt to unavoidable climate change and its consequences) as well as mitigation (i.e. actions to reduce emissions of harmful greenhouse gases).¹

With regard to mitigation, the challenge is clear. In order for greenhouse gas emissions (GHG) to be reduced significantly enough to avoid catastrophic climate change, a fundamental re-engineering of the world’s energy system is in order. Most importantly, that requires a comprehensive shift from fossil fuel-based energy sources to renewable sources of energy (or the introduction of technologies that make the continued use of fossil fuels environmentally sustainable). To be sure: Work on the supply side of the energy equation may not be sufficient to achieve the necessary emissions reduction targets. However, it certainly is a necessary precondition.

During the past decade, emissions trading systems (also called cap-and-trade systems) have emerged as one of the preferred policy tools to make that mitigation happen. In addition to the European Union (EU), many other key OECD economies – notably the US – have taken decisive steps to introduce carbon markets in their countries. The importance that experts and policymakers assign to carbon pricing is mirrored in the IPCC Fourth Assessment Report of 2007. Based on available modeling, the IPCC estimates that “[...] carbon prices in the range 20–50 US\$/tCO₂ (US\$ 75–185/tC), reached globally by 2020–2030 and sustained or increased thereafter, would deliver deep emission reductions by mid-century consistent with stabilization at around 550ppm CO₂-eq [...] if implemented in a stable and predictable fashion.”²

But there are good reasons to be skeptical with regard to how much emission trading systems are likely to achieve in the short- and medium-term in terms of setting pricing signals for private investments into the development of new clean technologies. Thus far, progress with the

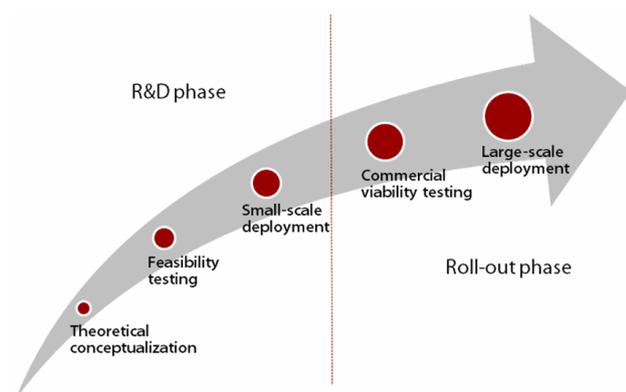
implementation of emissions trading systems has only been gradual, geographically limited and depends on significant long-term commitments to set aggressive caps by governments that, at least at this point, cannot be taken for granted.³ Indeed, the emergence of a carbon market with global coverage and an ambitious cap is a distant if not entirely unrealistic scenario.⁴ In addition, there are market failures endemic to the market for innovation in general, and the power market in particular, which imply that private spending on R&D will probably remain at socially sub-optimal levels. As the Stern Review of the Economics of Climate Change argues: “Carbon pricing alone will not be sufficient to reduce emissions on the scale and pace required [...] primarily because of lack of sufficient credibility of international decision-making on caps; the risks that are associated with new technologies; as well as the positive externalities associated with technology development that makes financing through capital markets difficult.”⁵

That assessment raises awkward issues. In its most recent World Energy Outlook, the International Energy Agency (IEA) estimates that between 2007 and 2030, roughly US\$ 26 trillion (in 2007 dollars) in investments in energy infrastructure will have to be generated in order to meet rising global demand. Investment in the power sector alone will have to amount to roughly US\$ 13.6 trillion. Indeed, much of that investment will have to go towards maintaining current supply levels.⁶ Consequently, that means that in case investments into the development of new low-carbon energy technologies are not made quickly, the future world energy supply will be based on established, fossil fuel-intensive technologies. Investments in the power sector are large and long-term, usually spanning at least a 30 to 50-year period. Many of the technologies that would be necessary to avoid such a lock-in either do not yet exist, have not been tested on a large scale, or their commercial viability has yet to be proven. One of the most significant examples for this is Carbon Capture & Storage (CCS, see box further below), a technology that plays a major role in almost all mitigation scenarios⁷ but that has yet to prove its large-scale technical feasibility and commercial feasibility.

What that means is that carbon pricing cannot and should not remain the only game in town when it comes to mobilizing the necessary funding for the transition to a low-carbon world.⁸ One area that has received renewed political attention in recent years

is the role of public research & development (R&D) support in the development and early commercialization of low-carbon technologies.

Figure 1a. Technology development path



Source: GPPI

In a simplified technology development path (depicted in Figure 1a above), two basic phases can be distinguished: The “R&D phase” and the “Roll-out phase”. The R&D phase can be subdivided into three stages: theoretical conceptualization, feasibility testing, and small-scale deployment. The “Roll-out phase” can be broken down into at least two stages: commercial viability testing and large-scale deployment. In practice, of course, the border between the two phases may be difficult to establish. The analysis in this paper focuses primarily on the “R&D phase”. This is not to suggest that public policies designed to foster technology deployment and large-scale roll out – such as guaranteed market access, legislated rate increases, and so forth – are not important. However, they are focused on a different phase in the technology development path and thus beyond the scope of this analysis.

Historically, public R&D has been credited in laying the groundwork for major technological breakthroughs. Most notably, public investments into R&D have been credited with the development of nuclear technology (the Manhattan Project, an investment of US\$20 billion in 2008 dollars) and Man’s exploration of the moon (the Apollo Project, an investment of roughly US\$100 billion, in 2008 dollars). Given the scale of the climate change challenge, some have recently suggested the need for a “Manhattan Project” or a “Marshall Plan” for energy, thus calling for a commitment of public funds into R&D to spur energy efficiency and renewable energy sources.⁹ During the Presidential Campaign, then-Senator Barack Obama stated: “There’s a reason that some have compared the quest for energy independence to the Manhattan Project or the Apollo moon landing. Like those historic efforts, moving away from an oil economy is a major

challenge that will require a sustained national commitment [...] Washington needs to get serious about working together to find a real solution to our energy crisis.¹⁰ The Brookings Institution recently called for the establishment of a network of “energy discovery-innovation institutes” to implement that agenda.¹¹

This sentiment is also reflected on the European continent. Announcing the launch of the European Commission’s Strategic Technology Plan that is supposed to commit more funding to energy R&D, European Commissioner for Energy Andris Piebalgs stated: “The Energy Policy for Europe calls for a new industrial revolution. Like all industrial revolutions, this one is going to be technology driven and it is high time to transform our political vision into concrete actions. [...] If we fall behind in the intensifying global race to win low carbon technology markets, we risk meeting our targets with imported technologies.”¹²

The call for more public energy R&D commitment has also been supported by the Stern Review on the Economics of Climate Change. The Stern Review argues that a doubling of public commitments to energy R&D to US\$ 20 billion a year may be necessary to facilitate the development of necessary technologies.¹³ Other studies call for similar increases.¹⁴

This paper provides some context for this evolving discussion on the role of public energy R&D, with a specific focus on the power sector.¹⁵ Starting from a brief review of the general case for public R&D support, and technology support measures in the climate change context in particular, the paper zooms in on three questions: First, what do the numbers tell us with regard to the development of public energy R&D commitments during the past two decades? More specifically, what explains the widespread stagnation, if not decline, of public energy R&D funds since the early 1980s? Second, to what extent are the recent calls for more funding for energy R&D heeded by deeds, and how likely is it that the funding upgrades called for by studies such as the Stern Review will be realized? Third, and finally, considering increasing public and political support for greater investments in energy R&D, what mechanisms should policymakers employ to minimize rent-seeking and investments in “pie-in-the-sky” energy proposals?

2. The case for public energy R&D support

2.1 The market for innovation and the case for public energy R&D support

The basic rationale for public spending on R&D is well-established.¹⁶ Based on the path-breaking work of Kenneth Arrow, generations of economists have pointed out that there are market failures with regard to the production of scientific knowledge.¹⁷ That market failure is a consequence of the “incomplete private appropriability” (also called “spillover effects” or “positive externalities”) in particular of basic research. As a result of that “incomplete private appropriability”, socially optimal levels of investment by private actors into R&D – in energy and other areas – will not be achieved. Because of “spillover effects”, private businesses do not have sufficient incentives to invest in basic research.

Figure 2.1a. The case for public energy R&D support



Source: GPPI

The Stern Review highlights additional market failures with regard to innovation that are peculiar to the energy sector and result in a disproportionately low private R&D intensity – and thus may make additional public outlays necessary.¹⁸ Those include:

- The nature of the learning process. It takes very long for new energy technologies to come online and become profitable, usually several decades. Also, there are no niche markets for “early adopters” in energy, so power companies are stuck with “learning costs.” In addition, the power sector operates in a tightly regulated context and is thus quite risk averse. “Together, these factors mean that energy generation technologies can fall into a “valley of death”, where despite a concept being shown to work and have a long-term profit potential they fail to find a market.”¹⁹
- The nature of prevailing infrastructure. Electricity grids have been developed for the

operation of large-scale centralized power plants. Distributed generation (i.e. the provision of power from many small sources) is not feasible with installed transmission networks. This requires network upgrading before market participants will invest in distributed generation capacity.

- Major market distortions. Market prices do not reflect the true cost of fossil fuels (i.e. their negative externalities, e.g. CO₂ emissions). In addition, many countries (e.g. India) still maintain massive fossil fuel subsidy schemes. As a result, there are reduced incentives for market participants to invest in the development of new low-carbon technologies.
- Market structure. In most countries, power markets are characterized by oligopolistic (sometimes monopolistic) market structures that undermine innovation.

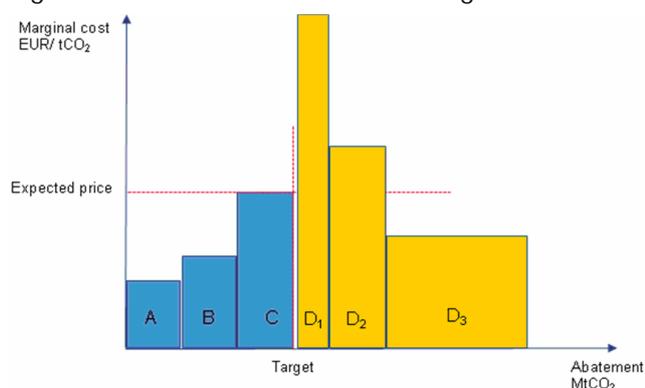
Those market failures extend to all forms of energy (fossil fuels and otherwise) and, taken together, seem to indicate that there is a strong case for public support for energy R&D, including for example the provision of direct funding to private research endeavors, the development of public research capacity (through governmental research labs, public universities, etc.), or the provision of other types of incentives to market participants to foster their engagement in scientific research.²⁰ The Stern Review calls for a set of public policies in this context with the ultimate objective to push a portfolio of low-carbon emission technologies towards commercial viability. To achieve this objective, the Review calls for increasing, predictable and stable public R&D support (broadly based and not focused on single technologies) and, for some technologies, also early stage deployment support. This public R&D support should leverage private R&D and thus encourage commercialization.

Also, focusing on the role of learning in technology development, Will Blyth has recently developed an intuitive model for understanding why public technology support through R&D expenditures plays a crucial complementary role to emissions trading regimes. By adding a dynamic technology learning dimension to the standard marginal abatement curves used in the analysis of how carbon markets impact energy sector investment, Blyth shows that the market mechanism implicit in carbon trading regimes may result in sub-optimal economic outcomes.

Figure 2.1b below summarizes the argument. In this

figure, technologies are still ordered according to cost, as in standard representations of marginal abatement curves. These models are based on the assumption that the market will move from the cheapest to the more expensive technology solutions, thus producing the most cost-efficient solution to carbon mitigation. However, this adapted version of the curve includes a technology – here represented by bar D3 – that only emerges after it has gone through earlier, higher cost development stages. In other words, in order to get to technology D3, it will have to move through stages D1 and D2, both of which require a higher carbon price to emerge. In fact, under this scenario, an economy may get stuck with technology C until a much higher carbon price is achieved that would incentivize market players to invest in D1. That would be an economically sub-optimal outcome. Thus, the solution would be to move technologies D1 and D2 forward in order for D3 to take its “natural place in the ranking.” That does not automatically call for more public investment through R&D expenditures. That again depends on the potential market failures associated with the development of technologies D1 and D2, i.e. the question whether the market provides business with sufficient incentives to invest in R&D or not.

Figure 2.1b. Combined cost and learning curve



Source: Will Blyth (2008), Linking carbon markets and technology support mechanisms: Making sense of the EU Climate Change Package. Chatham House EEDP Program Paper 08/01, p.4.

2.2 Shortcomings of the market failure perspective

In practice, however, the question whether or not “market failure” exists is not always as clear-cut as it may seem in theory. That requires a comprehensive understanding of market dynamics and incentive structures which are not always easy to dissect.²¹

More fundamentally speaking, the fact that a market failure may indeed exist does not automatically justify government intervention. Ideally, the costs of “market failure” would have to be compared to the costs of government intervention before making such a choice. This cost/benefit calculation is often difficult, if not impossible

to make, and applies in particular to high-stakes situations such as the fight against climate change where the search for potential technological “breakthrough solutions” is a matter of major political, economic and social significance. Investing in new technologies under these conditions may thus be the equivalent to taking (more or less calculated) bets, in particular in the absence of any good alternative policy options

Finally, even if government intervention in terms of public R&D support appears cost-effective, it does not say much about the precise structure such programs would have to take to be successful. Thus, the point here is not to argue that “government failure” must necessarily be more egregious than “market failure” (or the other way around). Instead, the key issue is that the design of public R&D programs must not end with the identification of a “market failure”, but instead must build on a careful analysis of the various underlying drivers and levers that influence private business behavior in energy markets, and how those can best be impacted in order to generate socially desirable results.

Various characteristics of “non-market” (i.e. government) outputs have been characterized that shed a useful light on the political-economic dynamics of government R&D support.²²

- Defining and measuring output. It is very hard, and in some cases literally impossible to define the outputs that are generated by R&D, or to quantify them. As a result, the value of public energy R&D is usually equated with the cost of inputs (i.e. budgets assigned to R&D activities). That, however, is a less than perfect approximation of its real value and contribution.
- Assessing quality. It is difficult to independently establish the quality of public energy R&D, primarily because one of the strongest mechanisms available in the marketplace – consumer signals – is unavailable. To assess the quality of outputs requires “precise, representative, and regularized feedback”²³ which is difficult to organize in a non-market context.
- Lack of competition and rent-seeking. Public energy R&D also will be impacted by a lack of competition, in particular in those cases in which implementation rests entirely with governmental research facilities. That lack of competition further impacts the quality of outputs. In case public funds are used to support or incentivize private market participants to get the job done, rent-seeking will likely become a significant problem. The establishment of funds or tax credits will

trigger competition for access to public resources that, if not properly managed, simply crowds out private R&D investment and, in a worst case scenario, does not result in the production of good science. Evidence from the US suggests that rent-seeking can be a phenomenon with considerable negative consequences.²⁴

- Lack of market test. Finally, public energy R&D is not exposed to a “bottom-line”, or market test. As with any other public program, the decision of whether or not to terminate or continue them is political. The fact that true demand and quality for public energy R&D are hard to assess (as discussed above) further undermine evidence-based decision-making.

There are also factors on the demand side for public energy R&D that need to be taken into consideration. Given that public energy R&D is subject to political decision-making, for example, public pressure plays a significant role in determining the distribution and size of budgets. Both in Europe and the US, governmental appropriations for R&D are subject to intense lobbying, and in a few cases, quite rancorous public debate. Also, it needs to be recognized that “[...] there is often an appreciable disjuncture between the time horizons of political actors and the time required to analyze, experiment, and understand a particular problem (namely, a market inadequacy) in order to see whether a practical remedy exists at all.”²⁵

All these issues, combined with a number of well-publicized failures of publicly championed R&D efforts²⁶, have triggered a significant debate during the past decades regarding the effectiveness and efficiency of public R&D programs, focusing primarily on its effectiveness (i.e. what are the social returns on public R&D support?) and additionality (i.e. whether and to what extent does public R&D support crowd in or crowd out private R&D?).

The assessment of returns on R&D generally is a difficult task because of many measurement complications.²⁷ However, existing studies indicate that the private returns to R&D investments by companies are generally thought to be substantial. While there is significant variation across empirical studies, most studies suggest that the private rate of return can be between 10 and 15 percent, and sometimes even higher.²⁸

Estimating social returns is even more complicated than assessing private returns since spill-over effects may cross industries as well as countries and are thus difficult to track. Various impacts need to be considered (economic, scientific, cultural etc.) as well as its scope and timing. Then, there are well

known attribution and causality problems that make a reliable assessment difficult. Generally speaking though, there is agreement that public R&D does generate social returns. Building primarily on case studies and tracing of individual technologies, such studies appear to suggest that these returns exist and can be quite substantial.²⁹ Optimistic assessments come to the conclusion that social return to R&D may even be 10 times higher than private returns.³⁰

These estimates of fairly high social returns on R&D have been used to justify government support, in the energy realm and beyond. However, the fact that social returns on R&D may indeed exist does not necessarily mean that subsidies or other types of support are the best ways to attaining it. In theory, social returns should materialize, no matter whether R&D is funded by the public or the private sector. The key question thus is where and to what extent public R&D support is important because it complements private R&D. Or put differently, where is public support warranted because otherwise R&D (with desirable social rates of return) would not happen, and where would public support simply substitute for private funds (and thus constitute a waste of public monies)?

The debate on substitution vs. complementarity has been at the heart of the discussion on public R&D support schemes for years, and in contrast to the issue of whether R&D generates social returns or not, the available empirical evidence is much less straightforward. Based on a major review of the available empirical evidence, David, Hall and Toole argue that conclusive evidence does not exist. While the majority of surveys that they include in their review appear to indicate that complementarity is more common than substitution, methodological problems and lack of comparability limit the extent to which these results can be generalized. Results vary across countries, as well as across different types of subsidy and incentive programs. As David, Hall and Toole note, “[...] the heterogeneity of experience created by the application of institutionally different subsidy programs to diverse industries and areas of technology provides strong grounds for doubting the usefulness of searching for the “right” answer.” In other words, the complementarity of public R&D support is decisively influenced by the tool chosen to deliver that support, as well as the broader political-economic context (or innovation system) in which it is delivered.³¹ In other words, it matters how public R&D programs are organized and executed, an issue this paper returns to in the Conclusion. Before doing so, however, a review of public energy R&D spending is in order, as well as an assessment of more recent trends with regard to

public technology support in response to growing concerns over climate change.

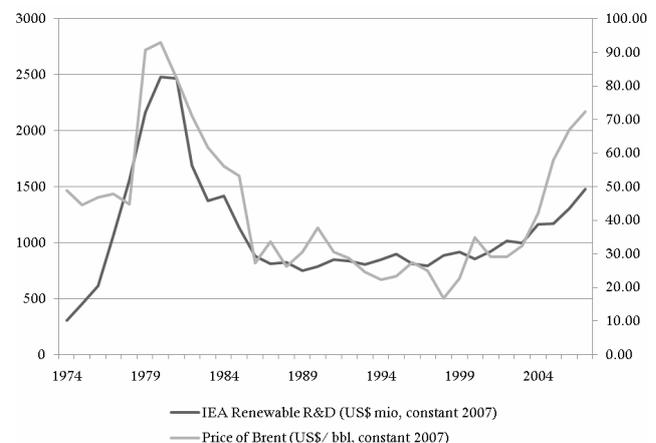
3. Public energy R&D budgets since the early 1980s

For much of the past two decades, spending on overall energy R&D has stagnated in the OECD world, including the US and Europe.³² After a dramatic fall of R&D spending in the early 1980s, overall funding levels have remained flat. The share of energy R&D as a share of overall R&D spending has continuously declined.

This development has been driven primarily by reduced financial commitments to energy R&D from the private sector. R&D investments into energy by the private sector are determined by a variety of factors, including the price of oil, the structure of the market within which companies operate as well as the policy environment. High oil prices provide incentives for companies to invest in the development of fuel alternatives and thus trigger higher R&D spending whereas low oil prices obviously provide no such incentives. The high volatility of the oil price over time has meant that private energy R&D has oscillated quite significantly. Furthermore, the willingness of private companies to commit resources towards energy R&D is also influenced by market structure. Put simply, in a deregulated (and thus more competitive) market companies have fewer incentives to collaborate on R&D projects. Industry groups, traditionally important convenors of private R&D activity, will have more difficulty attracting funding than in less competitive environments. In the US, for example, following widespread market liberalization, the budget of the Electric Power Research Institute was cut to a third within a matter of years after electricity market deregulation.³³ Finally, levels of private R&D funding specifically for renewable energy technologies are also impacted by the broader political and regulatory environment, most specifically with regard to potential policies designed to facilitate market uptake of new technologies (e.g. through feed-in tariffs etc.)

However, in addition to private energy companies, most governments in the OECD world also have reduced budget appropriations – despite the fact that “energy security” and climate change have surged to the top of policy agendas. Only data for the last two years indicate a shift in spending patterns that appears to be driven by the urgency of the climate change agenda (see also discussion below). As in the case of private R&D spending, public financial commitments to energy R&D track the price of oil quite closely, as figure 3a below indicates. However, other factors – including overall budget conditions – probably play a role in determining levels of funding.

Figure 3a. Oil price per barrel and global public renewable energy R&D expenditures, 1974 – 2007 (constant 2007 US\$)

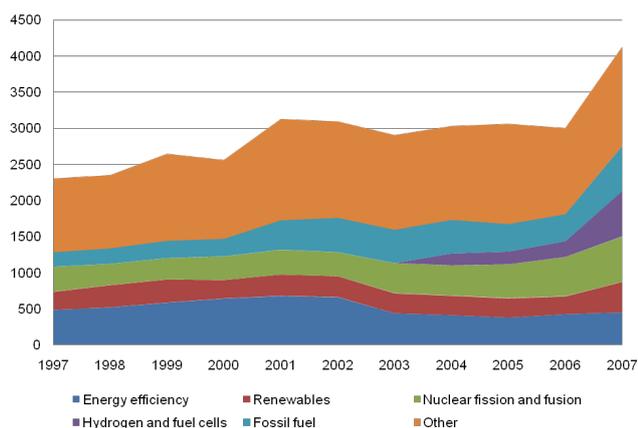


Source: Hillard Huntington and Christine Jojarth (forthcoming), *Financing the Future: Investments in Alternative Sources of Energy*, in: Andreas Goldthau and Jan Martin Witte, *Global Energy Governance: The New Rules of the Game* (Washington, DC: Brookings Press).

The US is a case in point. For a long time, total R&D (public and private) in energy has been stagnating. As reported by Nemet and Kammen, overall energy R&D (public and private) dropped from US\$ 5,833 billion in 1994 to US\$ 4,506 billion in 2003. This decline is all-encompassing, applying to all energy technology categories. However, overall R&D expenditures (i.e. across all sectors) during the same period increased by 6 percent. The reduction in the funds allocated to energy R&D has been primarily caused by reduced private commitments. The share of private to overall energy R&D used to be roughly 50 percent. Yet, by 2003 it had dropped to less than a quarter. This decline in R&D paralleled also by a drop in patenting intensity, except for the case of fuel cells.³⁴

Public R&D expenditures for energy have slightly increased in recent years, as Figure 3a above shows. The most significant share of funding is committed to fossil fuels, followed by energy efficiency, nuclear fission and fusion and renewables (R&D spending on Hydrogen and Fuel Cells has only started in 2004). The recent increase in federal spending for energy R&D is roughly in line with overall increases in federal expenditures on R&D. However, other areas (notably health and defense) have grown much more significantly (by 10 to 15 percent) than federal spending on energy.³⁵ In addition, the slight increase in federal funding for energy R&D has not been sufficient to absorb the overall drop in funding for energy R&D.³⁶

Figure 3b. Public energy R&D expenditures in the US, 1997-2007 (in Million US\$, 2007 prices and PPP)



Source: IEA Energy R&D Database (Note that since 2004, figures for fossil fuel also contain R&D expenditures on CCS.)

The figure below shows the development of public energy R&D as a share of overall public R&D spending, emphasizing the declining significance of energy R&D relative to the government's overall R&D budget. While in 1981 the US committed more than 10 percent of its entire R&D budget to energy, that share dropped to less than 2 percent by 2005.

Figure 3c. Share of budget outlays for energy R&D of total government budget appropriations for R&D – GBAORD – for the US according to NABS 2007



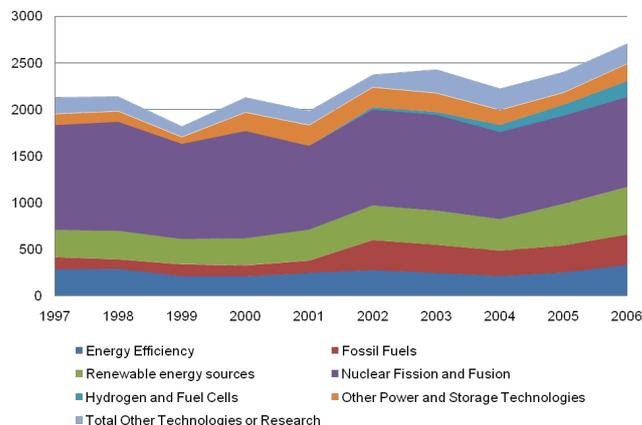
Source: OECD R&D Statistics

The situation in the EU provides a similar picture. Overall R&D expenditures on energy have stagnated during the past two decades, with the greatest decline in financial commitments made by the private sector. As Figure 3d below shows, between 1981 and 2006, the share of budget outlays for energy R&D of overall R&D funding by selected EU member countries has decreased, from almost 12 percent in 1981 to close to 7 percent in 2006.

As in the US, the overall share of spending on energy R&D of the overall R&D budgets has stagnated between 1981 and 2006, as the Figure 3d shows below. In 1982, the share of R&D funding

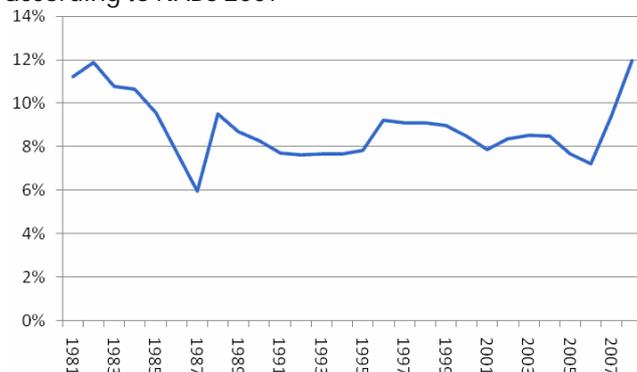
allocated to energy issues was 12 percent. By 2005, that share had dropped to less than 8 percent.

Figure 3d. Public energy R&D expenditures by selected EU member countries, 1997-2007 (in Million US\$, 2007 prices and PPP)



Source: IEA Energy R&D Database. Graph contains data from the following countries: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, United Kingdom. Data for other EU member countries not available.

Figure 3e. Share of budget outlays for energy R&D of total government budget appropriations for R&D – GBAORD – for selected EU member countries according to NABS 2007



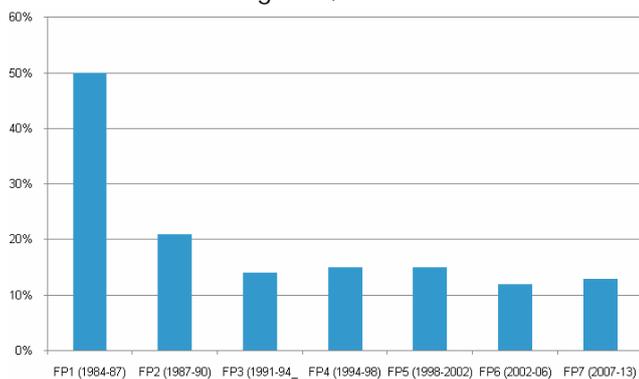
Source: OECD Statistics, own calculations. All EU member countries. No data available for Bulgaria, Cyprus, Estonia, Latvia, Lithuania, Poland, Romania, Slovenia.

In addition to individual EU member countries, the European Commission (EC) is also a source of energy R&D funding. The main tool for delivering R&D spending is the Framework Program (FP) for Research and Technological Development.³⁷ This is a research plan spanning four to five years, drawn up by the EC and approved by the European Council and the European Parliament. Last year, the EC launched the 7th Framework Program.³⁸

Over the years, the share of EU-level funding committed to energy R&D has stagnated. After an initial massive drop after FP1 (where energy funding constituted 50 percent of overall funding allocated), the share committed to energy has

hovered between 12 and 15 percent. Overall, compared to EU member state funding on energy R&D, the EU funding is rather small. Overall R&D funding by the EC is roughly equivalent to 4 to 5 percent of what member countries allocate. Under the ongoing FP7 program, overall funding committed to energy and environment (which includes climate change) amounts to EUR 4.24 billion over a six-year period (see Figure 3f below).

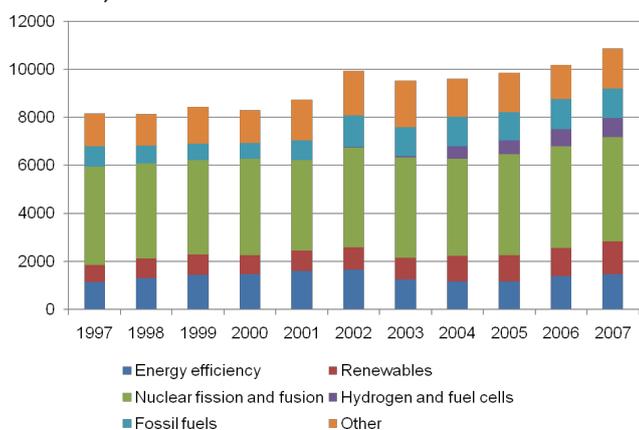
Figure 3f. Development of funding for energy R&D out of the Framework Programs, 1984-2007



Source: Paul Runci and Jim Dooley (2004), Energy R&D in the European Union. Pacific Northwest National Laboratory Technical Report PNWD-3474, p.10 and updated with data from <http://www.cordis.lu> (accessed 3 June 2009).

Funding trends in the EU and US are representative of a broader pattern in the OECD world (see Figures 3g and 3h). The below figures provide an overview of funding allocated to energy R&D across all IEA members, and confirm that the stagnation of energy R&D has been prominent not just in the EU and the US but virtually the entire developed world (with the exception of Japan).

Figure 3g. Public energy R&D expenditures among IEA member states, 1997-2007 (in Million US\$, 2007 prices and PPP)



Source: IEA Energy R&D Database

Various explanations have been put forward to account for this stagnation of public R&D commitment to energy over time. The Stern Review argues that one significant factor that helps to

explain the stagnation of public energy R&D is the reduced commitment to research nuclear power as a result of slackening public support for the technology, especially in the wake of the Chernobyl accident.³⁹

Figure 3h. Share of government budget appropriations or outlays for energy R&D -- GBAORD -- for all OECD member countries according to NABS 2007



Source: OECD R&D Statistics; own calculations.

Most importantly, however, the drop in public funding commitments during the 1980s and 1990s has primarily been a natural response to the skyrocketing expenses in the immediate aftermath of the oil price shocks of the 1970s during which consumer governments (and the private sector) invested massively in energy efficiency, the development of new energy resources (e.g. North Sea oil) and other means to reduce the dependence on OPEC oil. One of the most notable initiatives in this context was the so-called "Project Independence" announced by President Richard Nixon in 1973. In response to the Arab Oil Embargo, Nixon committed to making the US independent of foreign oil imports by 1980. One component of this strategy was a massive expansion of the federal budget for energy R&D.⁴⁰ Similarly, Japan and European nations also stepped up their efforts to reduce their oil dependence, and federal energy R&D budgets surged as a result. Some of these programs, especially those around energy efficiency, proved to be spectacularly successful. The oil intensity of GDP of IEA member countries dropped between 1973 and 1985 by an average of 20 percent. However, once the immediate pressure from the oil market went away, the funding streams trickled out.

4. Stepping up public energy R&D: Trends in the US and the EU

In more recent years, a major shift in funding commitments towards energy R&D seems to have occurred. Since 2007, after a long period of stagnating public energy R&D budgets, policymakers in both the EU and the US have ramped up spending. While it is too early to conclude whether or not this shift will translate into a longer-term pattern, it appears that Americans and Europeans have recognized public R&D as one potentially important lever in their strategy to transform the fossil fuel-based energy paradigm. A preliminary analysis of the available data does indeed suggest that much of that additional funding is geared towards the development of renewable energy technologies, hydrogen and fuel cells, as well as CCS.

4.1 Obama's "down-payment" on climate change

Significant changes in R&D policies were already initiated in the last years of the Bush Administration in the US, resulting in massive boosts for federal energy R&D budgets and reversing the decade-long trend of stagnating federal budgets for basic research.

In 2007, the Bush Administration launched the American Competitiveness Initiative (ACI)⁴¹ and the Advanced Energy Initiative (AEI)⁴² that resulted, among other things, in massive increases of the Department of Energy's R&D budget. Between 2007 and 2009, for example, the DoE's budget for applied energy R&D increased significantly, from US\$1.5 billion to US\$2 billion. The biggest increase came from the DoE's Office of Sciences, the US Government's main sponsor of physical sciences research.⁴³ After budget increases of 5 percent both in 2007 and 2008, the Office of Science was slated to get a whopping 19 percent budget increase in 2009. 90 percent of this budget would go to R&D expenditures.

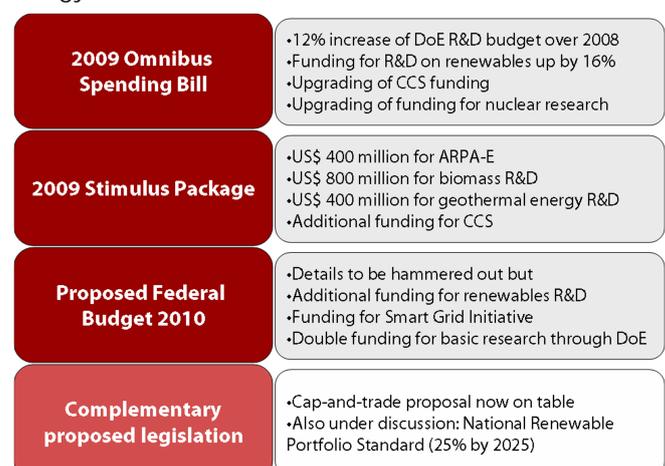
The budget increases for energy R&D applied across the board to all energy technology categories. However, they disproportionately benefitted research on low-carbon technologies which was the expressed intention of the Bush Administration. In announcing the AEI during the 2006 State of the Union Address, President Bush proposed to the US Congress a more than 20 percent increase in federal R&D money for clean technology research at the DoE. More specifically, the Bush White House committed to R&D funding for advanced biofuels (a 65 percent funding increase in the 2007 budget); a US\$281 million commitment to the Coal Research

Initiative (which also included funding for CCS); a US\$46 million increase in 2007 for hydrogen technology R&D; a significant investment of US\$250 million for the Global Nuclear Energy Partnership (GNEP); a US\$148 million commitment to the Solar America Initiative (almost a doubling of funding over 2006 levels); and finally, an (unspecified) increase in funding for wind energy R&D. These investments, however, should not distract from the fact that the Bush Administration continued to oppose tough international action on climate change, as well as the introduction of an emissions trading system in the US that were considered crucial additional components of a coherent US climate change policy.

With the election of President Barack Obama in November 2008, expectations were high for a dramatic shift in climate change policy generally, and energy R&D policy in particular. During the campaign, Senator Obama had indicated a radical departure from the policies of his predecessor, not the least promising a massive expansion of federal funding for energy R&D with a strong focus on clean technologies. That discussion also took place in the context of rapid oil price increases that put energy security front and center of the Presidential election context.

And indeed, after coming to office, the Obama Administration acted fast on various fronts of the climate policy agenda, reflecting significant shifts in the federal budget for 2009, the Federal Stimulus Package (put together in response to the accelerating global economic crisis), the proposed federal budget for 2010, as well as package of proposed legislation.

Figure 4.1a. Obama's 'down-payment' on public energy R&D



Source: GPPi

While the 2009 federal budget was still drawn up by the Bush White House, it was only passed in March 2009 and contained several important additions reflecting the new priorities of the Obama Administration and a Congress controlled by Democrats. The R&D budget of the DoE was one of the biggest winners of the 2009 Omnibus spending bill, with an increase of more than 12 percent over 2008 levels. Funding for R&D on renewable energy technologies was increased by more than 16 percent, to US\$1.4 billion. R&D funding for nuclear technology was also raised significantly, by 16.8 percent. Funding for R&D on fossil fuels grew by an astonishing 45 percent; however, this reflects the fact that fossil fuels had lost out in the budget rounds of previous years. Additionally, this funding bracket also contains the budget line for CCS research.⁴⁴

The Federal Stimulus Package (the American Recovery and Reinvestment Act) also contained some additional and sizeable commitments to federal funding for energy R&D. It adds to the DoE's budget US\$400 million for the Advanced Research Projects Agency-Energy (ARPA-E), an initiative recommended by the National Academy of Sciences in 2007, but not funded by the Bush Administration. The mission of ARPA-E is to "[...] develop new energy technologies that offer significant progress toward reducing imported energy; reducing energy-related emissions, including greenhouse gases; and improving energy efficiency." In addition, the stimulus package contained an additional US\$2.5 billion for research on energy efficiency as well as the development, demonstration and deployment of renewable energies. Furthermore, US\$800 million was allocated specifically for biomass and US\$400 million for geothermal energy. Finally, the bill contains significant appropriations for research on CCS.⁴⁵

Obama's proposed federal budget for 2010 contains further down-payments on the energy R&D front. Given the current economic climate and likely mounting pressures to reign in the burgeoning federal budget deficit, it is unclear at this point what will be left of the proposed additional budget appropriations for energy R&D. However, the priorities that have been laid out are clear. The proposed budget contains additional funds for DoE applied energy research, specifically on renewable energy technologies and the US Smart Power Grid Initiative, as well as a further increase of the DoE's Office of Science in an attempt to double funding for basic R&D.

Finally, the Obama Administration has also pushed forward a number of legislative initiatives to complement these massive increases in energy R&D and to shape a coherent climate change policy. The

most notable initiative is the introduction of an emissions trading system (discussed in chapter 2). President Obama has also proposed the introduction of a National Renewable Portfolio Standard that would commit power producers to switch at least 25 percent of all generated electricity to renewable sources by 2025, potentially instituting a major lever for the mass-deployment of renewable energies.

Overall, it seems clear that there is a major shift in US policy towards climate change generally, and public energy R&D more specifically. The increased financial commitments to public energy R&D will help to move towards the goal set out by the Stern Review (discussed above). Whether and to what extent the additional financial means that have been appropriated are sufficient and will be effective in producing the desired outcomes remains to be seen, however. In addition, the ongoing global economic crisis in conjunction with a bulging federal budget deficit casts a long shadow, especially over President Obama's spending plans for energy R&D, if not the introduction of a cap-and-trade system.

4.2 The European Union's "Strategic Energy Technology Plan" and CCS support

As noted above, comparing R&D spending trends across countries is notoriously difficult because of significant differences in the ways that countries track and categorize allocated budgets. However, there can be no doubt that during the past two years Europeans have also started to increase funding to energy R&D. That includes initiatives both by individual member states as well as by the European Commission (EC).

The latest data available for spending by EU member states is from 2007; for some countries budget numbers are available for 2008. Germany, for example, increased its energy R&D budget by 22 percent from 2006 to 2007, and by another 9 percent from 2007 to 2008. Similarly, France increased its budget commitments from 2006 to 2007 by 13 percent and from 2007 to 2008 by another 10.5 percent. Much like in the rest of the OECD world, UK energy R&D budgets decreased significantly during the 1980s and 1990s. In fact, in 2006, funding for energy R&D constituted only about 7 percent of funding levels seen in the early 1980s. Much like France and Germany, however, the UK has started to upgrade its funding into energy R&D in recent years, with large increases for energy efficiency, renewable energy sources and particularly fusion research.⁴⁶ Expenditures for basic energy research (organized under the UK Research Councils) rose by more than 75 percent between 2005 and 2008.⁴⁷ In 2007, the UK (in partnership

with a group of energy companies) launched the Energy Technology Institute that is supposed to advance low-carbon technologies from conceptual proof to commercial viability testing.⁴⁸ However, not all EU member countries have similar budget growth rates, and indeed some appear to have reduced their commitments. Overall, the growth rates in energy R&D budgets appear to be less significant than in the US.

In a sense, the somewhat slower growth in commitments to energy R&D in Europe may simply reflect the fact that the US has some “catching up” to do. As shown in the previous section, while public energy R&D budgets did decrease significantly in Europe as well, the overall share of energy R&D to overall R&D budget commitments remained significantly higher in most European nations than in the US. Also, many European countries (though by no means all), have ‘retooled’ their energy R&D program earlier than the US in order to reflect climate change realities. This applies not the least to Germany where energy R&D priorities have shifted since the 1980s towards reducing energy demand and innovation in renewable energy sources, especially solar and wind.⁴⁹ While spending levels oscillated over the years, public energy R&D focused on solar energy technologies (solar heating, photovoltaics, solar thermal power) and wind more than doubled between 1981 and 2000. Combined with powerful policies designed to promote market uptake (e.g. the Renewable Energies Act⁵⁰, “eco-taxes”, etc.), the German government has successfully fostered enhanced energy efficiency and broader use of renewable energy technologies.

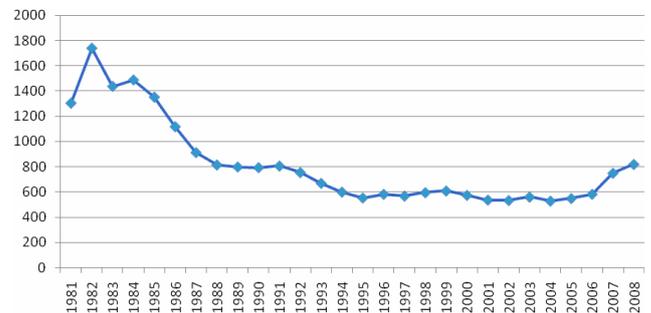
However, Germany’s commitment to funding energy efficiency and renewable energy technologies in public R&D spending is not a story of unqualified commitment and support. First of all, it is important to point out that – much like in the US – the overall public energy R&D budget has declined in Germany in a quite dramatic fashion since the early 1980s (see figure 3.2a below).

Until the early 1990s, public energy R&D budgets were dominated primarily by nuclear fission (see Figure 3.2b below). With decreasing public support for nuclear power (especially after the Chernobyl accident), political priorities shifted and budgets for fission research were axed. Between the early 1980s and 2005, overall public R&D funding for fission research declined by more than 90 percent in real terms.

Similarly, public energy R&D funding for fossil fuels declined, in the same period of time, by more than 95 percent in real terms. That includes research funding for more efficient fossil fuel combustion. However, the money that was taken out of nuclear

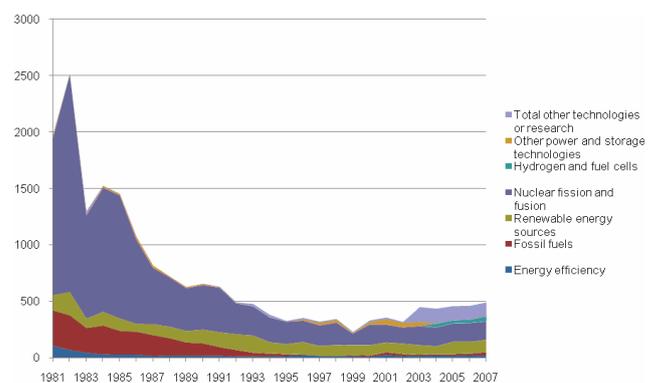
fission and fossil fuel research was not reinvested in other technologies but instead shifted elsewhere.

Figure 4.2a. Government budget appropriations or outlays for R&D in Germany – GBAORD – by socio-economic objective according to NABS 2007 – Energy (in US\$ Million current PPP)



Source: OECD R&D Statistics

Figure 4.2b, Germany’s public energy R&D budget, 1981-2007



Source: IEA R&D Statistics

Also, while public measures to improve energy efficiency and renewable energy technologies have had broad support throughout the entire political spectrum in Germany for many years, the financial commitment to relevant energy R&D has been rather volatile. Public investment in renewable energy R&D skyrocketed to more than US\$200 million in 1982 (clearly in response to the second oil price shock), but then was cut by more than 60 percent in the next year. Similarly, by 1993, the federal budget for renewable energy R&D had climbed again to US\$151 million, only to nosedive by more than 55 percent until 2004. While budgets were generally cut (primarily as a result of the rising costs of German unification which had an overall constraining impact on the federal budget), the appropriations for renewable energy technologies sustained some of the deepest cutbacks during those years. Expenditures for energy efficiency fluctuated quite substantially during that period

but increased overall.

Today, while Germany is one of the global cheerleaders in promoting energy efficiency and renewable technologies, the country's R&D budget development continues to provide a contradictory picture. In more recent years (2006 and 2007), appropriations for public energy R&D have gone up again quite significantly. Much of that increase is driven by more expenditures on fossil fuels (the R&D budget for coal combustion (to improve efficiency) almost doubled between 2005 and 2007, to close to US\$ 30 million), as well as increasing expenses for fuel cells (an increase between 2005 and 2007 of more than 35 percent, now more than US\$ 40 million). However, it is worthwhile to note that after some first and relatively minor appropriations in 2004 and 2005, Germany has not invested any more financial resources into R&D on CCS technology in 2006 and 2007.

As noted above, the European Commission has also been a player in promoting public energy R&D, albeit on a much smaller scale than the EU member states. Also, as indicated in Figure 2e above, overall financial commitments to energy R&D have stagnated in the successive Framework Programs through which the EC channels most of its support.

In conjunction with the political decision of the EU to redesign European energy policy around the 20/20/20 agenda (20 percent reduction in greenhouse gases, 20 percent reduction of primary energy use, and 20 percent of renewable energy in the overall energy mix), the EC has also proposed the adoption of a new "Strategic Energy Technology Plan" (SET-Plan) arguing that "[...] actions to develop new energy technologies, lower their costs, and bring them to the market must be better organized and carried out more efficiently."⁵¹ The objective is to develop a long-term framework for European policy on energy technology development.

With the SET-Plan, the EC claims it will accomplish four things:⁵²

- An improvement of coordination among existing research capacities in the EU.
- Higher effectiveness of implementation of energy innovation.
- Mobilization of additional resources.
- More and better international cooperation on energy technology development.

The SET-Plan identifies a range of technologies the EC believes Europe will need to develop and bring to market in order to accomplish its ambitious climate policy targets. The SET-PLAN expressly also includes a call to foster research on CCS as well as

nuclear technologies which has incited environmental groups.⁵³

The SET-Plan was endorsed by the European Council during the spring meeting of 2008 in which the Council "welcomed" the EC's plan and spelled out a number of fundamental principles for its implementation. However, the Council did not indicate that it would mobilize additional funding for the initiative and instead called upon the EC "to aim for substantial increases in European, and when appropriate, national funding for energy R&D [...]."⁵⁴ In fact, the financing of the SET-Plan has remained a contentious issue. A European Energy Technology Summit scheduled for 2009 is supposed to come to concrete results with regard to funding, but thus far details of such a financial plan and member state responses are unknown.

At least equally significant is a more recent decision by the EU that could play a crucial role in fostering CCS. In the adopted climate-energy legislative package, and the associated reforms to the European Union Emissions Trading System, the European Council stipulates that the proceeds from the auctioning of 300 million emissions allowances will be allocated to the financing of 12 CCS demonstration projects (and other renewable energy projects). The Council estimates that this will result in an overall financial commitment of EUR 6 to 9 billion, assuming carbon prices of either EUR 20 or EUR 30.⁵⁵

Overall, while there appears to have been increased commitment to spending on public energy R&D, the budget increases have not been very significant. The key drivers in this process will have to be the EU member countries; thus far the EC simply does not have the financial muscle to ramp up spending in significant ways. The difficulties of getting additional funding for the EC's SET-Plan indicates both the desire to keep the development of new technologies with potential relevance for competitiveness under tight national control, but also an unwillingness to commit fresh money in times of tight national budgets. As in the US, the global economic crisis will likely leave a dent in the ambitious plans of the EC and some EU members to take more aggressive measures.

In sum, while there appears to be a silver lining on the horizon, particularly with regard to increased US commitments to public energy R&D, thus far additional commitments that have been made in recent years are likely to be insufficient⁵⁶ to meet any of the targets that have been declared necessary, e.g. the doubling of global energy R&D to US\$ 20 billion per year.

More significantly, the ongoing global economic crisis will more likely than not leave a significant

mark on public spending abilities in future years. One of the most immediate effects will come as a result of the slash in the oil price, from its high of US\$ 147 in the summer of 2008 to roughly US\$ 60 at present. The oil price is, and will likely remain for the foreseeable future, one of the most powerful drivers especially for private investment in energy R&D. The various economic stimulus packages passed in Europe and the US, to some extent countervail that impact and may increase public energy R&D at least for some time. However, in the economic crisis will also adversely affect public investments. In a recent analysis, Huntington and Jojarth of Stanford University predict rather gloomily: "The future of renewable energy hinges [...] more than ever on politics. [...] Governments have become more reluctant to impose additional environmental regulation on companies already struggling for their survival and the implosion of tax revenues curtails their ability to finance renewable energy investments out of their own pockets. In short, the stellar growth of investments in alternative energy faces an uncertain future, and it remains to be seen whether the boom and bust cycle investments in renewables experienced in the aftermath of the 1970s will be repeated."⁵⁷

5. Maximizing the impact of public energy R&D support

There is growing consensus among experts and policymakers that public energy R&D has an important role to play in the global fight against climate change, and that current spending levels will have to be increased substantially in order to seize on the R&D potential. As Dooley and Runci note: “Climate change presents the most urgent and the most difficult public goods challenge from the perspective of energy R&D investment, since there is widespread agreement that the attainment of this public good will place enormous demand for the accelerated development and deployment of new energy technologies. Since neither price signals nor the regulatory environment in the U.S. now provide sufficient incentive for high levels of private investment in these technology areas, it is appropriate to consider ways in which public R&D policy and public sector investments in energy R&D can accelerate the development and deployment of the needed technologies.”⁵⁸ Also, Nemet and Kammen find that there is sufficient absorptive capacity in public as well as private sectors for a dramatic increase in energy R&D, and that the fiscal effects would be well within the range of previous programs and thus manageable.⁵⁹

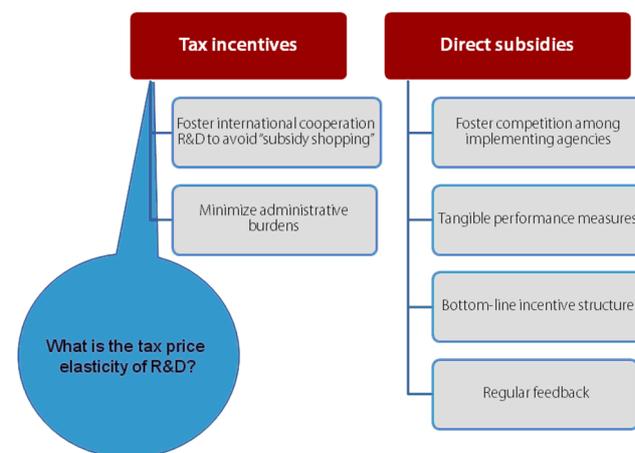
Yet, it would be misleading to suggest that the only challenge on the public energy R&D front is the commitment of more financial resources. In fact, there exists a broad and sophisticated literature that focuses on the design of public subsidy systems for R&D with the intention of avoiding investments in “white elephants” and excessive rent-seeking (which is an almost unavoidable feature of any public subsidy scheme.) In more recent discussions of public energy R&D support for the global fight against climate change these pertinent issues are usually not explicitly addressed. As many nations are now looking towards significantly expanding their financial commitments in those areas, it will be crucial not only to manage expectations about the contribution R&D can make to solving the climate change conundrum, but also to build in design features that ensure that tax dollars are spent wisely.

Various criteria matter in that context: First, as noted earlier in this paper, public spending on energy R&D should be complementary not a substitute. Ideally, funding programs would need to be designed such that they do not crowd out private spending. Second, while governments need to be the source of financial support they should introduce mechanisms that minimize their role in actively influencing technology choices. In the past,

governments around the world have proven to be less than perfect in determining the path of technological development by regulatory fiat. The Synfuels debacle in the US is just one prominent example of a white elephant promoted by the government at tremendous cost. Many more case studies exist. Third, and finally, governments need to be mindful about ensuring policy coherence. The type and scale of public energy R&D support needs to match with other policies that are being adopted in parallel as part of the overall effort to tackle climate change.

A detailed sketch of enhanced public energy R&D schemes is beyond the scope of this paper. However, some basic design principles should guide the development of any upgrading of public R&D programming. Here, we focus on two of the most mainstream ways in which governments are trying to deliver support to energy R&D: tax incentives and direct subsidy schemes (see Figure 5a below).

Figure 5a. Intelligent design of public energy R&D support



Source: GPPI

Direct subsidies to public and private labs. The analysis above suggests that one overall objective of public policy design for energy R&D should be to maintain as many characteristics of market solutions as possible. That should include, among other things:

- The introduction of competition among those who execute energy R&D activities. This requires opening up grant-making processes to a wide array of competent research institutions in the public and private sectors. Opening up competition for research

funds has the potential to increase the quality of outputs and has been widely practiced already in the EU and the US.

- The establishment of tangible performance measures. The design of subsidy programs should explicitly spell out performance measures and milestones. This will be difficult in many cases but it ensures that underperforming programs can be eliminated on the basis of evidence. Such performance measures should not just apply to large-scale endeavors (that anyway are subject to more public scrutiny) but also smaller grants processes that often do not attract much public attention and that can be renewed by government bureaucracies.
- Bottom-line incentive structure in implementing agencies. Those implementing research with public monies should face straightforward bottom-line incentive structures in the implementation of R&D. Unfortunately, public budgeting rules frequently set perverse incentives. Intelligent subsidy design should try to eliminate those hurdles.
- Ensuring regular feedback to improve public accountability. Feedback and evaluation procedures have long been part and parcel of public R&D subsidy programs in the EU and the US. Such programs enhance the accountability of programs, and can also help to reduce the incidence of “capture” of public R&D funds by special interest groups. Wherever possible, such evaluation should be conducted by independent agencies and not actors that have a stake in the process.

Provision of tax incentives to foster private energy R&D. Tax incentives have long been considered the tool of choice by market-oriented governments to spur private R&D activity.⁶⁰ Tax incentives are considered to be more efficient than subsidy programs that tend to be costly in administration as well as subject to capture by special interest groups. However, the politics and economics of tax incentives are not as straightforward as frequently suggested. Some studies suggest that the absolute tax price elasticity of R&D is low; thus, tax credits to incentivize R&D may not be as effective as they may seem. However, the evidence on that varies, with some studies suggesting that it may be more substantial than others.⁶¹

In addition, some observers have pointed out that the design and implementation of tax credit schemes can be rather complicated, putting administrative burdens on government as well as

benefitting companies. In the past, some schemes have also been shown to contain perverse incentives. Research also found that tax incentives may not necessarily result in more R&D being done but simply in a relocation of R&D activity across countries. That makes international cooperation on public R&D a sine qua non (see discussion below).

Finally, the design of public energy R&D programs should not be done in a vacuum. Instead, it is becoming increasingly obvious that policy coherence in the climate change arena will be one of the key challenges in the future.

There is indeed widespread agreement that policymakers will have to utilize a broad range of different tools in order to achieve the transformation of the prevailing energy paradigm. However, there is also early evidence to suggest that sometimes these tools, when not coordinated, can generate perverse results. For example, some modeling suggests that the EU Renewables Directive – stipulating that, by 2020, a minimum of 20 percent of all power generation in Europe needs to come from renewable sources of energy – may undermine the ability of the EU to generate stable and rising carbon prices.⁶² Coordination of these different tools in the overall climate change toolbox will be difficult but essential in order to generate results.

Box 1. Investing in CCS – Laying out the economic challenges

As the IEA notes in its 2007 World Energy Outlook, “CCS is one of the most promising routers for mitigating emissions in the longer term and could reconcile continued coal burning with the need to cut emissions in the longer term.” The technology itself consists of three parts: carbon capture (either pre-combustion, post-combustion, or oxy-fuel combustion), transportation of carbon (either through pipelines or tankers), and storage underground (e.g. in oil and gas fields, seabed, or saline caverns). The technology itself is not exactly new; the underlying principles of the technology have been proven and carbon sequestration has found widespread application in “enhanced oil recovery” methods, i.e. techniques designed to improve the extraction ratios of existing oil fields.

While the principle has been proven, CCS has yet to be proven on a large-scale commercial scale in the power sector where it is most needed. Thus far only a handful of demonstration projects exist. Not a single commercial-scale power plant is in operation that uses the CCS technology. However, while the technology is still in the early development stages, it plays a major role in virtually all mitigation scenarios that have been developing, indicating both the potential that scientists and policymakers assign to the technique but likely also the lack of good alternatives.⁶³ In its Special Report on CCS, for example, the IPCC expects that by 2100, CCS will contribute between 15 and 55 percent of CO₂ mitigation (depending on emissions scenarios).⁶⁴ Similarly, the IEA expects that CCS will be delivering 20 percent of mitigation by 2050.⁶⁵ In its 2008 World Energy Outlook, the IEA expects that for the world to achieve a stabilization of carbon dioxide levels of 450 ppm, roughly 350 GW of CCS capacity will have to be installed by 2030.⁶⁶ The Stern Review estimates that CCS will have to deliver on approximately 10 percent of mitigation by 2025 and 20 percent by 2050. In addition, Lord Stern posits that the marginal mitigation costs without CCS operating at commercial scale will increase by approximately 60 percent.⁶⁷ Finally, in its assessment of the economics of CCS, the consulting firm McKinsey & Company estimates the overall abatement potential of CCS eventually to be 3.5 gigatons per year, 0.4 gigatons of which would have to be realized in the EU, corresponding to roughly 20 percent of European abatement opportunities beyond the “business-as-usual” scenario.⁶⁸ It is also interesting to note that the IPCC mitigation scenario does not just expect widespread adoption of the CCS technology in developed countries but also in developing

countries. Thus, the IPCC assumes that not only will the technology be available but also that it will have been sufficiently diffused globally.

Realizing the potential of CCS poses both short-term as well as long-term economic feasibility issues.⁶⁹ The short-term challenges are primarily in proving the commercial viability of CCS by further developing the technology and building business models. Assuming that is successful, the long-term challenges relate primarily to the question how growth of CCS installed capacity can be fostered sufficiently fast in order to achieve mitigation targets.

With regard to the short-term challenges of proving commercial viability and building business models, McKinsey & Company has recently provided a rough assessment of CCS economics. McKinsey estimates that for Europe to achieve 0.4 gigatons of CO₂ abatement by 2030, at least 80 to 120 commercial-scale CCS projects are required. They conclude that in order for that to happen, significant upfront investments into a demonstration program need to be made. The incentives for the private sector to invest in such a demonstration program are arguably low, not the least as a result of relatively low carbon prices and uncertainty with regard to the long-term development of climate policy (and in particular the aggressiveness of future caps on emissions). McKinsey thus estimates that there will be an economic gap— i.e. an expected gap between the carbon price and lifecycle costs of CCS – that will amount to EUR 0.5 to EUR 1.1 billion per demonstration project. Also, the consultants argue that for the abatement target to be reached, the necessary groundwork for a commercial roll-out of CCS needs to be laid pretty much in parallel to the demonstration program. Overall, McKinsey estimates that for private investment to flow into CCS in the demonstration phase, a carbon price of at least EUR 60 to EUR 90 would be required (the reference case being a new coal-fired power plant). Early full commercial scale projects would require a carbon price of EUR 35 to EUR 50.

While these calculations are useful and indicate the scale of the short-term challenge at hand, they also need to be viewed with a grain of salt. Data on representative performance of CCS technology and associated costs simply do not exist. As Cullenward notes, “[...] it is extremely difficult to estimate the levelized costs of a power plant that sequesters carbon dioxide, because analysts draw only on limited experience with industrial (non-power plant) analogs. Because these two sectors (power and industry) are expected to host the primary climate mitigation applications of CCS technologies [...], specific assumptions about CCS

Box 1. Investing in CCS – Laying out the economic challenges, continued

costs have almost no empirical backing, and modelers are forced to rely on theoretical estimates.”⁷⁰ In other words, while indicative, the estimates provided by McKinsey may be subject to major revision as the CCS technology is further developed in the demonstration phase.

In addition to the significant short-term challenges of bringing the CCS technology to the commercial roll-out stage, there are also longer-term issues with regard to achieving the necessary CCS installation rates in order to meet mitigation targets. Building on a database of currently existing CCS projects, a recently published study from Stanford University estimates the necessary annual growth rates of CCS installed capacity in order for the technology to achieve the mitigation targets set out by the IPCC. In this context, the overall growth of the CCS industry depends on the actual emissions scenario applied as well as the targeted CO₂ atmosphere concentrations (i.e. the policy target). The study shows that between 2020 and 2100, for the realization of the 450 ppm target under the IPCC mitigation scenario, the CCS industry would have to grow by 6.4 percent to 10.1 percent annually. In the 550 ppm scenario, annual growth of CCS industry would have to be between 4.1 percent and 8.1 percent. As the author concludes, these growth rates are most likely “implausible.” “This suggests two possible interpretations. The first is that today’s expectations for the contributions from CCS are overstated, [...]. This would mean a larger role for other technologies, population choices, and behavioral changes to reduce carbon dioxide emissions. Here, too, one must project and estimate technical and economic potentials [...]. A second possibility is that we really do need to accomplish CCS on this level. Whether because alternative mitigation options prove similarly difficult to scale, or because the sheer magnitude of the carbon challenge requires every possible solution, we might need as much CCS as is currently projected.”⁷¹

- ¹ More recently, a controversial debate on so-called “geo-engineering” has picked up steam as well, focusing on the potential benefits as well as dangers of artificially manipulating the climate in an effort to avoid the harmful consequences of global warming. See e.g. David G. Victor, M. Granger Morgan, Jay Apt, John Steinbruner, and Katharine Ricke, *The Geoengineering Option: A Last Re-sort against Global Warming?* In: *Foreign Affairs*, March-April 2009.
- ² IPCC (2007), *Climate Change 2007, Chapter 11: Mitigation from a Cross-Sectoral Perspective* (accessible at <http://www.ipcc.ch/ipccreports/ar4-wg3.htm>, accessed 29 May 2009), p.621.
- ³ To illustrate, a recent analysis of the most recent legislation designed to institute a cap-and-trade system in the US comes to the conclusion that “[...] innovation investments in the bill remain far too small. [...], the bill would direct just US\$ 9 billion annually to technology innovation, assuming an average carbon price of US\$ 15 per ton. And it would reserve just \$735 million per year for the energy R&D centers. That may sound like a lot compared to the nation's current, anemic efforts, but it pales beside the US\$ 20 to US\$ 30 billion per year on R&D called for by Brookings (or the US\$ 15 billion annually called for by Barack Obama). And it's doubly disappointing given that the cap-and-trade system represents the best potential source for funding game-changing innovation in the face of tight budgets for the foreseeable future.” Mark Muro (2009), *Waxman-Markey: What about Innovation?* Brookings Institution, 26 May 2009 (accessible at http://www.brookings.edu/opinions/2009/0526_innovation_muro.aspx (accessed 5 June 2009)). In that context, it is also important to keep in mind that the IPCC scenario outlined above is based on top-down modeling. Adopting a global least cost approach, the IPCC estimates are based on “[...] universal emissions trading, assuming transparent markets, no transaction cost, and thus perfect implementation of mitigation measures throughout the 21st century.” These are necessary assumptions for modeling to generate results but are hardly realistic given what we know today about the political and administrative hurdles of implementing cap-and-trade-schemes. See IPCC (2007), *Climate Change 2007 – Synthesis Report* (accessible at http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf, accessed 29 May 2009), p.61.
- ⁴ See Timo Behr and Jan Martin Witte (2009), *Towards a Global Carbon Market? Prospects and Limits of Carbon Market Integration*. GPPi Global Energy Governance Program Policy Paper Series No. 5 (July 2009).
- ⁵ Nicholas Stern (2006), *Stern Review of the Economics of Climate Change* (Cambridge: Cambridge University Press), chapter 16, p.347.
- ⁶ IEA (2008), *World Energy Outlook – Executive Summary* (Paris: IEA), p. 5.
- ⁷ For example, the IPCC expects that CCS will contribute between 15 to 55 percent of the necessary CO₂ mitigation by 2100 to meet global abatement targets.
- ⁸ To be sure, very few climate change experts are suggesting that carbon pricing is the world's “silver bullet.” The IPCC, for example, has repeatedly emphasized the “[...] need for a range of cross-sectoral measures in addition to carbon pricing [...]”. IPCC (2007), *Climate Change 2007, Chapter 11: Mitigation from a Cross-Sectoral Perspective* (accessible at <http://www.ipcc.ch/ipccreports/ar4-wg3.htm>, accessed 29 May 2009), p.622.
- ⁹ See e.g. John M. Amidon (2005), *America's Strategic Imperative: A “Manhattan” Project for Energy*, in: *Joint Force Quarterly* 2005(39), pp.68-77. Jeff Wilson (2008), *The Manhattan Project of 2009: Energy Independence NOW* (New York: BookSurge Publishing). See also comments made by US Senator Lamar Alexander, “New Manhattan Project is Best Energy Solution,” 16 June 2008 (accessible at http://alexander.senate.gov/public/index.cfm?FuseAction=Articles.Detail&Article_id=c412196d-29b3-400e-acda-9a4859ac949b&Month=6&Year=2008 (accessed 2 June 2009)).
- ¹⁰ Senator Barack Obama (2008), *Energy Security is National Security*. Remarks of Senator Obama at the Governor's Ethanol Coalition, Washington, DC, 28 February 2006 (accessible at www.ethanol-gec.org/information/Obama-Energy-Security-National-Security_DC_3-1-06.doc, accessed 2 June 2009).
- ¹¹ See James Duderstadt, Mark Muro, Gary Was et al. (2009), *Energy Discovery-Innovation Institutes: A Step toward America's Energy Sustainability* (Washington, DC: Brookings Institution). Accessible at http://www.brookings.edu/~media/Files/rc/reports/2009/0209_energy_innovation_muro/0209_energy_innovation_muro_full.pdf (accessed 5 June 2009).

¹² “European Commission proposes a plan to accelerate energy technologies for a low-carbon future,” IP/07/1750, 22 November 2007 (accessible at <http://ec.europa.eu/research/index.cfm?pg=newsalert&lg=en&year=2007&na=na-221107>, accessed 2 June 2009).

¹³ “Though benefits of R&D are difficult to evaluate accurately a diverse range of indicators illustrate the benefits of R&D investments. Global public energy R&D support has declined significantly since the 1980s and this trend should reverse to encourage cost reductions in existing low-carbon technologies and the development of new low-carbon technological options. [...] A recent IEA publication on RD&D priorities strongly recommends that governments consider restoring their energy RD&D budgets at least to the levels seen, in the early 1980s. This would involve doubling the budget from the current level of around US\$ 10 billion. This is an appropriate first step that would equate to global levels of public energy R&D around US\$ 20 billion each year.” Nicholas Stern (2006), *Stern Review of the Economics of Climate Change*, op. Cit., chapter 16, p.371-372. See also OECD/ IEA report quoted in *Stern Review*, OECD (2006), *Do We Have the Right R&D Priorities and Programs to Support Energy Technologies of the Future?* (By Richard Doornbusch and Simon Upton). SG/SD/RT(2006)1 (accessible at <http://www.oecd.org/dataoecd/48/28/39356629.pdf>, accessed 2 June 2009).

¹⁴ See for example Gregory F. Nemet and Daniel M. Kammen (2007), *US Energy Research and Development: Declining Investment, Increasing Need and the Feasibility of Expansion*, in: *Energy Policy* 35(2007), pp.746, 752. “Investment in innovation in the US energy sector is declining just as concerns about the environmental, geopolitical, and macroeconomic impacts of energy production and use are intensifying. [...] We find that a five to ten-fold increase in [US federal] spending from current levels is not a “pie in the sky” proposal; [...] While expanding energy R&D to 5 or 10 times today’s level would be a significant initiative, the fiscal magnitude of such a program is well within range of previous programs each of which have produced demonstrable economic benefits beyond the direct pro-program objectives.”

¹⁵ Energy R&D can be defined as a “[...] series of linked processes by which technologies for energy supply, end use, or carbon management move from theoretical conceptualization to feasibility testing and, ultimately, to small-scale deployment. Energy R&D encompasses both basic and applied re-search, technology development, and demonstration associated with each phase of the energy lifecycle including: production (e.g., mining and drilling), energy conversion and power generation (e.g., nuclear fission and fusion, fossil and renewable energy systems, bioenergy, and hydrogen production), transmission, distribution, energy storage, end-use and energy efficiency, and carbon management. Carbon management technologies aim to manage anthropogenic releases of greenhouse gases such as those associated with the combustion of fossil fuel use, in an effort to mitigate the potential impacts of these emissions on climate systems.” See Jim Dooley and Paul Runci (2004), *Energy and Carbon Management R&D Policy: Framing Considerations and Recommendations for the National Commission on Energy Policy Joint Global Change Research Institute* College Park, MD, 30 March 2004 (accessible at <http://www.bipartisanpolicy.org/files/news/finalReport/VI.1.d%20-%20Energy%20and%20Carbon%20Management%20R&D%20Policy.pdf> (accessed 3 June 2009)). This paper focuses exclusively on public R&D. The development of private R&D is at least equally important but cannot be treated in detail here.

¹⁶ See e.g. Paul A. David, Bronwyn H. Hall and Andrew A. Toole (1999), *Is Public R&D a Complement or Substitute to Private R&D? A Review of the Econometric Evidence*, in: *Research Policy* 29(4-5), pp.497-529.

¹⁷ Kenneth Arrow (1962), *Economic Welfare and the Allocation of Resources to Invention*, in: Richard Nelson (ed.), *The Rate and Direction of Inventive Activity* (Princeton: Princeton University Press), pp.609-625.

¹⁸ Nicholas Stern (2006), *Stern Review of the Economics of Climate Change*, op. Cit., chapter 16, p.354-355.

¹⁹ Ibid.

²⁰ An alternative to programs that try to foster more basic research, governments have also taken various steps to enhance intellectual property regimes (IPRs) to assist market participants with “spillover effects.” However, rigid IPRs can have the tendency to slow the progress of innovation (because cumulative research is made more difficult as a result of legal barriers); in addition, they will slow the progress of technology diffusion and deployment.

²¹ In his paper, Blyth uses the example of CCS to show that public R&D support in the EU may be warranted, but only in the context of an aggressive overall cap on emissions (30 percent by 2020). The numbers that are employed in that model are highly uncertain, yet the basic underlying principle stands. See Will Blyth (2008),

Linking carbon markets and technology support mechanisms: Making sense of the EU Climate Change Package. Chatham House EEDP Program Paper 08/01, p.7.

²² Charles Wolf, Jr. (1979), Theory of Nonmarket Failure: Framework for Implementation Analysis Source, in: *Journal of Law and Economics* (22) 1), pp. 107-139. See also analysis in Ronald J. Sutherland and Jerry Taylor (2002), Time to Overhaul Federal Energy R&D. CATO Policy Analysis No. 424, 7 February that applies Wolf's analysis to energy R&D.

²³ Charles Wolf, Jr. (1979), Theory of Nonmarket Failure: Framework for Implementation Analysis Source, op. Cit., p.114.

²⁴ See Ronald J. Sutherland and Jerry Taylor (2002), Time to Overhaul Federal Energy R&D, op. Cit, p.7.

²⁵ Charles Wolf, Jr. (1979), Theory of Nonmarket Failure: Framework for Implementation Analysis Source, op. Cit., p.115.

²⁶ For example, the Synfuels Corporation in the United States, "Project Independence" by the Nixon Administration, as well as fusion research. For a critical appraisal see Peter Z. Grossman (2008), The History of US Alternative Energy Development Programs: A Study of Government Failure. Paper presented at Research Symposium on "Bad Public Goods." Searle Center on Law, Regulation, and Economic Growth, Northwestern University, 16 September.

²⁷ See e.g. Bronwyn H. Hall (1996), The Private and Social Returns to Research and Development, in: B. Smith and C. Barfield, *Technology, R&D, and the Economy* (Washington, DC: Brookings Institution and AEI), chapter 6, in particular pp. 141ff.

²⁸ See e.g. Bronwyn H. Hall (1996), The Private and Social Returns to Research and Development, op. Cit., p.145.

²⁹ See e.g. Bronwyn H. Hall (1996), The Private and Social Returns to Research and Development, op. Cit., p.159; Zvi Griliches (1992), The Search For R&D Spill-Over, in: *Scandinavian Journal of Economics* 94, pp. 29-47; J.D. Adams (1990), Fundamental Stocks of Knowledge and Productivity Growth, in: *Journal of Political Economy* 98(4), pp. 673-702.

³⁰ See the overview of different studies on measuring social returns to R&D contained in Rachel Griffith (2000), How Important is Business R&D for Economic Growth and Should the Government Subsidize it? Institute for Fiscal Studies Briefing Note No.12 (London: IFS) (accessible at <http://www.ifs.org.uk/bns/bn12.pdf> (accessed 4 June 2009)).

³¹ See also Lars Niklasson (2002), The R&D Paradox in "Varieties of Capitalism": More Public Goods by the Market in Liberal Market Economies. Paper presented at the American Political Science Association Meeting 2002. Paper on file with the authors.

³² It is important to point out in this context that a comparison of R&D figures across countries is notoriously difficult because of significant differences in the ways in which spending is tracked and categorized.

³³ See Gregory F. Nemet and Daniel M. Kammen (2007), US Energy Research and Development: Declining Investment, Increasing Need and the Feasibility of Expansion, op. Cit., pp.748.

³⁴ Gregory F. Nemet and Daniel M. Kammen (2007), US Energy Research and Development: Declining Investment, Increasing Need and the Feasibility of Expansion, op. Cit., pp.746-755.

³⁵ *Ibid.*, p.747.

³⁶ Note that the "Other" category includes energy systems research and other energy-relevant R&D spending. IEA (not dated), Energy Technology R&D Budgets. Documentation for Beyond 2020 Files (IEA: Paris), p.8.

³⁷ Nuclear research in the EU is organized separately under the Euratom framework. See <http://www.euratom.org/> (accessed 3 June 2009).

³⁸ For a detailed analysis of EU R&D programming, specifically with regard to energy, see Paul Runci and Jim Dooley (2004), Energy R&D in the European Union. Pacific Northwest National Laboratory Technical Report PNWD-3474.

³⁹ Nicholas Stern (2006), Stern Review of the Economics of Climate Change, op. Cit., p.354.

⁴⁰ "Project Realism," in: *Time Magazine*, 2 September 1974 (accessible at <http://www.time.com/time/magazine/article/0,9171,943755,00.html> (accessed 3 June 2009)).

- ⁴¹ For more on the R&D components of the ACI see http://www.ostp.gov/pdf/1pger_aci.pdf (accessed 4 June 2009).
- ⁴² For more background on the AEI see http://www.lgprogram.energy.gov/energy_booklet.pdf (accessed 4 June 2009).
- ⁴³ AAAS (2008), Department of Energy R&D in the FY 2009 Budget (accessible at <http://www.aaas.org/spp/rd/09pch8.htm> (accessed 4 June 2009)).
- ⁴⁴ See "DOE Launches the Advanced Research Projects Agency-Energy, or ARPA-E", April 29 2009 (accessible at http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=12478 (accessed 4 June 2009)).
- ⁴⁵ AAAS (2009), Final Stimulus Bill Provides US\$ 21.5 Billion for Federal R&D, 16 February 2009 (accessible at <http://www.aaas.org/spp/rd>, accessed 4 June 2009).
- ⁴⁶ For a review of UK energy R&D trends and policies see Gillian Glaze (2006), The UK Energy Re-search Landscape. Forschungszentrum Jülich, GIN/2006-01 (accessible at http://www.fz-juelich.de/ptj/lw_resource/datapool/__pages/pdp_105/UK_EnRes.pdf, accessed 23 June 2009).
- ⁴⁷ See <http://ukerc.rl.ac.uk/ERA002.html> (accessed 23 June 2009).
- ⁴⁸ See <http://www.energytechnologies.co.uk> (accessed 23 June 2009).
- ⁴⁹ Public energy R&D in Germany is coordinated by two ministries (the German Federal Ministry of Economics and Technology (BMWi) and the German Federal Ministry for Education and Research (BMBF)). The main coordinating institutions for public energy R&D is the Juelich Research Center, part of the Helmholtz Society of German Research Centers.
- ⁵⁰ For an English translation of the Renewable Energy Sources Act (updated version of 2004) see http://www.bmu.de/files/pdfs/allgemein/application/pdf/eeg_en.pdf (accessed 5 June 2009).
- ⁵¹ "European Commission proposes a plan to accelerate energy technologies for a low-carbon future," IP/07/1750, 22 November 2007 (accessible at <http://ec.europa.eu/research/index.cfm?pg=newsalert&lg=en&year=2007&na=na-221107>, accessed 2 June 2009).
- ⁵² European Commission (2007), Towards a Low Carbon Future: European Strategic Energy Technology Plan. Memo/07/493, 22 November 2007 and European Commission (2007), Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions: A European Strategic Energy Technology Plan (SET-Plan) – Towards a Low-Carbon Future. COM(2007) 723 final (22 November 2007).
- ⁵³ "(un)-Strategic Energy Technology Plan: Commission Fails to Choose Between Winners and Losers," Greenpeace Press Release, 22 November 2007.
- ⁵⁴ Council of the European Union (2008), Communication of a European Strategic Energy Technology Plan (SET-Plan) "Towards a Low Carbon Future" – Council Conclusions. 6326/1/08 REV1, 28 February 2008.
- ⁵⁵ Council of the European Union (2009), Council Adopts Climate-Energy Legislative Package. 8434/09 (Presse 77), 6 April 2009.
- ⁵⁶ Hillard Huntington and Christine Jojarth (forthcoming), Financing the Future: Investments in Alternative Sources of Energy, in: Andreas Goldthau and Jan Martin Witte (eds.), Global Energy Governance: The New Rules of the Game (Washington, DC: Brookings Press).
- ⁵⁷ Hillard Huntington and Christine Jojarth (forthcoming in 2009), Financing the Future: Investments in Alternative Sources of Energy, in: Andreas Goldthau and Jan Martin Witte (eds.), Global Energy Governance: The New Rules of the Game (Washington, DC: Brookings Press).
- ⁵⁸ See Jim Dooley and Paul Runci (2004), Energy and Carbon Management R&D Policy: Framing Considerations and Recommendations for the National Commission on Energy Policy op. Cit., p.2.
- ⁵⁹ See Gregory F. Nemet and Daniel M. Kammen (2007), US Energy Research and Development: Declining Investment, Increasing Need and the Feasibility of Expansion, op. Cit., p.752.
- ⁶⁰ See also Rachel Griffith (2000), How Important is Business R&D for Economic Growth and Should the Government Subsidize it? Op. Cit. for a discussion of tax incentives.
- ⁶¹ See e.g, Bronwyn Hall and J. van Reenen (1999), How Effective are Fiscal Incentives for R&D? A Review of

the Evidence, in: *Research Policy* 29, pp.449-469.

⁶² See Will Blyth (2008), *Linking carbon markets and technology support mechanisms*, op. Cit., p.8.

⁶³ Based on current consumption and investment patterns, the world will remain hooked on fossil fuels for the foreseeable future. Thus, in addition to renewable energies technologies will have to be found that reconcile that fossil fuel consumption with mitigation targets. There, CCS really is the only game in town.

⁶⁴ IPCC (2005), *Special Report on Carbon Dioxide Capture and Storage – Summary for Policymakers*. Approved in detail at the Eighth Session of IPCC Working Group III (Montreal, Canada, 22-24 September 2005), accessible at http://www.ipcc.ch/pdf/special-reports/srccs/srccs_summaryforpolicymakers.pdf (accessed 29 May 2009), p. 13.

⁶⁵ IEA (2008), *Energy Technology Perspectives 2008* (Paris, IEA).

⁶⁶ IEA (2008), *World Energy Outlook – Executive Summary* (Paris: IEA), p. 14.

⁶⁷ Nicholas Stern (2006), *Stern Review of the Economics of Climate Change*, op. Cit., chapter 24.

⁶⁸ McKinsey & Company (2008), *Carbon Capture & Storage: Assessing the Economics* (McKinsey & Company) (accessible at www.mckinsey.com/client-service/ccsi/pdf/CCS_Assessing_the_Economics.pdf, accessed 1 June 2009).

⁶⁹ Note that there are also still doubts with regard to the overall technical feasibility of introducing CCS at commercial scale, as well as technological risks associated with CCS that could undermine political support of the technology. While the debate about the feasibility and risks of CCS is far from over, in this report we focus on the economic challenges of bringing CCCS to necessary scale, as assumed in many of the mainstream mitigation scenarios.

⁷⁰ Danny Cullenward (2009), *Carbon Capture and Storage: An Assessment of Required Technological Growth Rates and Capital Investments*. Stanford University Program on Energy and Sustainable Development Working Paper #84, May 2009, p.18.

⁷¹ *Ibid.*, p.17.

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