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Linking Technology Development with Emissions Commitments: Exploring Metrics for Effort and Outcome

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Abstract
The challenges involved in establishing technology metrics are intimately tied to the complexity of the technology development process itself. Financial investment in R&D is necessary, but by no means sufficient. Effort must also be invested across a broad spectrum of objectives: building capacity, establishing new institutions, mobilizing political constituencies, creating new classes of assets, opening financing channels, changing behavior among firms and individuals, and leveling the playing field by eliminating subsidies and other policy biases in favor of incumbent technologies. This paper examines metrics, and the analytical tools that could be used to measure them. Five general categories of policies that could induce technology change – technology development, technology deployment, international technology cooperation and transfer, and (the reform of) fossil fuel subsidies, and direct environmental policy – are analyzed and compared. Case studies are investigated for all but the last category, given the technology focus of this paper and more considerable treatment of cap-and-trade, tax, and other direct environment policies in the literature and in climate negotiations to date.

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EXECUTIVE SUMMARY

Ever more widely, technological change, and policies that can induce it, are viewed as the key ingredients for tackling the climate problem. Some argue that the limitations of known technologies call for a long-term focus on technologies that have yet to be developed, commercialized, or perhaps even conceptualized (Hoffert et al, 2002). Others argue that currently available or near-commercial technologies can address much of the global emissions challenge for the next 50 years, pointing to the IPCC Third Assessment Report's finding that "known technological options could achieve a broad range of atmospheric stabilization levels" (Pacala and Socolow, 2004; Swart et al, 2003; O'Neill et al, 2003). The distinction between long-term technologies and known, existing technologies has important implications for climate policy, and in particular, for policies to induce technological change.[1] However, it can be safely said that there is a consensus within the climate research community − as well as among a growing set of policymakers − that the climate challenge demands an ambitious combination of the two: deployment and diffusion of known, cost-competitive technologies in the near-term, and innovation and development of new technologies for the longer-term.

Actors across the climate debate are thus calling for long-term technology development to be fundamentally integrated into a new international regime. Since climate is a global commons problem, the confidence-building associated with negotiating reciprocal national technology efforts offers the promise of greater effectiveness than individual, disparate, uncoordinated activities. Just as this is true of reduction commitments, it is no less true of technology activities. At present, however, technology innovation, and particularly, technology RD&D, transfer, and cooperation, falls largely between the cracks of existing international agreements, despite existing efforts within and outside the UN Framework Convention on Climate Change (UNFCCC), such as the Global Environmental Facility (GEF), the Expert Group on Technology Transfer, and the newer, Asia-Pacific Partnership on Clean Development and Climate (AP6). The shape of a future international climate regime, and specifically whether and how technology development and diffusion efforts would fit into it, remains an open question.

Technology could be incorporated into future, international climate agreements in a number of ways. At one end of the spectrum are enhanced requirements for reporting technology-related activities and accomplishments, for instance, in more detailed and consistent National Communications submitted under the UNFCCC. At the other end of the spectrum would be

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[1] Economic analysis published over a decade ago (Wigley, Reilly, and Edmonds, 1996) has often been cited in support of a long-term technology focus, since modeling results suggested that a delay in emissions reduction efforts would reduce the costs of achieving a given climate stabilization target, owing to autonomous technological change and the inertia of long-lived capital stock. Such findings spurred a wide debate about whether such models adequately account for endogenous technological change and for lock-in phenomena. Similarly, significant differences of viewpoint remain regarding the efficacy of various policies to induce technological change – from efforts to establish a long-term carbon price signal to direct investment in R&D, and new tools and insights are emerging from an economics literature increasingly focused on the question of induced technology change. Recent papers suggest that improved representation of technology change dynamics leads to much lower estimates of costs (Barker et al, 2006; Vollebergh and Kemfert, 2005) and that both top-down and bottom-up model results argue for value of near-term action (Wing, 2006).

explicit, quantified, obligations to advance technologies that are every bit as substantive and legally-binding as the Kyoto-style emission targets.

Some observers suggest that in a post-2012 framework parties could participate in a differentiated manner across a parallel "tracks" that might include technology development and transfer alongside mitigation targets and timetables, adaptation, and other tracks (Pew, 2005; Blok et al, 2005). In a differentiated framework, party A, for example, might expend greater effort on technology deployment policies to meet near-term quantified emission reduction targets, while party B might focus more heavily on technology research and development aimed at long-term reductions.

For any approach to incorporating technology into international agreements, it will be necessary to establish methods and *metrics* for providing credible substantiation of technology activities. Such metrics could reflect the *effort* invested or the *outcomes* achieved by technology policies or initiatives (Philibert, 2005). Effort metrics can be more closely linked with the goal of fairness among parties, while outcome metrics relate more directly to the goal of adequacy in addressing the climate problem. Metrics for effort could be as simple and straightforward as (incremental changes in) climate mitigation technology R&D or deployment expenditures, or as complex and challenging as the social costs of a carbon cap or tax. Metrics for outcome could include near-term and long-term cumulative emission reductions, or cost reductions and increased penetration of selected technologies, which require attribution and verification methodologies (if measured ex post), or hypothesized relationships or models (if estimated ex ante). Regardless of the metrics chosen, they would benefit from rigorous, quantitative *analysis* based on empirical evidence or common methodologies in order to be meaningfully compared across countries.

Metrics that enable technology actions to be compared could therefore become an essential element in a future regime where nations undertake obligations and/or actions of greatly varying types. The UNFCCC has committed nations to protect the climate "on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities."[2] By allowing actions to be assessed in terms of comparable indicators, for example net emission reductions or incremental expenditures per unit of GDP or per capita, metrics could help to establish a sense of fairness and build confidence that parties are participating according to their respective obligations, in terms of effort, outcome, or both. The development and analysis of comparison metrics has thus far received limited attention, but that is beginning to change, in part a reflection of a growing sense that a pluralistic climate policy regime could emerge in the post-2012 period (Natsource, 2003; Philibert, 2005).

The challenges involved in establishing technology metrics are intimately tied to the complexity of the technology development process itself. As many have noted, the advancement of technology is comprised of multiple steps and conducted by numerous actors. Financial investment in R&D is necessary, but by no means sufficient. Effort must also be invested across a broad spectrum of objectives: building capacity, establishing new institutions, mobilizing political constituencies, creating new classes of assets, opening financing channels, changing

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[2] Article 3, UNFCCC.

behavior among firms and individuals, and leveling the playing field by eliminating subsidies and other policy biases in favor of incumbent technologies (Grubb, 2005; Brooks et al, 2004; Milford; Grubb, 2005; Alic et al, 2003).

This paper examines metrics, and the analytical tools that could be used to measure them. Five general categories of policies that could induce technology change – technology development, technology deployment, international technology cooperation and transfer, and (the reform of) fossil fuel subsidies, and direct environmental policy – are analyzed and compared, as indicated in Table ES-1.[3] Case studies are investigated for all but the last category, given the technology focus of this paper and more considerable treatment of cap-and-trade, tax, and other direct environment policies in the literature and in climate negotiations to date.

Table ES-1. Application of metrics to case studies in five policy categories *(italics indicate items not analyzed quantitatively here)*

	Technology Development	**Technology Deployment**	**International Technology Cooperation and Transfer**	**GHG Intensive Policies**	***Direct Environmental Policy***
Ex post analysis of implemented policies	National R&D programs	Renewable energy incentives and requirements	Global Environment Facility support	Subsidies for fossil fuel production and/ or consumption	*EU ETS (Phase I)*
Ex ante analysis of policies in the future	3-fold scale-up of national R&D budgets	Renewable energy targets for 2010	Asia-Pacific Partnership (AP6)	*Subsidy removal*	*EU ETS (Phase 2) Future binding targets*
Metrics: Effort	• Direct Government R&D spending or subsidies • *Net economic impact (return on investment, "crowd out")* • *Indirect and non-federal support* • *Private R&D spending* • *In-kind contributions*	• Government expenditures • Direct cost impacts • *Net (macro) economic impact*	• Government contributions to program • *Net economic impact* • *In-kind contributions* • *Other (technology sharing agreements, intellectual property right support)*	• Subsidy levels • *Net economic impact of subsidy (removal)*	• *Direct expenditures (Program administrative and transaction costs)* • *Net economic impact of achieving targets*
Metrics: Outcome	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• *Realized (or potential) emissions reductions or increases*	• *Realized (or potential) emissions reductions*

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[3] This paper focuses largely on metrics for policies and actions that promote technology development and change, since this represents an area of substantial difference in government perspectives and academic viewpoint. This difference is exemplified by the Asia-Pacific Partnership on Clean Development and Climate (AP6), "a new effort to accelerate the development and deployment of clean energy technologies" outside the UN-based climate negotiations. While officially portrayed as not representing an alternative to the Kyoto Protocol and its emission reduction targets and timetables, the AP6 initiative is widely viewed as a reflection of fundamental preference among its partner countries for technology-oriented, sector-specific, incentive-based solutions as compared with economy-wide emission controls. http://www.dfat.gov.au/environment/climate/050728_final_vision_statement.html

Technology development: Public energy research and development budgets in OECD totaled over $9 billion in 2004. Though public spending on R&D for GHG mitigation technologies provides an incomplete picture of national technology development efforts – it fails to reflect, for example, private sector and hard to monetize efforts such as the sharing of intellectual property rights) – it offers the advantage of regular international reporting over many years. While they still lack sufficient robustness and consistency to be used for rigorous comparisons, International Energy Agency R&D data can still be used to make some general comparisons, and to illustrate how effort metrics might be applied, as shown in Figures ES-1 and ES-2.

Figure ES-1. Per GDP public energy R&D budgets, 2004

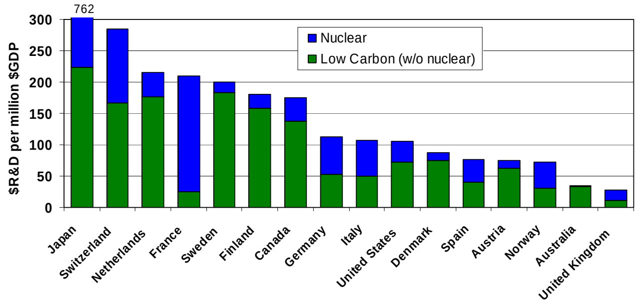
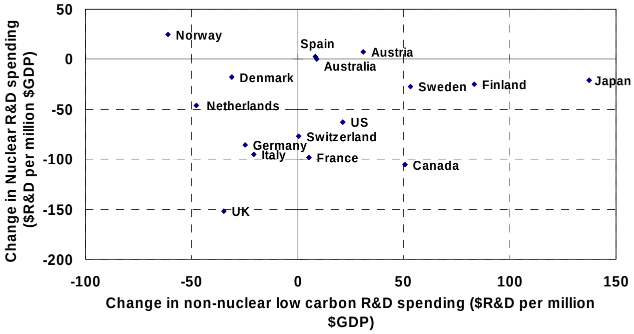


Figure ES-2. Changes in public R&D spending, 2004 vs. 1990



Source: IEA, 2006; IEA, 2004; USDOE, 2005

Figure ES-1 shows the wide disparity among countries in terms of national R&D budgets (on a per GDP basis) in what might be roughly categorized as low carbon technologies. The rationale for these levels of investment − which span more than thirty-fold difference (between Japan and the United Kingdom) vary: for instance, Japan's import dependence and goal of energy security accounts for its intensive non-fossil fuel R&D. A similar rationale underlies France's ongoing nuclear investment. While the comparisons are informative, they suffer from limitations in the underlying data: countries do not necessarily report to the IEA in a consistent manner, and the ability to categorize R&D investments as "low carbon" is hampered by inadequate dis-aggregation (e.g. Norway's significant investments in carbon capture and storage do not show here) as well as fundamental uncertainties on what technologies might ultimately reduce emissions (e.g. hydrogen). Furthermore, different policies can shift the expenditure burden from the government to private actors (or vice-versa); for example, private sector R&D can be leveraged through tax credits or matching funds, achieving higher technology investment levels than R&D budgets might indicate. Nonetheless, even using existing, flawed data, the types of cross-country comparisons shown above may be useful for illuminating trends, informing international negotiations, and − to the extent they provide misleading perceptions − could help to stimulate cooperation in improving data collection and reporting. With this in mind, initiatives underway at the IEA and elsewhere to improve the consistency, accuracy, and disaggregation of R&D data should be strongly supported.

This case study also raises a number of issues that recur across metrics, including the appropriateness of expenditure as a proxy for effort, the "additionality" of effort and outcome, and the choice of denominator. With respect to the latter, figures shown here index effort to GDP, since economic output can reflect of ability to pay, but R&D efforts could also be indexed to population or historical or current emissions (as a proxy for responsibility to mitigate). Ultimately, this choice will be informed by the agreed principles upon which climate agreements are made.

Similarly, the importance of establishing the additionality of effort and outcome – i.e. whether they would have occurred regardless of specific actions to reduce GHG mitigation – is largely a question for negotiators to resolve. Figure ES-2 presents changes in nuclear and other low-carbon R&D budgets against a 1990 baseline, similar to the approach implicitly used in the Kyoto Protocol to address additionality. It also faces similar problems here: the potential for 1990 to be non-representative year, and other non-climate factors that could influence trends since 1990. For instance, Japan, which exhibited the largest increase in low-carbon R&D budgets in Figure ES-2, doubled its overall energy R&D in part as a stimulus to its stagnant economy in the 1990s. That said, use of an historical marker year, perhaps adjusted for spurious factors, represents one of the more objective means to benchmark what might be considered "additional" climate effort or outcome.

Turning to technology development outcomes, the US National Research Council conducted one of the most comprehensive *ex post* assessment of R&D programs ever completed (NRC, 2001). The NRC analyzed specific technology research programs in terms of their *realized benefits* that are "almost certain", *option benefits* that could result if economic and policy conditions become more favorable, and *knowledge benefits,* other advances in understanding from R&D that has not (yet) succeeded. The NRC used relatively crude methods to ascribe realized benefits in terms of GHG emissions reductions to specific R&D programs, such as the fluorescent ballast (45 million tons CO2 cumulative) and integrated gasification combined cycle (IGCC, 48 million tons CO2 cumulative) programs. However, as the NRC itself notes, over time, the options and knowledge benefits of R&D activities will likely overwhelm any currently realized ones. Indeed since the time of the NRC's study, the economic and policy conditions have become considerably more favorable to IGCC investment and the amount of proposed new IGCC capacity has increased by an order of magnitude since 2001; what was an option benefit just 6 years ago may soon become a realized one.

A number of bottom up and top down models can be used estimate option benefits, by projecting future outcomes from R&D investment *ex ante* subject to market conditions, competing technologies, and policy variables. For this paper, we use the POLES model[4] to assess the impacts of a three-fold scale up in OECD government R&D budgets in the coming two decades, on the scale of recommendations by various policymakers and researchers (NCEP, 2003; Kammen and Nemet, 2005).

Figure ES-2 presents the results under three scenarios, distinguished by global emphasis on action to address climate change: a *limited action* (LimAct) scenario that presumes slow and

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[4] The POLES model incorporates the dynamics of induced technology change in a bottom-up energy system model through detailed two-factor learning curves that translate cumulative production (learning-by-doing) and R&D investment (learning-by-researching) into technology cost reductions based on historical relationships.

weak interventions (Annex I carbon price of 30€/tCO2 by 2050), an *action* scenario that presumes significant societal pressure and political will to address climate change (Annex I carbon price of 130€/tCO2 by 2050), and a *delayed action* scenario, that posits slower but eventually more significant action. These modeling results suggest that the overall emissions reductions available from R&D investment in known technologies, shown by the dotted lines, are relatively limited in comparison with the emissions reductions induced by the varying price signals shown here. However, such findings are subject to large uncertainty; the projected outcomes depend heavily on model choice, key assumptions, and a multitude of parameters (e.g. learning rates) that are not necessarily well understood.

Figure ES-2. Global Energy-related CO2 Emissions, 2001-2050, by Scenario

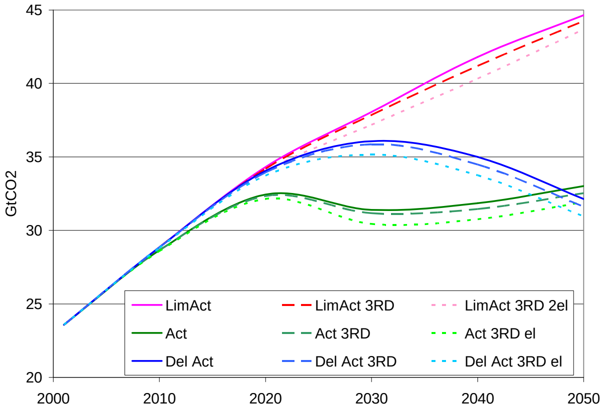
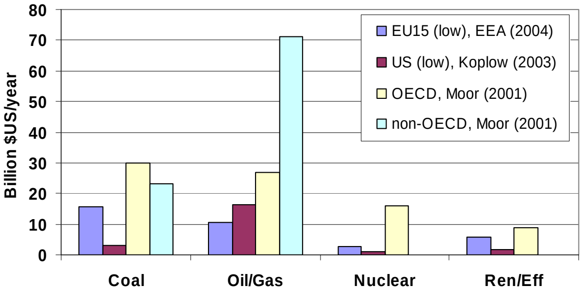


Figure ES-3. Estimates of energy subsidies, various sources[5]



As noted in Chapter 3, with further refinements, better empirical grounding, and integration of top-down and bottom-up model strengths, models could prove well-suited to reflecting incremental changes in "known technologies". However, they are likely to remain hard-pressed to anticipate the more radical changes in technological systems and techno-economic paradigms (as witnessed in the classic example of stage coaches to railways) that might ultimately deliver deep emission reductions.

Technology deployment: A brief analysis of OECD renewable energy policies, such as renewable electricity obligations, tax credits, and feed-in tariffs, suggests, not surprisingly, that development and assessment of metrics for technology deployment and diffusion is more tractable than for R&D investment. Incremental costs and emission reductions can be calculated for much of the OECD, based on available reports (see Table 7). However, significant work is needed for consistent estimates and robust methodologies for attributing increased technology penetration to specific policies. Furthermore, the incremental costs associated with technology mandates such as renewable obligations are not directly comparable to subsidies (like a feed-in tariff) or foregone tax revenue (for a production tax credit), which may correspond in part to

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[5] Both US and EU are "low" estimates by study authors. Estimates do not include government R&D spending. US estimates include $12 billion in defense-related costs for security oil supplies.

transfer payments rather than overall social costs. Nonetheless, simply compiling and comparing the estimated impacts of technology deployment policies using consistent methodologies, whether for renewable energy or other emission-reducing technologies (efficiency, biofuels, fuel switching, etc.), as with R&D metrics above, could help to spur improved analysis and reporting, inform policy makers, and build trust within international negotiations.

International cooperation: Of all categories of action considered here, international technology cooperation and transfer is perhaps the least amenable of all to metrics and quantification of effort and outcome. In spite of the popularity and abundance of such initiatives, while estimates of total contributions by different parties can be found, evaluations of impacts and outcomes are scarce, for reasons that are not altogether surprising: the limited scale of many existing efforts, their frequent focus on capacity-building and assessment activities (e.g. the Climate Technology Initiative), and delicateness of important intellectual property rights issues. Nonetheless, emissions reduction outcomes have been estimated for two particular cases, the well-established GEF climate change portfolio and the nascent AP6 initiative. However from the two cases examined, and their reliance on rather speculative or optimistic assumptions, it is clear that more methodological work would be needed to if consistent, if not robust, outcome metrics were desired.

Given these limitations, it might be preferable to consider effort rather than outcome metrics for international technology cooperation and transfer activities. Much like R&D data compiled by IEA, national budget reporting could provide expenditure information to enable metrics for effort on international climate technology cooperation, however, reporting standards would need to be developed and agreed upon. An alternative approach, which would sidestep the challenges of developing a common reporting standard, would be to focus on efforts that are conducted through specific internationally vetted channels, such as those directed through common global climate technology programs such as the GEF.

GHG-intensive Policies: The final case study considers the scale and impact of fossil fuel subsidies. These are not generally categorized as mitigation activities, even though they may significantly exceed all of the other policies considered here in terms of public expenditures as well as emissions impact (see Figure ES-3 and Table ES-2). An assessment of current subsidies and their reform would arguably be an important component of any meaningful comparison of national climate policies. These policies inhibit technology change away from incumbent fossil fuel technologies. Quantitative assessment of subsidy efforts and outcomes would require significant advances in the transparency of subsidy policies and in the estimation of their impacts, as well as common agreement on what constitutes a subsidy and what efforts are associated with their reform. A handful of studies provide order-of-magnitude guidance on likely subsidy reform impacts or outcomes (Pearce, 2003; Pershing and Mackenzie, 2004). This area of research deserves further attention, and would enable subsidies and their reform to be considered alongside other initiatives to promote technology change.

Table ES-2. Comparative Effort (incremental costs, subsidies, and expenditures) by policy type ($US/million 2004 $US GDP), selected countries, annual

	Technology Development	**Technology Deployment**		**Int. Technology Coop & Transfer**	**GHG Intensive Policies**
	Public R&D for low-carbon technologies* (2004)	Renewable Electricity Deployment (2001/3)	Renewable Electricity Deployment (2010)	GEF climate change contributions (2002-2006)**	Subsidies for Fossil Fuels (current)
	Expenditure (ex post)	*Incremental cost (ex post)*	*Incremental cost (ex ante)*	*Expenditure (ex post)*	*Various*** (ex post)*
EU15	50	350	1200	6	2100
Australia	30		500	3	
Japan	220		60	6	
US	70	2	100	2	1700

Conclusions: Overall, establishing accepted metrics for technology effort or outcome could have significant value even if these metrics can be neither robust nor comprehensive and comparable. The quantification apparatus in place now (e.g., R&D budget surveys, technology development modeling tools) provides rough indicators of some aspects of effort and outcomes that can be employed for coarse assessments in support of reporting on general, non-quantitative technology-related commitments (such as for National Communications). They may provide a basis upon which fairness and adequacy can be *more* objectively judged. Further clarification of metrics and common methods to measure and compare national/regional contributions can bring greater rigor and comparability across national and regional initiatives, and help to establish common ground for future negotiations. They can provide a level of credibility and rigor often missing from claims of efforts expended or attendant outcomes. As such, they are an important area for further inquiry.

There are some aspects of climate technology development that may be amenable to quantification once additional progress is made on data gathering, methodologies, and common reporting protocols. Public sector investment in R&D is one such aspect. Another may be the (near-term) outcomes of certain straightforward environmental policies such as renewable obligations. Certain other aspects of technology development might be amenable to quantification if there is not only progress on data, methodologies, and protocols, but also substantial improvements in transparency. Fossil fuel subsidies fall into this category.

Yet other aspects appear to be too rife with uncertainties and subjective decisions to be amenable to rigorous quantification. For instance, ex ante assessment of the long-term impacts of R&D is questionable, owing to the inherently uncertain nature of technology R&D. The more intangible benefits of R&D (option benefits and knowledge benefits) often greatly exceed the concrete (realized) benefits, but quantifying those benefits requires scenario analysis, assumptions, and subjective decisions. Attempts to quantify those intangible impacts can be interesting, indicative exercises, but cannot be considered definitive predictions of future impacts.

The immature stage of development of effort and outcome metrics has important implications for the design of future climate regimes. At least for the post-2012 framework discussion, an international framework built upon a notion of differentiated investment by parties across "tracks", with Party A investing more heavily in technology development and Party B more heavily in emissions reductions, cannot (yet) be underpinned by rigorous and defensible metrics. Lacking credible effort or outcome metrics, Party A will find it difficult to demonstrate its contribution to the global mitigation effort, and others will be less likely to perceive Party A as earnestly taking part in a global regime of reciprocal obligations. Lacking credible outcome metrics, it will be difficult to assess the impacts of Party A's activities and the overall effectiveness of the climate regime.

Ultimately, even if the goal of rigorous quantification in support of strict tradability is out of reach, there is still much to be gained from further development of metrics and approaches for their quantification. Technological transitions are a critical part of the climate problem, and any steps that help Parties more credibly demonstrate the efforts they are making and the outcomes they are achieving will help to build trust, instill confidence, and motivate more resolute action toward solving the climate problem.

1. INTRODUCTION

1.1 Why focus on technology?

The International Symposium on Stabilisation of Greenhouse Gases, convened in 2005 by UK Prime Minister Tony Blair and widely followed in the international press, came to some sobering conclusions. Recent analysis now suggests that an atmospheric concentration target often considered as politically and technically achievable – 550 ppm CO2 – would likely be insufficient to meet the European Union's official goal of limiting warming to 2 degrees Centigrade. Various greenhouse gas (GHG) emission pathways could still limit warming to 2 degrees C. Such pathways will require very deep long-term emission reductions, along with substantial near-term actions to begin the transition towards a low-GHG future. As the Symposium's Steering Committee noted, "if action to reduce emissions is delayed by 20 years, rates of emission reduction may need to be 3 to 7 times greater to meet the same temperature target."[6]

The EU released its climate policy several weeks after the Symposium, and in doing so, was careful not to specify emissions targets and timetables for the post-2012 period, nor to suggest a long-term global strategy for achieving the 2 degree goal. The EU position recognizes the need to engage the large "non-Kyoto" emitters – i.e. those without binding commitments, such as the US, India, China, and Brazil – in a common agreement. It acknowledges the inherent resistance of countries with high rates of emissions growth, with other development priorities, or with large fossil fuel lobbies, which express concern over binding emissions targets that, they claim, would constrain economic growth, impose competitive disadvantages, or, in the perspective of developing countries, would inequitably assign emissions rights to industrialized countries.[7] Though these countries' positions on climate policy issues vary considerably, they all emphasize the need for technology development and technology transfer. Whether for near-term reductions based on commercial technologies, or for deep long-term reductions based on technologies not yet developed, there is broad agreement that limiting climate change will entails a fundamental technological transformation.

In countless workshops and white papers, considerable thought has been directed to overcoming this climate policy "logjam". The logjam has two key dimensions: the near-term process and the long-term framework. While a more inclusive and effective near-term process would restore the momentum to global efforts to tackle the climate change problem, a long-term framework is ultimately required to achieve a 2 degree C or other climate stabilization goal. Thus far, the Kyoto Protocol has provided a largely near-term process focused on near-term actions and emissions commitments. In contrast, numerous long-term climate stabilization frameworks have been proposed, but none yet appears ready for widespread agreement. Furthermore, the fora for

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[6] International symposium on the stabilisation of greenhouse gases Hadley Centre, Met Office, Exeter, UK 1-3 February 2005, Report of the Steering Committee. http://www.stabilisation2005.com/Steering_Commitee_Report.pdf

[7] Most proposed target and timetables are based on reductions relative to recent emissions levels (e.g. 1990), thereby ignoring the larger, cumulative contributions of industrialized countries to atmospheric concentrations and temperature change.

international negotiations on climate change policy have multiplied; for over a decade following its signing in the 1992, the UNFCCC provided the single, dominant framework for all parties; now the landscape has changed, with a shifting set of parallel conversations and initiatives with widely varying and often overlapping participants: (Kyoto, UNFCCC, Asia Pacific, Gleneagles, G8+5, local action).

For several reasons, an approach to climate agreements that more effectively supports, and provides explicit credit for, technology development and transfer efforts may provide important tool for breaking through the climate negotiation logjam. From a purely strategic standpoint, such an approach plays to the professed concerns and apparent interests of the large emitters currently outside the Kyoto process of binding commitments. Widening the negotiation space to more explicitly account for technology investment and progress might help bring the large emitters to the bargaining table, and get the near-term process back on track. Moreover, greater emphasis on technology, and more broadly on infrastructure development such as transit-oriented urban design, may be essential to any successful long-term framework for climate stabilization. As currently construed, targets, timetables, and trading, especially if limited to five-year commitment periods are unlikely to send strong, long-term market signals, and could thus fail to spur the technology innovation and change needed to achieve a 2 degree stabilization goal.

Put another way, the Kyoto Protocol may lead to carbon prices of up to €10-30/tCO2eq over the next decade, but these prices are unlikely to provide sufficient “pull” for technologies like carbon capture and storage, hydrogen and electric vehicles, solar photovoltaics, advanced urban design, and other technologies that might be ultimately necessary for deep emissions reductions. Arguably, technology change commensurate with the climate challenge will also require a major “push” through research and development (R&D) as well as market creation, far exceeding today’s levels. This conclusion comes as no surprise to many who have looked at this question in both academic and policy circles.[8] Indeed, the Asia-Pacific Partnership on Clean Development and Climate (AP6), the Gleneagles G8 Plan of Action, and ongoing discussions within the international climate negotiations, have all placed technology cooperation and development at the fore of efforts to combat climate change.[9] These indications suggest that a post-2012 climate framework may, for political as well as practical necessity, place technology development and transfer in a more central role, as a complement to Kyoto-style binding emissions commitments.

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[8] It is generally accepted that the private sector historically under-invests in long-term R&D, because technology development is risky and expensive and private firms are unable to internalize all the benefits of technological advances, even in markets with extensive protections of intellectual property rights. These challenges are particularly acute for the energy sector, due to increased deregulation and privatization as well as the limited scope for product differentiation that drives much private R&D: unlike pharmaceuticals or information technology where new drugs and devices can stimulate new demand, electricity and fuels are relatively undifferentiated products. (Schock et al, 1999; Margolis and Kammen, 1999; Grubb, 2005)

[9] http://www.dfat.gov.au/environment/climate/ap6/charter.html ; www.iea.org/G8/index.asp

1.2 Which technologies and how to spur them?

While there appears to be broad agreement that new initiatives to spur further technology development are critical to progress in combating climate change, important differences of viewpoint remain. Should technology and climate change policies target the development and deployment of existing technologies to reduce emissions over the next few decades, or "breakthrough technologies" for the longer-term? Do path dependency, the possibility of future technology breakthroughs, and the perceived cost of rapid action argue for placing more emphasis on developing big, potential long-term solutions compared with near-term emission reduction actions? Or should the immediate emphasis instead be on implementing ambitious climate policies and deploying known technologies in order to avoid locking-in emissions intensive infrastructure and maintaining a greater likelihood that climate stabilization targets can be met?

This dichotomy, played out in both academic literature and policy positions, as described in Box 1, has perhaps been overstated. The past 10 years have witnessed a fundamental shift in energy-economic modeling, towards one that explicitly incorporates induced technological change and suggests the long-term returns of near-term policy actions (Vollebergh and Kemfert, 2005.) Rather than representing an alternative to long-term technologies, investing in deployment of near-term, more known technologies can in fact enable a more profound long-term technological transformation to unfold. As noted by a recent US Congressional Budget Office (2006) review of modeling analyses, "near-term reductions in emissions could allow time for fundamentally new technologies to be developed and put in place." (p.18)

In addition to the question of *which technologies*, the question of *which policy instruments* would be most effective and efficient at stimulating technological change. Nearly all climate mitigation strategies will induce technology change to some extent, however, economists and technology specialists hold a range of perspectives on the most efficient and effective policies, as illustrated in Box 1. Environmental regulation has been claimed to accomplish both ends. The much debated Porter hypothesis contends that regulation creates first mover advantage, enabling firms to find solutions that, given their bounded rationality, they would not have otherwise detected (Jaffe et al, 2003). In looking at a case study of technology forcing with catalytic converters, Gerard and Lave (2005) found that models of behavior show that private firms are more likely to invest in R&D in the face of: competitive pressures or credible regulation where enforcement of standards is viewed as probable. However, as Jaffe et al. (2005) note, economists tend to view such case studies as selective, and argue instead that hidden costs are significant, and inefficient regulation often stifles innovation.

Goulder (2004) maintains that the promise of a long-term price or market signal via emissions commitments and cap and trade systems will effectively induce innovation, and that by indicating their intentions to establish deeper targets (higher carbon prices) in the future, governments would spur research and development in low GHG technologies. Wilcoxen and McKibben (2006) argue further that the prospect such mechanisms for the long-term will create new classes of assets and new incumbent interests and political constituencies to capitalize on them. Such logic might seem self-evident: long-term investments require long-term signals.

However, the incentive carried by the prospect of a rising cost of carbon may not be sufficient. Montgomery and Smith (2005) contend that emission reduction commitments (or carbon taxes) announced for the long-term, lack credibility among investors and developers of low-carbon technology; simply put, national politics can change over time. They go so far as to suggest that such long-term government signals could deter investment in innovation, as industries might expect future governments to appropriate the economic rents generated by advances in low-GHG technologies; they cite the provision of AIDS medications at cost to developing countries as an example.[10] Barrett (2003) argues that the binding emissions reduction commitments as found in the Kyoto Protocol – the price-signaling instrument most commonly assumed feasible at the international level – will be undermined by the pervasive incentive to free ride on others' mitigation efforts and to avoid costly actions that risk competitive disadvantage. Barrett goes back to the need for immediate signals in the form of technology standards as a means to promote technological change while limiting free ridership.[11] Brooks, Milford, and Schumacher (2004) agree that the incentive corresponding to an internalized cost of carbon may be too blunt a tool. They argue that an analysis of historical pattern of technology turnover reveals "the transition to a new technology is rarely driven by cost. Most often, the new technologies are more expensive, but they possess new, unique qualities demanded by the marketplace."

Whether one views these critiques of long-term frameworks for emission reduction commitments as credible or not, there is little question that technology change presents an imperative challenge for international collective action to further a global public good. Ultimately, no single policy is likely to be sufficient for successful technology development. Just as renewable energy technologies have evolved as the result of a series of often overlapping policies designed to stimulate innovation, create markets, and enable experimentation (IEA, 2004), a multiplicity of policies will surely be needed to develop and diffuse a full complement of climate mitigation technologies (Gallagher, Holdren, Sagar, 2006). The technology innovation process is complex and non-linear and requires catalytic and intermediary actions. The wide gap between technology creation (from the RD&D "push) and real market adoption (created by market "pull" efforts) must be spanned by barrier removal, market creation, and other intermediary activities in order for technological transformations to occur (Milford and Schumacher, 2004; Alic et al, 2003, Sagar and van der Zwaan, 2006). Sanden and Azar (2005) articulate a "two-pronged strategy" that calls upon price incentives to bring cost-competitive technologies to market, alongside complementary technology policies for advanced, pre-commercial technologies. In a similar vein, Jaffe et al (2005) note that "technology policy can be a costly approach, however, if it is used as a substitute for, rather than complement to, environmental policy."[12] If these and other authors (Goulder, 2004; CBO, 2006) are on target in this respect, a key challenge for future

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[10] They suggest instead a focus on R&D successes through consortia, grants, or prizes, before any price or quantity instruments for GHG control are considered.

[11] Viewing the climate change mitigation challenge largely as a classic "prisoner's dilemma", however, represents a rather jaundiced view of human nature, albeit rooted (in Barrett's case) in a review of experience with international environment agreements. Furthermore, a compelling framework for international technology standards has yet to be articulated. Indeed, R&D and standards, if voluntary as suggested, could be subject to free riders just as international emission commitments could be.

[12] p.169

climate frameworks is thus to ensure that these two types of policies are treated as complements and not substitutes.

1.3 Implications of a diverse, multi-track approach to international climate agreements

Several observers suggest that the way forward, post-2012, could involve differentiated actions and commitments depending on national circumstances and preferences, with some industrialized countries leaning more heavily on a technology approach (R&D, international cooperation, standards), others more heavily on a quantified emission reduction targets or policies.

A single, common framework across key countries and/or sectors, whether a harmonized carbon tax or emission cap, allocation, and trade system, is commonly viewed by economists as the "first best" solution to address climate change in an economically-efficient manner. It could provide the clear, internationally harmonized price signal that Goulder and other argue is essential for long-term technology development. It could also be designed in a manner to address fairness and equity, for example, using a global development rights, historical responsibility, and/or convergence approaches (Athanasiou, Baer, and Kartha, 2006). However, experience suggests that, international negotiations may not deliver such first-best solutions for years to come (Pizer, 2007).

Instead, for better or worse, international climate negotiations might be headed towards a system of overlapping, competing, and occasionally linked systems and initiatives. Indeed, when senior policymakers and stakeholders from 15 countries met as part of the Pew Climate Dialogue over the course of 2005, they came to the conclusion that:

> "Multiple approaches could be pursued in parallel as different groups of countries engage with one another along different tracks… [targets and trading; sectoral approaches; policy-based approaches; technology cooperation; and adaptation] But an ad hoc assemblage of initiatives may not produce an overall effort that is sufficiently timely or robust. A more integrated approach could produce a stronger outcome. **By linking and negotiating across tracks**, governments may arrive at an arrangement flexible enough to accommodate different approaches and reciprocal enough to achieve higher levels of effort (Pew Center on Global Climate Change, 2005, p. 3)." [emphasis added]

Such an approach, if pursued, raises a central question for future negotiations: How can one "link and negotiate across tracks"?[13] It "could take the form of sequential bargaining" (p. 19 Pew, 2005), reminiscent of the pledge-and-review process widely discussed, and ultimately rejected, in the run up to Framework Convention (Grubb and Steen, 1992). If it could produce an agreement that is broadly considered as fair, this type of negotiated, integrated approach could produce a result that is better than independent, disparate, and unharmonized activities undertaken by individual nations.

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[13] The parallel tracks suggested in this report include: targets and trading; sectoral approaches; policy-based approaches; technology cooperation; and adaptation.

Given the potentially disparate mix of actions across countries – ranging from technology R&D to specific emissions reduction targets – evaluating fairness and effectiveness becomes a major challenge for analysts and negotiators, perhaps even more complex than the evaluation and negotiation tasks under a Kyoto-style, quantified emission reduction agreement. Indeed, as the Dialogue report notes, perceived "fairness" is essential and requires "assess[ing] relative levels of effort."(Pew, 2005, p. 20) Comparing proposals "requires each party… have strong and independent analytical capacity". A multi-tracked approach would appear to require clear metrics to compare across policy tracks (e.g. technology and targets and trading), as well as the means to evaluate them.

Unfortunately, to date the question of metrics for comparing disparate national actions has received scant attention in the literature (Philibert, 2005; Natsource, 2003), despite the fact that the usefulness of such quantitative assessment has been identified.

A recent EU report (Blok et al, 2005) notes that technology approaches could be treated in any of three different ways in any future climate agreement:

- A climate technology agreement separate from agreement on other climate elements (goals, targets and trading, adaptation)
- One comprehensive climate agreement, technology treated as a parallel "non-tradable" element
- One comprehensive climate agreement, technology is "tradable" with other elements

Historically, international negotiations have tended to approach technology in one of the first two ways. The ongoing AP6 and perhaps the G8/Gleneagles process as well are variants of the first approach: discussions aiming towards technology agreements separate from the ongoing UNFCCC process. The second approach is embodied in the UNFCCC agreement itself, with its parallel articles and activities (e.g. Article 4.5 and the Expert Group on Technology Transfer).[14] It is the third "tradable" option that is the focus of this paper, as it could provide the means to "break the logjam" and enable different parties to place different emphases on technology development and deployment activities.[15] Or it could be that such "tradability" or integration of a technology approach is simply too complex and intractable for the international climate process, and that it would bog down already complex negotiations (Viellefosse, 2005). Indeed, by attempting to develop metrics that could be used for integration of technology efforts such as R&D as a fungible element of a climate protocol, this research aims to further inform the choice among the above three core options.

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[14] Article 4.5 states that "[t]he developed country Partners…shall take all practicable steps to promote, facilitate and finance as appropriate, the transfer of, or access to, environmentally sound technologies to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention."

[15] The ultimate "tradability" scheme between development and deployment would be to assign a century-long budget to each country and to allow unlimited banking and borrowing, which would theoretically internalize the incentives long-term R&D (ignoring factors such as high private discount rates and the credibility of long-term commitments).

1.4 Goals and structure of this paper

This research was motivated by interest in exploring possible equivalence between R&D and emissions commitments. The original goal was to develop and utilize an analytical framework to assess the relative contributions of different strategies, e.g. one party investing in technology RD&D and cooperation and another adhering to emissions targets and timetables. Armed with acceptable methods to estimate equivalence, the thinking goes, negotiators could reckon and adjust their strategies so that an equitable yet differentiated solution could emerge. Put another way, it might enable a climate agreement whereby some countries might contribute more in terms of longer-term technology development and others more in terms of technology deployment to realize near-term emissions reductions.

Suspending judgment on whether such a differentiated approach would be desirable, this paper now explores a prior question. Are the building blocks for such an agreement – ways to compare and evaluate equivalence of different types of climate actions – in fact feasible? In particular, it seeks to:

- Develop and evaluate possible frameworks for integrating technology development and deployment in future climate agreements through the use of comparison metrics for effort and outcome;
- Investigate how such comparison metrics might be applied in a number of illustrative cases, associated with technology development (e.g. government R&D programs), technology deployment (e.g. renewable energy incentives and requirements), and international technology collaboration, among other types of climate policy interventions.

A key premise of this paper is that the ability to define, measure, and compare common metrics – of which emissions-reduction-equivalence is only one – needs to be better understood before it will be possible to seriously entertain climate regime proposals that would rely on such metrics.

Chapter 2 describes the general parameters that need to be considered in developing comparison metrics along with the general categories of mitigation technology development and deployment policies and measures to which they might be applied. It explores the pros and cons of metrics, by laying the essential questions – for instance, whether they should be based on effort or outcome – and how they might be defined and measured from both ex ante and ex post perspectives. Chapter 3 examines the prospects and challenges in developing metrics for an illustrative set of case studies. Chapter 4 summarizes the lessons that can be drawn from these case studies, and draws conclusions with respect to the use of metrics, the further development of data and methodologies, and implications for climate policy.

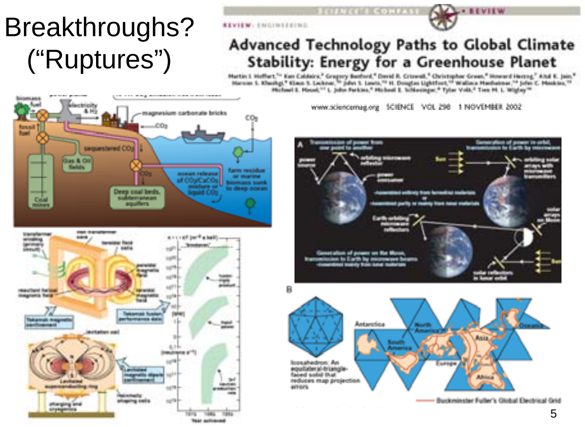
Box 1. Today's technologies or tomorrow's?

The climate change policy-maker confronts a dizzying array of challenges – political and economic feasibility of climate stabilization strategies; equity along several dimensions; adequacy to the task; the forces behind incumbent technologies; and the ability to negotiate new terrain in international environmental law, among others. In this context, the growing allure of "technology as salvation" is quite understandable. Technological cooperation and change offer the promise of overcoming constraints in natural resources, in the productivity of capital and labor, and in the perceived limitations of international law (Barrett, 2003). While doing so, it can create new incumbents whose interests coincide with those of climate stabilization. It is not surprising then, that amidst a growing sense of urgency about the climate problem, and increasing critiques -- whether well-founded or not -- of the Kyoto-style targets and timetables approach, technology-focused strategies have captured the limelight.

Not surprisingly, viewpoints and positions begin to diverge when looking more closely at technology pathways. In a debate that has played out on the pages of the journal *Science,* Pacala and Socolow (2004) argue that currently available or near-commercial technologies can address much of the global emissions challenge for the next 50 years, as captured by their now widely-cited "wedges" paradigm. Swart et al (2003) and O'Neill et al (2003) underscore this conclusion, and point to the IPCC Third Assessment Report's finding that "known technological options could achieve a broad range of atmospheric stabilization levels". In contrast, Hoffert et al (2002) argue that the IPCC and others overstate the technological readiness and the capabilities of existing technologies, and suggest that revolutionary new technologies – e.g. fusion, fission-fusion, solar power satellites, and/or geoengineering – are be needed to address the climate problem.

These two perspectives can be interpreted in a fashion that leads to disparate policy approaches one could caricature as "act-and-deploy" and "long-term research", respectively. The act-and-deploy camp in part reflected in the Kyoto Protocol parties and various sub-national entities undertaking major efforts to deploy existing and emerging low-carbon technologies, while the long-term research camp is reflected in recent US administration climate policy. Both positions can look to the economic literature for support. For example, in their widely-cited modeling analysis, Wigley et al (1996) found that economically-optimal stabilization pathways implies delaying major investment in to take advantage of technology progress as well as the inertia of capital stock and the marginal productivity of capital. Grubb (2002) and others argue that the ability to induce technological change and the risk of "locking-in" long-lived, emissions-intensive infrastructure argues for more urgent near-term mitigation.

Most likely both approaches will need to be pursued: the urgency of the climate problem will force an act-and-deploy response, while the depth of the problem will require technologies that will only emerge with adequate long-term research.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("Ruptures")

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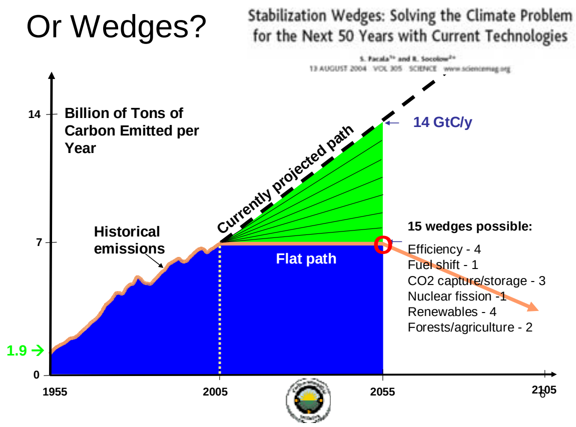
Or Wedges?

Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies

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2. METRICS FOR COMPARING AND INTEGRATING CLIMATE ACTIONS: ISSUES AND OPTIONS

A multi-track agreement on post-2012 climate policy would require that a set of obligations be negotiated, progress tracked, and compliance assessed. This is not a new challenge; the UNFCCC and Kyoto Protocol already have many Articles and programmes addressing various goals and obligations: technology transfer, strengthening national capacity, implementing adaptation, building public awareness, providing financial resources, and, of course, meeting emission commitments.[16] Clearly, among them, emission commitments have attracted the most attention, resources, and investment. Measuring progress towards emission targets is relatively straightforward; methodologies for national emissions inventories are well established, and benefit from many years of application and improvement. However, the same cannot be said of other mitigation-related obligations, such as technology development and cooperation. The means of measuring progress, and even the conceptual frameworks for assessing progress, are still nascent.

To operationalize a multi-track regime would require developing the metrics needed to reflect progress toward obligations, to ensure both fairness among parties and adequacy of response. The feasibility of the integrated and differentiated approach discussed by the Pew Climate Dialogue and the European Commission (Blok et al, 2005), among others, may thus rest on the ability to find practical and acceptable **metrics** for measuring and comparing different types of actions. Metrics could be used to indicate the relative level of **effort** (as a proxy for fairness) or the relative contribution to **outcome** (as a proxy for adequacy or effectiveness). Formalized in a quantified or otherwise measurable fashion, metrics would initially provide a platform for more transparent negotiation, and subsequently as basis for tracking implementation progress and monitoring effectiveness. The exploration of common metrics for integration and negotiation across different types of future climate actions is area that is only beginning to receive serious analytic attention (Philibert, 2005; Blok et al, 2005; Natsource, 2003).

The choice of metrics, and the tools to measure them, will depend upon their intended purpose (e.g. information, negotiation, policy design, or compliance), the underlying goals they aim to represent (fairness, adequacy, or efficiency), their perceived ability to credibly reflect these goals, and their feasibility of implementation (i.e. the availability of adequate, reliable, and comparable data). If metrics are intended for policy design or negotiation purposes – e.g. setting targets for technology cooperation spending, technology cost reductions, or specific emissions levels – then *ex ante* assessment of their likely outcome (e.g. emission reductions) or level of effort (e.g. costs of achieving targets) will be needed. Ex ante assessments would intrinsically be less certain than ex post assessments by virtue of the fact that they are predictive exercises. Economists are developing increasing sophisticated models for understanding induced and endogenous technology change, which could certainly prove helpful even though they have not

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[16] UNFCCC Article 4.5; Kyoto Protocol Article 10c.

been developed specifically for this purpose, and are still subject to a large degree of uncertainty.[17] We return to these modeling issues in the case studies in Chapter 3.

Monitoring of achievement and compliance becomes essential if a multi-track agreement is adopted. This application implies a different toolkit designed for *ex post* assessment. As discussed in Box 3 below (see Chapter 4), some have suggested the option of a CDM-like methodology process for determining the outcome of technology targets or initiatives in terms of equivalent emissions reductions. While any agreement specifying or crediting parties' contributions to technology cooperation or development would almost surely require monitoring and verification of such contributions in terms of effort or expenditure, assessing outcome faces added challenges not dissimilar to those faced by the CDM itself. At the heart of this challenge is whether causality can be demonstrated (within reason), i.e. making a credible and verifiable claim that a specific technology initiative has lead to reduced technology costs, increased technology penetration, and displaced GHG emissions relative to a counterfactual baseline. Making such a case at a project-based level, as in the CDM, is sufficiently challenging; doing such analysis for technologies as a whole, with many other factors at play, is yet more challenging. We return to these questions in the case studies (Chapter 3) and conclusions (Chapter 4).

2.1 Which actions to consider?

Countries undertake a wide range of actions that can be labeled as climate change policies and measures. National communications to the UNFCCC are replete with lists of such actions.[18] IEA's database of policies and measures "taken or planned in IEA Member countries to reduce greenhouse gas emissions" contains over 2000 records covering a seven-year period.[19] Including actions addressing non-energy emissions would expand this count even further.

The plethora of such actions complicates the task of applying metrics: which policies and measures should be considered and compared? Which are truly climate-driven, and does that matter? Should only "significant" actions be compared and if so by what criteria should significance be determined? Can individual policies be examined in isolation or only in combination with other policies (e.g. R&D and deployment activities)?

The wide variety of policies and measures – ranging from voluntary to mandatory, incentive to regulation, and fiscal to institutional – presents yet another challenge to the comprehensive use of common metrics. One of the added advantages of binding targets and timetables – and other

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[17] Particularly relevant are modeling studies looking at induced technological change and the comparative costs and returns from R&D investments, as compared with technology deployment strategies and emissions reduction targets (e.g. Buchner and Carraro, 2005; the entire volume 54 of *Ecological Economics* (2005); Sue Wing, 2006)

[18] UNFCCC national communications provide information on the project impacts (outcome) of policies and measures for many parties. However, the methods used to assess outcome varies greatly making comparison problematic. Guidance for the most recent national communication (2006) suggests that these communications should provide more thorough and consistent assessments of policies and measures and their emissions impacts. (http://unfccc.int/resource/docs/cop5/07.pdf, FCCC/CP/1999/7, 16 February 2000)

[19] http://www.iea.org/textbase/envissu/pamsdb/index.html

so-called "first-best" approaches such as a harmonized carbon tax – is that they largely avoid the need to answer these questions, at least to first order.[20] Indeed, were such "first-best" policies without significant opposition in many key countries, the present analysis might be largely irrelevant.

For this analysis, we focus specifically on the development and application of metrics to a subset of policies and measures related to technology change. This subset spans a variety of market pull and technology push strategies, from the more technology-specific to the more comprehensive, as illustrated in

Table 1. The "environmental policies" shown in the upper right quadrant, i.e. those that aim to directly address environmental externalities through prices or targets on GHG emissions, are "technology-neutral" − they leave, in principle, the choice of winning technologies to the market (or other policies) to determine. Environmental policies stand in contrast to the "technology policies" shown in the bottom row, from technology-targeted R&D programs to incentives or requirements for specific technologies (e.g. renewable energy standards and tariffs). Considerable debate remains in the literature on the extent to which types of policies – environmental or technology, push or pull – is ultimately most effective at inducing technology change (Jaffe et al, 2005). Indeed, many analysts suggest that a combination of policy instruments across the innovation chain are likely to be needed to induce technology change and maintain a diverse portfolio of technology options (IEA, 2006; Grubb, 2005; Alic et al., 2003).

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[20] Yet even under a Kyoto-like framework, any analysis of fairness/effort, and to some extent, adequacy/outcome, needs to consider for how "hard" each party pushes in terms of policies and measures and to account for resource endowments, cultural preferences, and political dynamics that influence each party's portfolio of policies and measures.

Table 1. Typology of Climate-Related Technology Strategies
(italics indicate options examined in this paper)

	Technology push	**Market pull**
Comprehensive Strategies	• R&D tax credits, matching funds, or other R&D incentives • Competitive R&D funds (contests or bidding processes) • Instruments for public-private partnerships in R&D • Broad R&D "portfolio strategies" • Patent/intellectual property rights (support and transfer) • Technology transfer protocols • Support for education and training	• *Economy-wide GHG taxes, permits, trading, or standards* • *Removal of subsidies for GHG-intensive activities* • Sector-specific GHG permits or regulations (e.g. requiring all new power plants as net zero-emission after 20xx) • GHG criteria for international finance (e.g., development bank or export credit agency rules) • Voluntary ("avoid regulation") GHG programs "Environmental Policy"
Selective Technology-Specific Strategies (pick winners or "clusters" of winners, or eliminate losers)	• *Targeted government R&D programs* • Collaborative research programs and support for private R&D • *Technology cooperation and transfer programs* • Technology demonstrations • Knowledge diffusion (e.g. extension services, marketing and publicity) "Technology (Development and Transfer) Policy"	• *Incentives, requirements, and other support for low GHG technologies (feed-in tariffs, portfolio standards for renewable electricity or fuels, tax credits for nuclear and renewable energy, government procurement of efficient equipment or renewable fuels and electricity, etc.)* • Regulatory (technology-forcing) standards (e.g. emissions standards, appliance efficiency standards) "Technology (Deployment) Policy"

The italicized options indicate policies analyzed further here in terms of effort and outcome metrics, with specific case studies shown in Table 2 below. They represent options widely implemented or discussed in international fora, for which assessment of effort and outcome across countries would be useful. Other strategies shown in Table 1 may be of significant value as well, but are harder to assess. For instance, international technology partnerships such as the Climate Technology Initiative and the IEA GHG R&D programme[21] can, in principle, enable sharing of information, access to advanced technology, avoid duplication, reduce costs, and thereby increase the scale of RD&D activities (Montgomery and Smith, 2005).

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[21] http://www.ieagreen.org.uk/networks.html; http://www.climatetech.net/

Table 2. Types of policies considered *(italics indicate items not analyzed in case studies)*

	Technology Development Policy	Technology Deployment	International Technology Cooperation and Transfer	Environmental Policy	GHG Intensive Policies
Policies in place today *(ex post analysis)*	RD&D programs (for climate-friendly technologies)	Renewables incentives and requirements	Global Environment Facility support	*EU ETS*	Subsidies for fossil fuel production and/or consumption
Future options *(ex ante analysis)*	R&D Scale-up	Renewables targets	Asia-Pacific Partnership	*Future binding targets or comprehensive tax options*	*Subsidy removal*

2.2 Underlying objectives

Perhaps most central to the question of "which metric" is the underlying objective one seeks to represent. Most climate policy proposals are driven by one or more of three objectives: fairness, adequacy, and efficiency. The first two objectives map directly into the two types of metrics considered here: effort can serve as a proxy for fairness while (environmental) outcome provides a means to assess adequacy. Unlike the other two objectives, economic efficiency – expressed either in metrics of cost-effectiveness ($/tCO2e reduced) or overall benefit-cost (total NPV) -- is not as directly relevant for comparing the contributions of individual parties. In essence, cost-effectiveness is a ratio of effort (expenditures and impacts) to environmental outcome (emissions reduced),; it reflects a feature of an activity, but says nothing about its scale.

The key elements of addressing fairness are responsibility -- based on current emissions, historical emissions, or other metric for contributions to emissions, concentrations, or climate impacts -- and ability-to-pay to reduce future emissions. Those responsible and able to afford should, by moral imperative, undertake the greatest efforts to reduce emissions. Effort might be represented by the direct expenditures on, or the full social costs of, climate-driven policies enacted. In fact, a number of climate proposals reflect these criteria directly – for example, Schelling's proposed Climate Marshall Plan (Schelling, 2002)[22], the equal mitigation costs approach (Babiker and Eckhaus, 2000), or harmonized carbon taxes (Nordhaus and others, as cited in Aldy, Barrett, and Stavins, 2003) -- and thus imply the use of an effort-based climate policy framework for which effort-related metrics would be appropriate.

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[22] Nobel Prize winning economist, Thomas Schelling (2002) has suggested an explicitly effort-based approach, given "a major U.S. unilateral initiative in research and development oriented toward phasing out fossil fuels over the next century would produce welcome returns and display American seriousness about global warming" Bodansky et al 2004 refer to this as the Climate Marshall Plan approach "Alternative approach to mitigation, focusing on the inputs of climate policy (policies, programs, taxes, subsidies, regulations, investments, R & D, and so forth), rather than on the outputs (emissions). Climate Marshall Plan provides a possible model for how national policies could be coordinated and burdens shared, based on "multilateral reciprocal scrutiny" among states rather than on any formal quantitative criterion."

Adequacy is perhaps a more challenging objective to define, especially given the century-plus time scale of the climate problem and perceptions of the need for urgent action. Ensuring that global average temperatures not exceed two degrees above pre-industrial levels – a goal adopted by the EU and suggested by many scientists and non-governmental institutions – may well require limiting emission concentrations to levels below 450 ppm CO2e (Meinshausen et al., 2006), and deep emissions reductions in cumulative emissions this century. Many scientists also now argue that prompt action is needed if we are to stand a chance to avoid serious disruption of human and natural systems, given the strong lock-in and path dependence of long-lived investments in emissions-intensive energy systems (Hansen et al., 2006). Therefore, climate policies and measures may need to be "adequate" both in near-term and long-term. Arguably, then, separate metrics for adequacy might need to consider two types of outcomes, similar to the dichotomy of technology perspectives described in Box 1:

- **Near-term emissions reductions from "known" technologies.** Support for mature technologies, resources, and actions that appear highly likely to reduce GHGs (renewable and nuclear energy; non-CO2 GHG management; carbon capture and storage)
- **Longer-term "options" for deep emissions reductions.** Support for less-proven technologies and resources that may be needed to achieve deeper reductions that available from available technologies (e.g. biomass CCS, fuel cells, electricity storage technologies)

2.3 Comparing effort or outcome

Since both fairness and adequacy are likely to be core objectives in any future climate regime, it stands to reason that both effort and outcome metrics would be needed for comparing parties' climate actions under the type of differentiated approach noted above.[23] Table 3 provides a framework for developing broad effort and outcome metrics. The suggested outcome metrics reflect the two objectives noted above -- near-term emission reductions and long-term cumulative emissions reductions – as well as the need to manage risk through a diverse portfolio of market-ready mitigation options. While achieving actual emission reductions (or emissions targets) are the ultimate goals of climate policy, the large uncertainties in how these reductions can be achieved – including the costs, effectiveness, penetration, and other impacts of specific policies and technologies – suggests the need for diverse portfolio of mitigation options (Sanden and Azar, 2005). Therefore, limiting the outcome metrics solely to projections of potential emissions reduction impacts is too narrow and limiting. However, comprehensive metrics for risk management and portfolio diversity are less obvious. They could include broad measures such as proxies for accumulated knowledge (see macroeconomic models), indicators of option diversity (e.g. availability multiple technology options to address given emissions sources), or

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[23] Some observers argue that agreements based largely on outcome metrics, like the Kyoto Protocol (meeting specific emission targets), are inherently problematic (Schelling, 2002; Barrett, 2003), and thus agreements should be solely effort-based. At its most ambitious, an effort-based agreement could provide a framework for comprehensive action (e.g. Climate Marshall Plan) – a global funding mechanism could finance a global transition to a low-emissions economy, with a schedule of payments based on ability-to-pay, current emissions, historical responsibility, or some combination of the above. Other proposals (e.g. multi-stage) are almost wholly outcome-based.

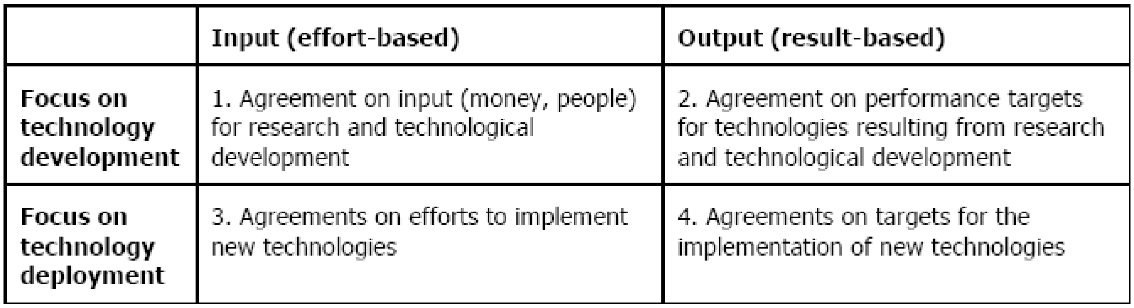
option value, a mathematically complex approach applied to financial markets, and potentially applicable to R&D as illustrated by Davis and Owens (2003).

Table 3. A Framework for Climate Action Metrics

Objective		Metric	Key Issues
Adequacy (Outcome)	Low-emission trajectories	Near-term emission reductions (e.g. between 2008 and 2012)	• Defining goals • Urgency • Assumed baseline scenario (SRES issue) • Attribution of emissions savings to climate policies (causality/double counting) • Diversity of models and assumptions for ex ante estimation
	Long-term emissions stabilization	Long-term cumulative emissions reductions (e.g. 2010-2100)	
	Risk management (path dependency and irreversibility)	Options/knowledge benefits: diversity of available options, targeted cost reductions, technological readiness	
Fairness (Effort)	Balanced, equitable commitment/ effort	"Expenditures", costs directly incurred by government and/or society in implementing a climate policy	• Defining the non-intervention baseline scenario and what is additional to it (CDM issue) • On-budget vs. off-budget expenditures
		"Impacts", i.e. economic costs and (non-climate) benefits and opportunity costs (e.g. crowd-out effects of R&D) that result indirectly from climate policies	• Assumed baseline scenario (SRES issue) • Attribution of costs/benefits to climate policies (causality/double counting) • Leakage and Spillover • Diversity of models and assumptions for ex ante estimation
		Distribution of costs and benefits (equity among and within countries)	• Competitiveness (or first mover) issues • Ability of different parties to capture spillover

Alternatively, outcome metrics could be more technology-specific, such as targets for cost reductions (e.g. $1/W-peak solar cells), technological readiness (e.g. proven post-combustion carbon capture technologies), or actual deployment (e.g. 1 million hydrogen fuel cell vehicles in use). In fact, a recent EC report on post-2012 climate change regime options suggests technology-specific targets as the potential for outcome-based technology agreements, as illustrated in Table 4. The challenge here would be agreement on which technologies to focus on, given the problems inherent in picking "winners", a concern that could be limited by a transparent, deductive process for selecting a sufficiently broad array of targeted technologies.

Table 4. Possible target types for technology agreements (Blok et al, 2005)



	Input (effort-based)	**Output (result-based)**
Focus on technology development	1. Agreement on input (money, people) for research and technological development	2. Agreement on performance targets for technologies resulting from research and technological development
Focus on technology deployment	3. Agreements on efforts to implement new technologies	4. Agreements on targets for the implementation of new technologies

For most technology development initiatives, effort will likely prove simpler and more straightforward to measure than outcomes. Technology agreements can be established on the basis of expected investment of resources, which can be tracked *ex post*. With respect to public R&D investment at least, a variety of databases and publications provide documentation of expenditure by year in climate-friendly technologies (as described in the case studies in the next Chapter). There are important questions with respect to comparability of data across countries, and IEA and EU task forces have been working on their resolution. There are also questions as to which R&D expenditures correspond to technologies with promise for future GHG emissions reductions, as to whether all expenditures in such technologies should be given equal weight in terms of “effort”, and thus the extent R&D investments represent real “effort” in terms of a contribution to the global public good of climate stabilization. Still, many issues need resolving.

Effort metrics can range from the straightforward (expenditures) to the demanding (broader economic impacts) in terms of complexity of definition and estimation. They can account for only direct, government expenditures, for the combined expenditures of the public and private sector[24], or for full societal costs, including indirect or opportunity costs, such as the crowd-out effect of targeting R&D at climate technologies. While these are challenging issues, the measurement of technology development effort − defined in a fairly limited sense − does appear to be a tractable exercise. We turn to this exercise in Chapter 3.

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[24] Philibert (2005) notes that Schelling’s use of the Marshall Plan and NATO as analogs to argue for the historical precedent of large scale collective international government expenditure for a public good overlooks a key distinction, i.e. that climate mitigation efforts will involve contributions from the private sector and local and regional entities, not merely or largely national governments.

3. CASE STUDIES: ANALYZING EFFORT AND OUTCOME

"While most of the debate in the literature is about whose forecasts of climate change impacts are most realistic, there is a tendency to lose sight of the fact that all future prognostications of technological change are ultimately derived from assumptions". (Edmonds, Roop, and Scott, 2000, p.22)

A full and comprehensive assessment of effort and outcome for current and prospective GHG mitigation actions, if deemed worthwhile or necessary for progress towards a future climate agreement, could prove a Herculean task. It would require the availability of reliable data regarding a multitude of different climate actions --- even if just focused on technology development the list is long as shown in Table 1 -- consistently reported across countries using common procedures.. Just as challenging is the development of credible methodologies for interpreting the empirical data and drawing robust conclusions about effort and outcomes.

The chapter explores some of these challenges through a series of case studies as indicated in Table 5. These examples are illustrative of some of the different types of climate actions for which metrics might be of interest: government RD&D investments, renewable incentives and requirements, support for international technology cooperation (the case of GEF), and (the reform of) subsidies for fossil fuels. Some specific current and potential policies are considered, options for metrics reviewed, and some initial conclusions are drawn.

3.1 Technology development effort: Ex post analysis of government R&D expenditures

OECD countries fund major energy research and development programs, totaling over $9 billion in 2004 (IEA, 2006). Public spending on R&D for GHG mitigation technologies can thus provide one metric for gauging effort with respect to climate technology development. The International Energy Agency (IEA) regularly collects budget data on these programs, providing a basis for international comparisons of public spending, but not without challenges in interpretation and robustness.[25]

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[25] Note that R&D investment in non-energy GHG mitigation technologies, such as HFC substitutes or methane capture methods, would not be included in the IEA database.

Table 5. Application of metrics in selected case studies *(italics indicate items not analyzed here)*

	Technology Development	**Technology Deployment**	**International Technology Cooperation and Transfer**	**GHG Intensive Policies**	***Direct Environmental Policy***
Ex post analysis of implemented policies	National R&D programs (Section 3.1 and 3.3)	Renewable energy incentives and requirements (Section 3.5)	Global Environment Facility support (Section 3.6)	Subsidies for fossil fuel production and/ or consumption (Section 3.6)	*EU ETS (Phase I)*
Ex ante analysis of policies in the future	3-fold scale-up of national R&D budgets (Section 3.4)	Renewable energy targets for 2010 (Section 3.5)	Asia-Pacific Partnership (AP6) (Section 3.6)	*Subsidy removal*	*EU ETS (Phase 2)* *Future binding targets*
Metrics: Effort	• Direct Government R&D spending or subsidies • *Net economic impact (considering return on investment, "crowding out")* • *Indirect and non-federal government support* • *Private R&D spending* • *In-kind contributions*	• Government expenditures • Direct cost impacts • *Net (macro) economic impact*	• Government contributions to program • *Net economic impact* • *In-kind contributions* • *Other (technology sharing agreements, intellectual property right support)*	• Subsidy levels • *Net economic impact of subsidy (removal)*	• *Direct expenditures (Program administrative and transaction costs)* • *Net economic impact of achieving targets*
Metrics: Outcome	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• Realized (or potential) emissions reductions • *Knowledge/ option benefits*	• *Realized (or potential) emissions reductions or increases*	• *Realized (or potential) emissions reductions*
Tools: Ex post analysis	• Monitoring and verification of expenditures and technology penetration/operation • Causal models for attribution of outcomes to actions • Monitoring and evaluation techniques			• Agreed procedures for defining and measuring subsidies • Monitoring/ verification of subsidies • Causal models for attribution of outcomes to subsidies	• *Direct monitoring and verification of environmental outcomes (i.e., national emission inventories)*
Tools: Ex ante analysis	• Bottom-up energy system models using two-factor learning curves (Kouvaritakis et al, 2000b, Berglund and Soderholm, 2006) • Top-down macroeconomic models with endogenized technological change (Goulder and Schneider, 1999; Popp, 2005) • Heuristic approaches (Schock et al, 1999; Kammen and Nemet,2005)		• Heuristic approaches (Maytsek et al, 2006); formal models lacking	• Same as technology development/ deployment	

R&D budget data are reported annually to IEA by national representatives, who are provided with a detailed questionnaire, reporting guidelines, and a taxonomy of technology types. However, these data have historically been organized in terms of broad fuel and technology categories -- e.g. "coal combustion" or "electric power conversion" – that do not necessarily include all climate-related R&D, and that sometimes aggregates climate R&D with non-climate R&D. It is therefore not always clear which R&D investments can be counted as GHG mitigation efforts. Investment in potentially important GHG mitigation technologies, such as carbon capture or electricity storage (e.g. to support greater wind power penetration) can be difficult to discern. [26,,27]

While they are not yet of sufficient robustness and consistency to be used for rigorous comparisons of national technology development effort, IEA data can still be used to make some general comparisons, and to illustrate how effort metrics might be applied. One of the first questions is whether national R&D spending should be compared on the basis of economic activity (e.g. GDP), population, GHG emissions, or another indicator. Economic activity can provide a proxy indicator for nation's capacity to invest in R&D, while GHG emissions (current or historical) can provide a proxy for responsibility to mitigate emissions. For the purpose of illustration, Figure 1 shows the relative R&D budgets on a per GDP basis in what might be roughly categorized as low carbon technologies.[28]

Taking into account the data limitations indicated above, these data do nonetheless suggest that some countries invest much more heavily in R&D for GHG technologies (on a per GDP basis): Japan (which is double the investment rate of the next country), Canada, and several EU

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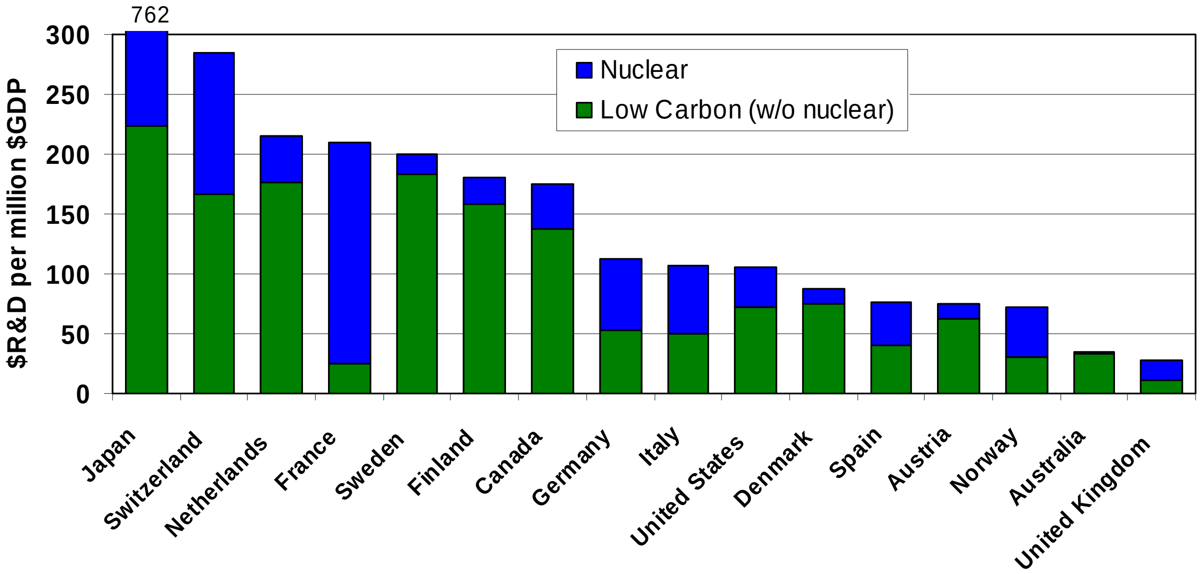
[26] For instance, the coal combustion category includes R&D that supports technologies that could potential increase GHG emissions by reducing their costs (e.g. conventional coal boilers), as well as those that could be instrumental in reducing them (e.g. IGCC). IEA is currently working to improve its data collection in a number of ways that would enable a truer comparison of national spending on GHG mitigation technology R&D – including separate reporting of R&D for CCS, hydrogen, and fuel cells, overall improvements in the consistency or completeness of data, which currently present significant issues. For example, some countries report budgets, while others report actual expenditures. IEA questionnaires can be interpreted in different ways; some countries report sub-national (regional, state, local) R&D expenditures, while others do not (EC 2005, Dooley 2000). Use of national and multi-country (e.g. Eurostat) reports can yield more precise estimates, but such efforts are more subject to more inconsistency (Dooley, 2000).

[27] According other sources, public R&D investment in carbon capture and storage (CCS) totaled approximately $100 million, or 1% of public global energy R&D budgets as of 2005. In contrast, public R&D spending on hydrogen and fuel cell research is likely in the range of $0.6 to $1.0 billion, with private spending 3-4 times this level (IEA, 2004, Haug, 2005, and US DOE 2006, http://www1.eere.energy.gov/hydrogenandfuelcells/printable_versions/budget.html.).

[28] What types of technology investment should be counted as GHG mitigation effort is a recurring challenge across the various case studies analyzed here. For the purposes of simplicity, low carbon R&D budgets here are limited to the categories of conservation, renewable energy sources, and nuclear as taken from the IEA R&D database (IEA, 2006), as well as CCS, hydrogen and fuel cell budgets, as collected from other sources. Since this does not include broad categories of R&D such as electric power conversion, which may include investments in power plant efficiency or improved storage that could yield GHG benefits, the figures shown here may understate total climate-friendly energy R&D.

countries (Switzerland, the Netherlands, France, Sweden, and Finland) stand out, France especially so owing to its large nuclear research program.[29] .

Figure 1. Per GDP public energy R&D budgets, 2004



Source: IEA, 2006; IEA, 2004; USDOE, 2005

Figure 2 provides a more detailed, though still incomplete, look at R&D budgets by technology type on a per GDP basis. This chart shows budgets not only for technologies that are likely to reduce GHG emissions (nuclear, energy efficiency, renewable energy), but for fossil fuel technologies that would have a more uncertain impact on GHG emissions. The fossil fuel A category includes oil, gas, and coal production technologies (e.g. oil shale and tar sands) that are likely to increase global emissions if R&D improves their readiness and cost-effectiveness. The fossil fuel B category refers to IEA's classification of coal combustion, conversion and other coal-related R&D that mix together technologies that might either increase or decrease emissions. A country's effort in addressing climate should thus consider not only its' investment in technologies that clearly mitigate GHG emissions but also its support for technologies that might actually increase emissions. However, improved reporting is needed to better understand the nature of investments, and their likely contribution to potential GHG mitigation solutions, especially within the fossil fuel and "other" categories.[30] It is quite likely for instance that a significant portion of what is shown here under Norway's unusually large fossil fuel R&D is in fact directed towards its Climit (eco-friendly gas-fired power technology) program, which supports Sleipner and other carbon capture and storage activities. This again points to the need

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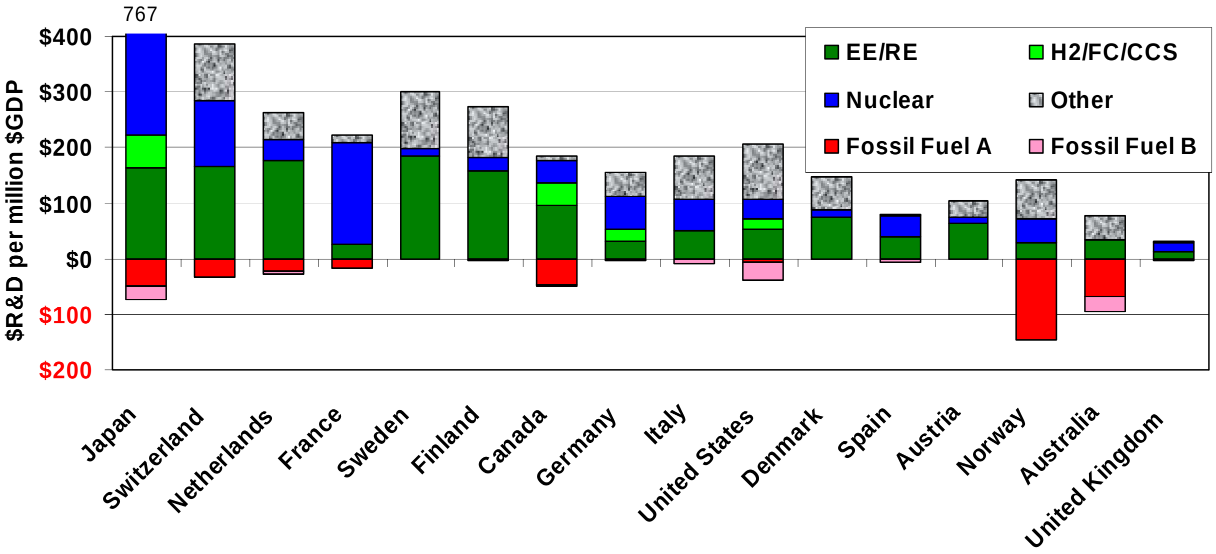
[29] It is important to bear in mind that unlike many other energy technologies, such as fuel cells or renewable energy, where public R&D spending can leverage significant private sector contribution, for nuclear energy research, where government spending dominates (Batelle, 2000), leveraging impacts are limited

[30] More complete cross-country reviews of national R&D programs, are conducted on an occasional basis by researchers (e.g. Dooley, 1999; EC, 2005), which shed greater light into the nature of actual investments within each of these broad categories. However, such reviews are scarce and hardly systematic

for more detailed and thorough R&D reporting, if IEA data are to provide a better sense of countries' climate-related R&D contributions (some of which is already underway).

Figure 2. Public R&D spending, 2004, per GDP by technology type



Source: IEA, 2006; IEA, 2004; USDOE, 2005
EE/RE = Energy efficiency and renewable energy. H2/FC/CCS = Hydrogen, fuel cells, and carbon capture and storage. Fossil A includes IEA research categories for enhanced oil and gas, refining transportation and storage; oil shale and tar sands; other oil and gas; coal production, preparation, and transportation; Fossil B includes IEA research categories for coal combustion, coal conversion and other coal. Since this analysis was completed (2006), IEA has begun to compile a separate category for carbon capture and storage technologies, which may be shown under the fossil fuel categories here.

Assuming, then, that IEA and others can improve R&D budget reporting to address various quality concerns, other questions will need to be addressed if R&D data are to be used as a proxy for "effort". For instance, some method will be needed to decide which R&D investments should in fact be considered as GHG mitigation-oriented. GHG mitigation is dependent on which technologies are avoided as well as what is encouraged, and thus the same super-efficient gas or coal-based technology may avoid emissions (e.g. if displacing less efficient gas or coal technologies) or increase them (e.g. if competing against lower carbon technologies), depending on circumstances. Similarly, judgments might be needed as to whether alternative vehicle fuel technologies such as hydrogen or biofuels lead to GHG mitigation, depending on a host of other factors (assumed feedstocks or ultimate climate stabilization targets). This issue stretches across other effort and outcome metrics as well – reflecting the fundamental uncertainty of going so far up the causal chain from actual emissions to R&D. No purely objective methodologies are possible, and judgments would ultimately be required.

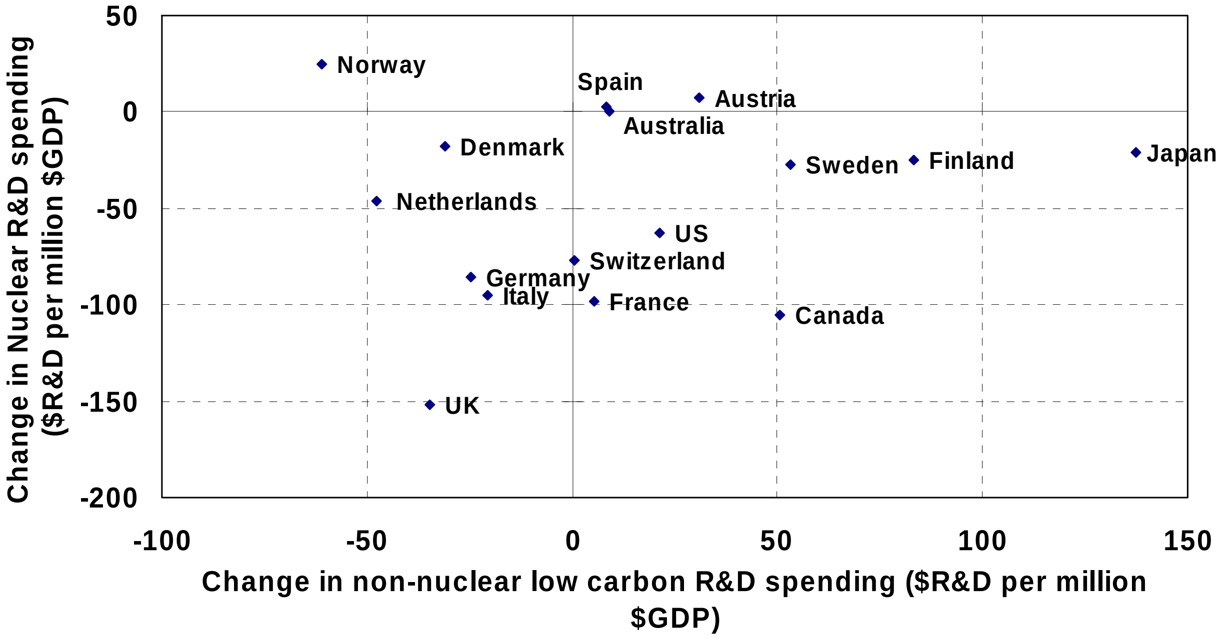
It may also be desirable to consider what R&D investments in GHG mitigation technologies are "additional" to those that would otherwise be undertaken for other non-climate motivations. For instance, two countries driven by concerns about energy security might pursue alternative fuels: one country investing in coal-based synfuels, and another in biofuels.. Each country's R&D

priorities tend to be shaped by its particular resource endowment, technology expertise, and industrial strengths. Furthermore, these priorities are often shaped by the politics of R&D funding, often driven by social capture and parochial interests.

The "additional effort" question could be approached in a manner similar to how emissions targets are established in the Kyoto Protocol, for instance, by selecting a base year defining any increment above that base year level of investment to be additional, as illustrated in Figure 3. Figure 3 shows, in the bottom right quadrant, that half of the 16 countries have decreased their per GDP funding for nuclear energy while increasing funding for other low-carbon technologies. The amount of overall increase is relatively small in most cases, with a few countries showing significant increases relative to their overall 1990 energy R&D levels: Japan, Finland, Sweden, and Canada, and Austria in particular. For other countries, increases appear to be modest, and in several cases spending has declined.

This example illustrates some of the difficulties with this approach. A single base year can be non-representative, and events since the base year that are unrelated to climate change policy could strongly influence R&D levels. This problem is well known with Kyoto targets (with Russia benefiting from its economic collapse, Germany from reunification, etc.) In the case of R&D, it so happens that the increase in Japan's investment is a function of its pledge to double public energy R&D spending during the economic recession of the 1990s in order to stimulate science and technology innovation (Dooley, 1999).

Figure 3. Changes in public R&D spending, 2004 vs. 1990



For a number of reasons, public R&D budgets (or expenditures) directed to specific technologies provide only a partial picture of national "effort" in climate technology development. Other policy instruments can be directed towards R&D, such as corporate R&D tax credits. The boundary between R&D, demonstration, early diffusion, and other catalytic activities is often fuzzy as well; and technology innovation clearly involves far more than public R&D spending (Hargadon, 2004; Sagar and van der Zwaan, 2006).

This short exploration suggests that while R&D budgets present a potential basis for technology development "effort" metrics, considerably more work is needed to improve the consistency and robustness of the underlying data, to illuminate other relevant efforts not included in these budgets (e.g. other innovation efforts, and in-kind and off-budget contributions), and to consider whether and how to present the relative level of effort (i.e. whether on a per GDP or other basis and whether and how to account for the climate motivation or "additionality" of R&D spending, such as in the 1990 comparisons shown here). At the same time, even using existing, flawed data, the types of cross-country comparisons shown above may be useful for illuminating trends, informing international negotiations, and to the extent they provide misleading perceptions, could help to stimulate cooperation in improving data collection and reporting.

3.2 Technology development outcomes: Key challenges

Despite data and other limitations, R&D expenditures can, in principle, be measured and monitored in a relatively straightforward manner. In contrast, assessing R&D outcomes is complex. Efforts to do so have relied heavily on assumptions, hypotheses and models, in order to: a) attribute observed outcomes to specific R&D investments (ex post analysis), and/or b) project future outcomes based on levels of R&D investments (ex ante analysis).

The first challenge – establishing causal connections between R&D activities and observed outcomes (ex post analysis) -- is the domain of R&D program assessment, addressed in the next section with a case study of the US DOE's R&D program. Summarizing the findings of an extensive program review by the US National Research Council, it shows that careful and consistent analysis can provide an indication of environmental and other outcomes, but that these estimates are very rough and inherently judgment-driven. More importantly, it indicates that while realized benefits are most often quantified, options and knowledge benefits, while less immediate, certain, or tangible, are the real fruits of many R&D activities.

The second challenge – projecting the outcomes that might result from R&D spending (ex ante analysis) -- is significantly more daunting not just because of fundamentally speculative nature of R&D activity, but also due to the multitude of factors other than public R&D spending levels that will ultimately influence R&D effectiveness and outcomes. These factors include among others, specific research program design, complementary R&D activity in the private sector, policy or market signals that encourage diffusion and deployment, the emergence of competing technologies, and consumer behavior.

In light of this inherent complexity, a variety of analytical techniques have been developed that can help project the potential outcomes associated with energy technology R&D investments: a) improvements in technology cost and performance have been investigated with two factor learning curves; b) competition with, and displacement, of other higher-carbon energy technologies have been investigated with energy system models; c) patent-based models have been used to project knowledge generation in specific sectors, and its contribution to productivity; and d) general equilibrium and other macroeconomic models have been used to estimate the higher order impacts of energy R&D investment, including the opportunity costs related to "crowding out" other productive R&D (Goulder and Schneider, 1999; Popp, 2004; Miketa and Schrattenholzer, 2004; Buchner and Carraro, 2005; Klaassen et al, 2005; Wing, 2006). While model complexity tends to render most of these techniques rather non-transparent, and some may question their empirical robustness (Papineau, 2006), they still each have something to contribute to the exercise of estimating outcome metrics for R&D. As the recent dates of publication indicate, research on the links between R&D, innovation, technology change, and GHG emissions reduction is relatively new and rapidly growing. It is thus not unreasonable to hope that the predictive value of modeling techniques will further improve in the years to come.[31]

3.3 Technology development outcomes: Ex post analysis of the US DOE R&D program

In 2001, the US National Research Council conducted what is perhaps the most comprehensive assessment of R&D program outcomes ever completed (NRC, 2001). Evaluating over two decades of federal DOE energy R&D expenditures totaling over $85 billion (2000 US$), they found that a small number of the individual research programs (specifically in energy efficiency and fossil energy) provided the majority of economic and environmental benefits. This finding is characteristic of R&D programs in general, where the winners and losers can't be anticipated in advance.

The NRC's evaluation framework highlights the importance of distinguishing between three classes of benefits. First, the NRC defines *realized* benefits (economic, environmental, and/or security) as those that derive from technologies at or near commercialization, by which it means actual benefits that are observable or likely and can be attributed to the technology in question. *Options* benefits refers to realizable benefits of technologies that are not yet diffused, but which *could* be deployed if market conditions were to become favorable (e.g., a rise in the price of a competing conventional fossil fuel), or if a policy decision were made to foster the technology's diffusion (e.g., a tax incentive to increase its attractiveness). Option benefits reflect a distinct benefit in terms of risk reduction, Finally, the NRC defines *knowledge* benefits as advances in understanding that derive from R&D that is not yet complete or has failed to yield technologies that could be commercialized.

Table 6 illustrates the NRC's findings with respect to three R&D programs: the fluorescent lamp electronic ballast program funded at a cost of $6 million from 1977 to 1983; the advanced batteries for electric vehicles program, ongoing since 1978 at a cost of $376 million by 1999; and the IGCC program that cost over $1 billion in R&D and another $1.3 billion in demonstration and deployment from 1978 to 1999. As shown, the realized benefits differ rather dramatically across the programs. The electronic ballast program, at minimal R&D cost, is viewed as having accelerated the market penetration of electronic ballasts, thus yielding significant major

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[31] Furthermore, there are similar limitations in the tools and knowledge with the respect to the impact of other emissions reduction policies, such as carbon taxes or permits, though arguably these limitations are less significant given the higher degrees of understanding and determinism.

economic benefits ($15 billion in energy savings) and CO2 savings (45 million tons, cumulative across years). In contrast, the NRC report found that the advanced battery program had yet to yield significant realized benefits. Similarly, it found limited realized benefits for the IGCC program: no economic benefits as of 2000 and an expectation of 48 million tons of lifetime CO2 savings on the assumption of 1700 MW of new IGCC plants built by 2005, an assumption that was not in fact realized.[32] However, as we will return to below, events since the timing of the NRC report (2001) have demonstrated the significant option benefits associated with both the IGCC and advanced battery programs; as of this writing, there are currently plans and proposals for over 17,000 MW of new IGCC plants within the US, and auto manufacturers have recently announced plans to market Li ion hybrid vehicles in the next few years.

Table 6. Ex post evaluation of R&D - examples of benefits realized by past USDOE research (based on NRC 2001)

	Investment*, Key outcomes	Realized Benefits/Costs*	Options Benefits/Costs	Knowledge Benefits/Costs
Fluorescent Lamp Electronic Ballast Program	Funded from 1977-1983 Substantial sales started in 1985 Cost: $6 million	Economic Benefit: $15 billion Electronic ballasts captured 25% of market by 1998 CO2: 45 million tons Other: Reduce power plant air emissions	Significant economic and emissions benefits after 2005	Development of advanced control systems Spillover for high-intensity discharge lamps
Advanced Batteries for Electric Vehicles	Funded since 1978 by DOE Cost: $376 million US battery industry in intense competition with Asian industry	Few benefits thus far Niche market for NiMH battery vehicles GHG benefits depend on marginal electricity sources	Potential market of Li and NiMH systems if economics become more favorable	Advances in lithium polymer and lithium ion batteries Other battery applications
Integrated Gasification Combined Cycle (IGCC)	Funded since 1978 by DOE R&D Cost: $1065 million DOE Demo and Deploy Cost: $1281	No realized economic benefits as of 2000. (Predicted CO2 benefits: 48 million tons assuming 1700MW in place by 2005.)	Preserves option for coal-based low-emissions electricity, assuming CCS advances. Flexible options for chemical processing using coal feedstocks	Critical knowledge for other emission reduction technologies such as hot gas cleanup

*Investment is cumulative through 2000 in constant 1999 US dollars. Realized benefits include those projected to span full economic lifetime for installations through 2005.

In the search for simple outcome metrics, it might appear appealing and straightforward to use methodologies such as the NRC's and ascribe realized emission benefits to specific R&D programs. These outcomes could be tracked over time and assumptions monitored. For

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[32] Aside from a 240 MW petroleum coke facility, no other new IGCC plants were built in the US between 2000 and 2005.

example, only 240 MW of IGCC capacity rather than the NRC's projected 1700 MW were added between 2000 and 2005, and estimates of realized benefits could be adjusted accordingly. However, when evaluating federal R&D, it would be shortsighted to concentrate excessively on realized benefits and costs (NRC, 2001). This would inherently favor R&D programs that are near completion or that provide discrete near-term benefits.

A focus on realized benefits may also fail to address the timescale and magnitude of GHG reductions needed to achieve climate stabilization. Some observers view IGCC as potentially central to the success of carbon capture and storage as a major contributor to deep GHG emissions reductions. As a result, the options and knowledge benefits for the IGCC program may be more important any of the realized benefits shown in Table 6. Furthermore, conditions that turn an option benefit into a realized benefit can change very rapidly. The rapid commercialization of hybrid vehicle technology was likely unanticipated just a few years ago when the NRC report was published (2001). Hybrid vehicles utilize NiMh batteries, and will likely soon utilize lithium-ion batteries models (e.g. General Motors' Volt; Saturn Vue Green Line), technologies that have received considerable support from the advanced battery and other DOE research programs. Similarly for the IGCC program, its early support for the Great Plain gasification project in the 1980s, laid the groundwork for what became the first carbon capture and storage pilot in 2000 (the Weyburn project).

The NRC study itself emphasized that "mechanical" cost-benefit analyses of R&D investments are inherently problematic, since benefits will often not have fully materialized at the time of any retrospective study. Furthermore, options benefits are very difficult to evaluate without heroic assumptions and/or the use of mathematically complex option value techniques (Davis and Owens, 2003). R&D investments -- even those in efforts later judged as "failures" -- may contribute to the aggregate stock of scientific and engineering knowledge, with future benefits that cannot be estimated (Gallagher et al, 2004).

Another difficulty is the challenge of attribution of outcomes to a given R&D effort. If several ongoing R&D programs are concurrently trying to advance a technology − as is the case with most important technologies that have considerable potential − it is unclear how the outcomes should be allocated across these efforts. A related issue is what could be referred to as "additionality", after its notorious analog in offset or Clean Development Mechanism markets. As NRC notes, "all impacts [of R&D programs] should be measured relative to what would have happened without DOE." (p.92) Therefore, as with CDM projects, estimating program benefits requires a counterfactual scenario of how a technology would have otherwise developed absent the R&D program. One way of constructing a stylized counterfactual is to use a standardized procedure that sacrifices program-specific accuracy for simplistic but comparable estimates; in most cases, the NRC methodology follows such a standardized procedure. Where a DOE program was deemed successful in accelerating a technology's commercialization, it is generically assumed that the technology was commercialized five years earlier than would have otherwise been (e.g. as in the ballast case shown). This particular methodology is simple, but may tend to yield low estimates of benefits to the extent that five years is a conservative benchmark for how quickly the market would have otherwise changed. However, its validity still hinges on a fundamental counterfactual: in the absence of the DOE R&D program would the same technology have still emerged (perhaps owing to private sector R&D)? Or would another (and perhaps even better) technology have emerged instead? Ultimately, such assessments must rely heavily on judgment, and simple objective indicators may prove difficult to establish.

On the purely "mechanical" level, outcome assessment faces more mundane issues, including data availability and comparability across countries, consistency of evaluation methods, and the costs of conducting evaluations: the NRC report was US-specific, one-of-a-kind, and no doubt relatively costly.

This brief review suggests that *ex post* R&D outcomes can indeed be assessed, but that straightforward metrics that convey the full benefits of R&D would be difficult to establish. Methodologies for attributing realized benefits to R&D programs remain relatively crude and highly approximate, even retrospectively. But more importantly, estimates of realized benefit fail to reflect the central benefits of R&D in terms of option values and knowledge. R&D is essentially a gamble, in which a few "home runs" are responsible for the majority of returns on investments, which underscores the importance of maintaining a diversified portfolio of investments, rather than simply maximizing realized benefits (NRC, 2001; Gallagher et al, 2004). Widely credited with the spawning the internet, creating stealth technology, and advancing the global positioning system, the US Defense Advanced Research Projects Agency (DARPA) has, as one observed has put it, "successfully resisted 'bean-counting' measurements of success."(Lane, 2005, p.5) While periodic assessment of national R&D programs may be invaluable for building support and developing broad recommendations on future program design and appropriations, it is of limited value in providing robust metrics that can be used to compare policy outcomes, such as realized emission reductions.

3.4 Technology development outcomes: Ex ante scenario analysis of R&D scale-up

Now we turn our gaze forward: if R&D budgets for low-GHG technologies could be vastly expanded, as many scientists and policy makers urge, what outcomes might we anticipate? The previous section illustrated the challenges in assessing outcomes for historical R&D programs. However, historical or ex post R&D program assessments such as the NRC's are limited by design; they avoid projecting potential outcomes decades ahead, where, as the NRC itself notes, options and knowledge benefits will likely overwhelm any currently realized ones. Projecting possible future outcomes from R&D investment is the domain of scenario analysis, using models that seek to reflect the host of factors affecting technology development and penetration: market conditions (e.g. demand levels, fuel prices), competing technologies characteristics, and policy variables (e.g. incentives, regulations, and/or shadow prices), among others. Using scenario analysis, one can get a partial sense of how current option benefits of R&D might be realized in the future.[33]

As noted above, an increasing number of researchers are applying models to estimate the impact of energy R&D on future GHG emissions and societal costs. The methodologies used reflect the

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[33] Because scenario analysis, by definition, hand-picks only a subset of possible futures, it presents only a partial view of "option benefits."

classic split between top-down and bottom-up modeling approaches (Popp, 2005). Top down approaches, such as Goulder and Schneider (1999) and Popp (2004), consider accumulated knowledge (cumulative R&D investment) as a factor of production in a traditional macroeconomic modeling framework. The high level of aggregation in these models – typically, R&D investment is considered for the energy sector as a whole or a single representative technology – may offer greater transparency than more detailed bottom-up models with dozens of technologies and learning parameters, yet is a simplistic aggregate representation of the dynamics of energy systems. The potential to induce technology change and yield emissions and economic benefits differs significantly among sub-sectors and technologies; for example, R&D and learning-by-doing may yield significantly greater returns for less mature technologies such as fuel cells or renewable energy as compared with conventional power plant technologies. These returns will also be conditioned by the dynamics of the relevant sectors (e.g. the timing of new power plant requirements, costs of competing power sources, and hurdles faced by new technologies). Bottom-up models seek to capture these dynamics through detailed specification of energy demands by region and sector, and the dynamics of technology selection (comparative costs, hurdle rates, etc.).

For the purposes of illustrating the use of models to estimate outcome metrics for R&D investment, we develop a series of scenarios using the bottom-up POLES model.[34] These scenarios are designed to assess the response of global energy systems over a 50 year time-horizon to varying combinations of carbon shadow prices (a proxy for direct policy interventions in energy markets, such as carbon taxes or cap-and-trade systems) and R&D "shocks" (up to a three-fold increase from current R&D levels). From this analysis, we seek to draw insights regarding the relative impact of R&D investment in *known* technologies, tempered by the limitations of the two-factor learning curve approach and deterministic modeling frameworks.

The "two-factor learning curve" lies at the heart of the bottom-up model analysis. The two factors refer to R&D investment ("learning-by-researching") and cumulative production ("learning-by-doing"), which comprise the main contributors to technology change (Sagar and van der Zwaan, 2006). These two factors can be represented using a conventional learning curve equation, wherein a doubling in cumulative R&D investment or cumulative production results in a decline in a technology's cost by a given percentage, i.e. a "learning rate".[35] These learning rates are typically derived from historical data, and have been applied across a variety of technologies as illustrated in Figure 4.[36]

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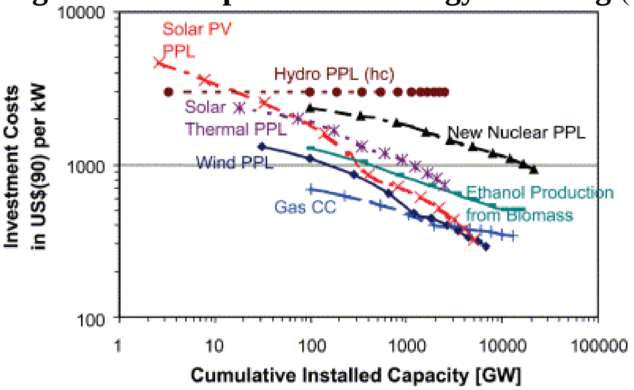
[34] For a fuller discussion of the POLES model, see Criqui et al, 2006.

[35] In "The Economic Implications of Learning by Doing" (1962), Kenneth Arrow observed that manufacturing costs tend to decline with the level of experience in manufacturing rather than with time. As more and more units are produced, manufacturers find ways to reduce costs by using materials more efficiently, improving processes, increasing economies of scale and so on. Manufacturing cost per unit (C) is a function of the cumulative output produced (O) and an elasticity β , expressed as $C = k X^{\beta}$, where k is a constant. The "progress ratio" is defined as the percentage to which cost declines with each doubling of X, and is given by 2^{β}. Similarly, the learning rate $1 - 2^{\beta}$ is the fraction by which cost is reduced by a doubling). The two-factor learning curve merely adds another variable for cumulative R&D spending (R, typically covering both government and private R&D) and elasticity, such that $C = k X^{\beta} R^{\sigma}$

[36] Kouvaritakis et al (2000) were among the first to expand the simple learning-by-doing model to include "learning-by-researching", a concept further expanded by several other researchers (Kobos et al, 200x; Miketa and

Figure 4. Examples of Technology Learning (from Riahi et al, 2004)



While capturing some important technology and energy system dynamics, the two-factor learning curve approach is not without its weaknesses. Empirically-derived learning curves, by definition, can only reflect known technologies that have "survived the natural technology selection process" (Sagar and van der Zwaan, 2006, p. 2605), an effect sometimes referred to as survivorship bias. Learning rates can only be estimated for technologies that have been deployed at sufficient scale to enable the meaningful analysis of cost trends; however, a considerable amount of R&D is directed at technologies that have not advanced to this stage. As a result, models based on learning curves have considerable difficulty in representing more radical technological change. Like other empirically-based parameters such as price elasticities, learning rates also suffer from the implicit assumption that future trends will resemble the past. On a broader level, the two-factor learning curve approach does not capture the opportunity costs of learning. In particular, R&D in the energy sector may "crowd out" R&D in other sectors, limiting the availability of skilled researchers and research funding, and thus economic growth, in other sectors. Taking this into account, Popp (2006) finds that crowding out can limit the economic gains from induced technological change, though the magnitude of this impact depends on the extent of crowd out, which has been debated in the literature.[37]

We develop three stylized scenarios for the POLES model analysis, distinguished by global emphasis on action to address climate change. The *limited action* (LimAct) scenario presumes slow and weak interventions that increase the carbon price from 10€/tCO2 in 2010 to 30€/tCO2 by 2050 in Annex 1 countries (all prices in 2005€).[38] For this and other scenarios, we make the

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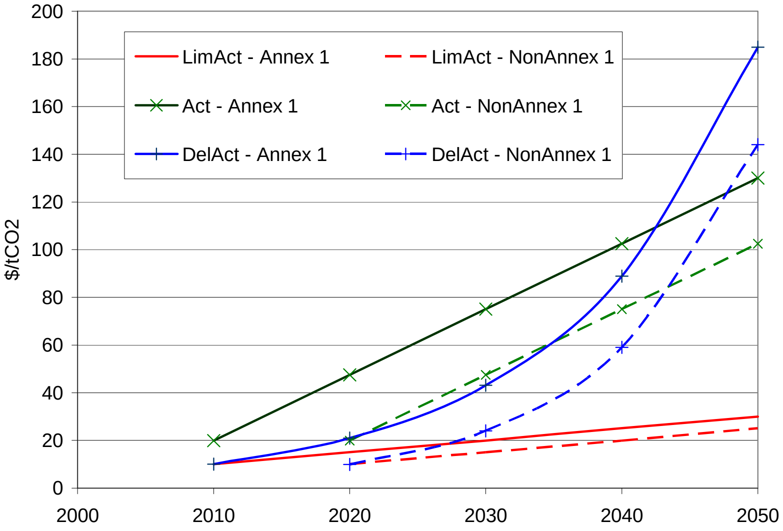
Schrattenholzer, 2004). Building off of these developments, the POLES model considers some key dynamics absent from early learning curve formulations, including: a) technology floor costs, based on expert judgment; b) spillover in learning among related or clustered technologies; and c) depreciation of accumulated knowledge (older research being worth less over time). As such, POLES and its two factor learning curves provide a potent analytical tool for assessing the future R&D investment as well as direct GHG policies (e.g. carbon taxes) on future technology costs and penetration, and on global GHG emissions (Criqui et al, 2006).

[37] For example, in stark contrast to the notion that R&D is a limited resource, Nemet and Kammen (2007) considering past trends in US R&D patterns, find that "large government R&D initiatives [have been] associated with higher levels of both private sector R&D and R&D in other federal programs."

[38] The 2010 value is relatively consistent with the current price amongst the Annex 1 parties to the Kyoto Protocol. While the US and Australia are not currently Kyoto parties, vigorous GHG mitigation initiatives currently under way at the sub-national level in these two countries, along with signs that Kyoto parties are unlikely to move

simplifying assumption that non-Annex 1 (developing) countries follow a similar trajectory for action (i.e. carbon shadow price), but with a ten-year lag, as illustrated in Figure 5.[39] The *action* scenario presumes significant societal pressure and political will to address climate change, leading to the implementation of policies that increase the price of carbon linearly from 10 €/tCO2 in 2010 to 130 €/tCO2 in 2050 in Annex 1 countries.[40] The *delayed action* scenario, in contrast, posits slower but eventually more significant action, as represented by a quadratic rise in the price of carbon, which exceeds the level of the *action* scenarios by 2040.[41]

Figure 5. Assumed Carbon Shadow Prices, by Scenario



We select these carbon shadow price assumptions specifically to elucidate the relative impact of R&D investment. Each of these three scenarios is then analyzed for three different variants of R&D investment: a) business-as-usual, i.e. no change from current public and private spending by technology and region; b) ramp-up to a three-fold increase in OECD R&D[42] funding levels by

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forward post-2012 without the US on-board, suggests that the strength of climate policy will be unlikely to differ significantly across Annex 1 countries in the longer term. As a result, we treat Annex 1 as a single region in terms of carbon price, even though the model provides the capability country-specific specification.

[39] We recognize that it is highly unlikely that developing countries would be capable of, or agree to, paying for such levels of action on their own. We simply take the view that significant action in the South is necessary under any scenario that aims to avoid dangerous climate change; who pays for that action is not the subject of this paper.

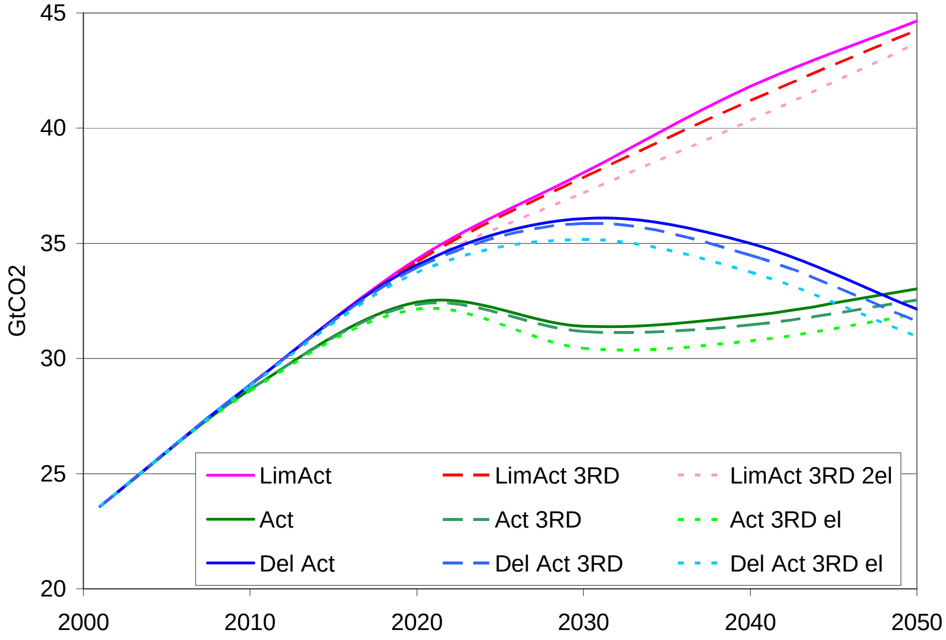
[40] It is also important to note that we do not attempt to assess the level of response that might be needed to avoid major climate change risks, as is done in scenarios that aim to reach, for instance, 450ppm CO2 or 2 degree maximum warming scenarios. (Meinshausen et al., 2006; Hansen et al, 2006)

[41] Widely-cited analysis by Wigley, Reilly, and Edmonds (1996) suggests that there may be advantages to delaying action in order to benefit more fully from investments in R&D and technology development. Therefore, we consider whether R&D would provide greater benefits in such a scenario. However, we caution readers not to draw conclusions regarding the desirability of delaying action from this analysis, which would require a different analytical framework and scenario assumptions. Such a comparison requires a framework that accounts for the risks and uncertainties regarding future climate damages (Stern, 2006). It is the largely interactions of R&D and the timing of action that we aim to observe here.

[42] Significantly reduced returns (emission reductions) to investment were found at higher levels of R&D funding. The three-fold increase was selected on this basis, and in consideration of existing calls to significantly increase

2010, maintaining these levels through 2030, with increased funding directed towards renewable energy, carbon capture and storage, fuel cells, hydrogen, and advanced vehicles[43]; c) the same three-fold increase in R&D, coupled with an assumption that R&D can be made twice as effective in terms of yielding cost reduction (i.e. doubling the learning-by-researching progress ratios).

Figure 6. Global Energy-related CO2 Emissions, 2001-2050, by Scenario



LimAct = Limited Action scenario; Act = Solid lines correspond to energy R&D investments continuing at current levels; dashed lines correspond to a tripling of overall energy R&D investment, directed towards low-GHG technologies; dotted lines correspond to same tripling but with assumed doubling in R&D effectiveness.

As illustrated in Figure 6, modeling results appear to show that the overall emissions reductions available from R&D investment in known technologies are limited. The modeling analysis suggests that a reduction in global emissions of no more than 4% by 2050 would be directly attributable to a three-fold increase in R&D funding, even assuming a doubling in R&D effectiveness. (In fact, the greatest benefit associated with increased R&D funding come in the Action and Delayed Action scenarios, both in relative and absolute emission reductions, further suggesting the complementarity and synergism of R&D and direct GHG policies.) This finding does not, however, indicate that a) R&D is not worthwhile, or b) that increased R&D might not be essential to addressing the climate problem.

On the contrary, at the levels considered here (three-fold increase in current levels), energy R&D appears to be a highly cost-effective investment, yielding emission reductions at lower cost than

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R&D spending (NCEP, 2003; Schock et al, 1999; Kammen and Nemet, 2005). It is assumed that private R&D would increase in concert with increased public R&D.

[43] For simplicity, R&D funding levels were increased proportionately to current funding levels by technology type. More targeted R&D funding strategies might yield greater returns to investment.

many other policies and possibly yielding important positive technology externalities.[44] Furthermore, R&D is a source of technology "breakthroughs" or "surprises" that are not modeled here. Such a breakthrough could be the trigger for a significant evolution in our energy use patterns, through a major transition to low emission transportation infrastructures, fuel and electricity supply systems, and development patterns. Such discontinuities, however, are difficult to anticipate and model in any deterministic analytical framework, such as the one used here. It is important, therefore, to frame these findings within the dynamics and limitations of this modeling analysis.

First, it is important to recognize that *the productivity of R&D investment*, in terms of cost reduction and performance improvement, is based on a combination of historical experience and expert judgment for a discrete set of *known* energy technologies. The POLES TFLC approach benefits from a richness of technological detail often missing from macro-economic modeling of R&D.[45] Therefore, the modeling approach contains a "realism" often absent from other approaches. At the same time, as with all econometrically-based models, there is an implicit presumption that the future will mimic the past. It is quite possible that progress ratios could be improved by better R&D practices, a rationale for investigating the doubled R&D effectiveness variants presented here.

This modeling approach focuses on known technologies, and also assumes they are subject to *incremental* improvements – a change in cost and penetration rate of a few percent per year. This approach is certainly more appropriate for the electricity, building, and transport sectors than most consumer product sectors, due the significant inertia of often long-lived capital stock and relative immunity of these sectors to rapid changes in cultural preferences (aside from vehicle choice). Nonetheless, some argue that the best hope for a solution to the climate challenge lies in radical changes and in technologies that may be more distant from the drawing board: yet to be demonstrated technologies for electricity storage, hydrogen production, global electricity transmission, fusion, or other (see Hoffert, et al, 2002). Such changes are indeed difficult to consider in any modeling framework.

In this respect, Gallagher (2005), drawing on Freeman (1992) provides a useful typology of technological change, outlining four broad types of change:

- incremental innovations that typically occur continuously as industries try to improve quality, design, performance, and adaptability;

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[44] Model results suggest that the reduction in technology costs far exceed the costs of R&D, leading to a net social cost benefit. Model results do not enable a full cost savings analysis, however the following partial results are telling: the cost reductions accruing from a three-fold increase in public R&D spending (an added $20 billion per year by 2030) yield savings in overall energy technology investment costs of over $300 billion US in 2030 (for the "Action" scenario). Given that the R&D increase leads to a 0.7% reduction in global energy-related GHG emissions, suggests that fuel expenditure savings will be considerable as well.

[45] For example, macroeconomic models often assume a single productivity factor for knowledge stock for the energy sector as a whole, one each for low-emitting vs. high-emitting technologies and resources, and in some cases for a backstop technology (e.g. Popp, 2006). This approach does not typically take into account the competition among different resources and technologies, and are thus unable to identify when new technologies are likely become cost-competitive with incumbent technologies, nor the market dynamics whereby incumbents (e.g. oil suppliers) might lower prices in response to a competitive, new technology.

- radical innovations, discontinuous inventions that are usually the result of deliberate research and development that lead to a radical departure from previous production practice (such as Schumpeter's example of stage coaches to railways);
- changes of technological systems, far-reaching changes in technology as a result of a cluster of radical innovations that affect several branches of an economy; and
- changes of techno-economic paradigm, those technological systems that affect directly or indirectly every other branch of the entire economy (such as the information and communication technology revolution).

Energy system models such as POLES and even macroeconomic models as described by Popp, 2006; Wing, 2006) are generally capable of reflecting the first type of technological change, i.e. incremental innovation. However, they tend to capture radical innovation and changes in technological systems in only a very limited manner[46], and are likely unable to reflect the deeper changes of techno-economic paradigms.

Overall, this case study illustrates that models can indeed be used to estimate the emissions impacts of R&D investment. However, such findings are subject to large uncertainty; the projected outcomes depend heavily on model choice, key assumptions, and a multitude of parameters (e.g. learning rates) that are not necessarily well understood. While models could eventually be used to develop outcome metrics for R&D, they currently lack the robustness needed to guide policy design. Further research and empirical grounding could enable models to provide improved prospective estimates of R&D outcomes for commercial and near-commercial technologies (e.g. solar PV, wind), technologies for which future learning coefficients (R&D and learning by doing) can be reasonably extrapolated from historical trends. Further research is also needed to marry the strengths of the top-down and bottom-up models and thus capture both energy system dynamics and macro-economic feedbacks (e.g. crowd out effects), perhaps including stochastic uncertainty into learning curves. However, it is unclear whether mathematical models could ever adequately reflect unknown or immature technologies, the complexities of innovation, the exploratory nature of research, or the nature of radical or disruptive technology transitions.

3.5 Technology diffusion and deployment: OECD renewable energy policies

In comparison with R&D, technology diffusion and deployment represents a more tangible stage at which to attempt to quantify outcomes – penetration rates can be measured, and the displacement of higher GHG-emitting technologies can be estimated using established methodologies. Indeed, markets for CDM and other GHG offset projects are built upon this premise (though arguably they have the perhaps easier job of quantifying evaluating individual projects featuring a given technology, rather than the overall diffusion of the technology.) Unlike R&D however, where budget allocations and spending are often clearly defined, effort directed towards diffusion and deployment can prove much harder to define and quantify than outcomes. Typically many actors are involved (government agencies from local and national

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[46] For example, POLES models the potential transition to hydrogen vehicle technologies, which has elements of radical innovation and represents something of a change in technological systems. However, it presumes conventional travel patterns, economic structures, and urban configurations, which might all change in unforeseeable ways as a result of a radical technology transformation – just as in the case of the historical shift from stage coach to railway.

levels; private sector players from developers to retailers), and multiple policy levers are utilized, from technology standards to incentives to mandates.

Renewable electricity technologies represent a potentially fruitful area to explore metrics for diffusion and deployment, given they represent a well-defined and closely monitored set of GHG mitigation technologies, with a long history of public policy initiatives and a multitude of private sector actors. Public policies to support renewable energy include, for example, direct price supports (feed-in tariffs[47] and standard offer contracts), quantity targets (renewable portfolio standards or obligations[48]), tax breaks and subsidies (production tax credits, tax exemptions), and purchasing strategies (green power options and obligations) (Martinot, 2005; Eurelectric, 2004). (In addition to renewable electricity, there are growing deployment activities for renewable fuels, in particular ethanol and biodiesel, and to a lesser extent some recent resurgence of interest in solar water heating.[49])

Over 50 countries have implemented a variety of renewable electricity policies, rendering a comprehensive assessment of overall effort and outcome somewhat premature and rather complex (OECD/IEA, 2006; Martinot, 2005). For simplicity, this analysis focuses on two deployment strategies for renewable electricity. The first is tax-related subsidies, for which level of effort could be inferred as subsidy costs, but outcome is more uncertain. The second is the renewable obligation, for which outcome (if obligations are achieved) is straightforward, while effort is less obvious, but for which some indication can be inferred through analysis of incremental costs.

Table 7 illustrates the comparative levels of support for renewable electricity deployment via these two strategies in selected OECD regions, and projected outcomes in terms of incremental renewable generation (TWh) and resulting emissions reductions. The EU's ambitious renewable electricity obligations and feed-in tariff policies appear to have delivered nearly 100 TWh of renewable electricity in 2001, and are expected to result in over 300 TWh of renewable generation by 2010 across 15 countries (see sources in Table 7). In comparison, renewable obligation or portfolio standards are expected to deliver nearly 10 TWh in Australia and about 5 TWh in Japan, as well as over 50 TWh in the US due to initiatives at the individual state level and the indirect support provided by the federal Production Tax Credit.

In terms of the direct cost implications for consumers and utilities (and taxpayers), Europeans provided over $4 billion in direct support in 2001, while the US provided economic support an order of magnitude lower ($0.4 billion). Assuming renewable obligations in place as of 2003/4

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[47] According to Martinot (2005), "by 2005, at least 32 countries and 5 states/provinces had adopted such policies, more than half of which have been enacted since 2002." (p.20)

[48] According to Martinot (2005), as of 2005, "43 countries, 18 U.S. states (and the District of Columbia) and 3 Canadian provinces have targets based on renewables portfolio standards." (p.20)

[49] Currently in vogue, biofuel support strategies are particularly complex to evaluate in terms of contribution to GHG emissions reductions: subsidies for ethanol production can be significant but difficult to track (overlap with farm subsidies), and the relative emissions impacts are highly dependent on the fuel, feedstock, and farming practices. Draft estimates by Koplow (2003) prepared a few years ago suggest that federal ethanol subsidies in the US ranged from $1.3 to $2.1 billion, and with the increased support in recent US federal and state legislation this amount appears to have risen to $5 billion to $7 billion in 2006. (Koplow, cited in Business Week, March 19, 2007).

are achieved by 2010, Europeans will be supporting renewable electricity deployment at the level of nearly $15 billion compared to less than $1 billion in the US, and $300 million each in Japan and Australia.

Table 7. Renewable Electricity Support in Selected OECD regions

	Support for Renewables*		Incremental Cost		Incremental Generation		Emission Reductions**	
	Billion $US (2004)		US c/kWh		TWh		MMtCO2	
	2003* **	**2010**	**2003*** **	**2010**	**2003*** **	**2010**	**2003*** **	**2010**
EU15	$4.3	$14.9	5.0	4.7	87	317	47	165
Australia		$0.3		3.7		9		8
Japan		$0.3		5.4		5		4
US, of which	$0.5	$1.2	3.8	2.9	7	53	6	43
State Renewable Portfolio Standards****	*$0.1*	*$0.5*	*2.0*	*1.0*	*7*	*53*		
Federal tax credits	*$0.4*	*$0.7*	*1.8*	*1.9*	*n/a*	*n/a*		

Sources: Eurelectric (2004), US OMB (2006), Petersik (2004), US DOE EIA, UNFCCC National Inventories, Energy Supply Association of Australia, Nishio and Asano (2003), authors' estimates

* Excludes large hydro

** Emissions reduction estimates assumes recent year average emission rate of thermal resources

*** Data reflects 2001 for EU, 2003 for other countries

**** Estimates are based on RPS policies in place in as of 2003, and do not significant increases in RPS targets since that time.

While subject to incompleteness (in terms of coverage of deployment efforts) and considerable uncertainty (in terms of impacts), the above estimates illustrate that comparative effort and outcome can be at least roughly estimated for selected deployment strategies, in this case support for renewable electricity resources. However, the disparate sources used to compile these estimates use somewhat different methodologies, e.g. for attributing increased renewable penetration to specific policy initiatives and estimating incremental costs.[50]

This brief analysis suggests, not surprisingly, that development and assessment of metrics for technology deployment and diffusion is more tractable than for R&D investment, but that significant work would likely be needed to develop consistent data and attribution methodologies. Some policies do imply a quantifiable level of effort, such as an explicit subsidy (like a feed-in tariff), foregone tax revenue (for a production tax credit), or consumer premium (for green power marketing). However, many of the high-impact diffusion and deployment policies, such as technology standards or mandates, are not explicitly framed in a manner that lends itself to quantification of the required effort. For example, renewable obligations and standards, are not associated with specific financial inputs, though their financial implications can be costed (i.e. incremental cost analysis). Furthermore, incremental costs are not necessarily comparable to the costs associated with subsidies; the latter are a measure of actual transfer

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[50] The EURELECTRIC estimates large focus on direct (off-budget) support and do not cover: “indirect support” (i.e. added costs of intermittent non-dispatchable resources), tax fiscal subsidy supports, R&D contributions, among other costs.

payments, which may not reflect incremental costs, especially in cases where subsidy programs are inefficiently designed.

Renewable energy policies in a given country are often multiple and overlapping, and have synergistic effects: a combination of incentives, standards, and barrier removal policies may achieve far greater impact than the same policies implemented in isolation (Martinot, 2005). Therefore, assessing the effort entailed by individual policies may be more difficult than assessing the effort of aggregated policy packages. Nonetheless, simply compiling and comparing the estimated impacts of technology deployment policies using consistent methodologies, whether for renewable energy or other emission-reducing technologies (efficiency, biofuels, fuel switching, etc.), as with R&D metrics above, could help to inform policy makers, build trust, and spur improved analysis and reporting.

3.6 International technology cooperation and transfer: GEF, AP6, and national plans

Of all categories of action considered here, international technology cooperation and transfer is perhaps the least amenable of all to metrics and quantification of effort and outcome. Yet it remains one of the most critical areas for tackling the climate issue, given the global nature of the problem, the fundamental disparity between the historical contributions to climate forcing and the financial/technological resources of OECD countries on the one hand, and the rapid emissions growth and financial/technological needs of the non-OECD countries on the other. Many pages have been written on modalities and challenges of climate technology transfer (IPCC, 2000), and over a dozen major international technology cooperation initiatives have been launched since the Rio conference in 1992. These include among others, the Climate Technology Initiative, Global Environment Facility (certain operational strategies and activities), the Carbon Sequestration Leadership Forum, the International Partnership for a Hydrogen Economy, the ITER nuclear fusion effort, various IEA task forces and implementing agreements, as well as numerous bilateral and other efforts. (See Philibert, 2005 and Gallagher and Holdren, 2004 for useful discussion).

Most recently, the G8/Gleneagles process and the AP6 have grabbed headlines with various new and repackaged efforts at international technology cooperation. In spite of the popularity and abundance of such initiatives, estimates of total contributions by different parties and evaluations of impacts/outcomes are scarce (at least in the publicly-available literature). In the US, as Gallagher and Holdren (2004) note, it remains unclear how much money is spent on international energy technology collaboration, and few systematic analyses have sought to examine the dynamics and benefits of such activities.

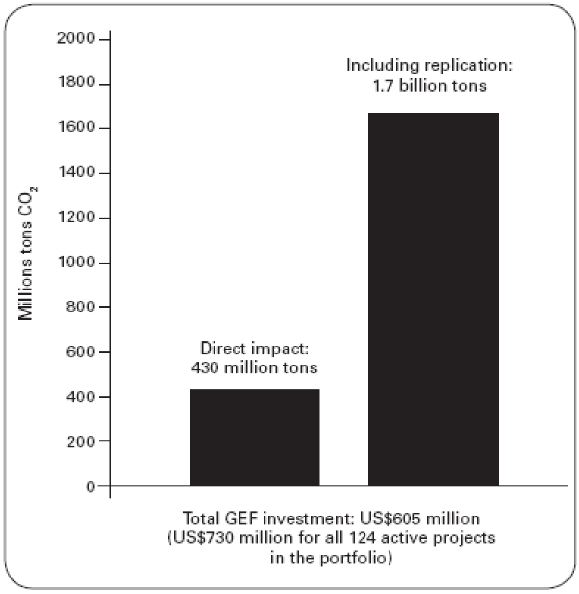
The paucity of evaluations is not completely surprising. Some efforts like the CTI have focused primarily on providing fora for stakeholder interaction (e.g. technology needs assessments), have changed course over time, and in spite of considerable fanfare have actually possessed limited funding for follow-up activities. Perhaps most importantly, though, the assessment of such programs is very difficult. It is widely presumed that exchanges and interactions can be the catalysts for change. However, establishing causal linkages between specific cooperative activities and technological advances or future emissions reductions is by no means straightforward.

It is difficult to attribute outcomes to cooperative activities for several reasons. First, the most promising cooperative opportunities often where technologies are already commercial, but slow diffusion or market barriers have thus far restricted their penetration. It can thus be difficult to distinguish the impacts of a cooperative activity from the normal dynamics of emerging technology markets. Second, intellectual property rights and the maintenance of competitive advantage are major concerns in international technology cooperation. This can lead to a certain level of deliberate non-transparency; simultaneous global negotiations underway to address these issues, e.g. through the World Trade Organization, may form a dominant backdrop against which it can be difficult to detect the influence of specific cooperative agreements.

Having spent over $1.5 billion on climate change initiatives since the early 1990s, the Global Environmental Facility provides a case of a technology cooperation and transfer program with a lengthy history and extensive evaluation. The most recent evaluation estimated that over 2 GtCO2 of cumulative lifetime emissions reductions could be attributed to GEF's overall climate change portfolio, as shown in Figure 7. Assuming an impact lifetime of 20 years, this corresponds to about 100 million tons CO2 saved per year. By way of comparison, the annual emissions reductions associated with the GEF climate portfolio to date are about half of the projected direct annual emissions reductions associated the EU's renewable electricity policies (165 million tons CO2 per year in 2010). The total GEF climate budget to date is an order of magnitude lower than projected annual cost of the EU's renewable policies in 2010 ($15 billion per year, see Table 7), suggesting it is a singularly effective program.

These seemingly stark differences in cost-effectiveness are attributable to a number of factors. First of all, the GEF portfolio includes a number of energy efficiency and other projects that yield significant emission savings at lower costs than many renewable energy technologies.[51] More importantly, the GEF is designed as a leveraging program. As shown in Figure 7, only one-fourth of the estimated GEF program emissions savings are directly attributable to the GEF-funded activities; three-fourths are indirect benefits, associated with replication, learning, improved enabling environments, development of markets, and improved access to finance catalyzed by GEF activities (Eberhard et al, 2004). In the EU renewables example, only direct benefits are considered; similarly, the EU renewable electricity cost estimate represents the full estimated incremental technology cost, a theoretical construct[52], whereas the GEF

Figure 7. Projected CO2 Reductions from Active GEF Projects (Eberhard et al, 2004)



* For 104 projects having CO_2 estimates.

total emission reductions shown in Figure 7 (Eberhard

gy minus the cost of the avoided or displaced costs are actual budgeted project expenditures. The EU-GEF comparison serves to illustrate the challenges in comparing effort and outcome across different policy types and contexts.

By design, the GEF seeks projects that catalyze, innovate, and stimulate learning rather than simply maximize near-term direct emission reductions.[53] A notable GEF success story is the China Industrial Boilers project, the largest GEF climate project to date, accounting for a third of all emission reductions associated with the GEF portfolio (Eberhard et al, 2004). It is widely credited with transforming the market for Chinese industrial boilers, through technical assistance and modernized designs, a success attributable to transferring not only technology, but knowledge and intellectual property rights (Philibert and Podkanski, 2005). The GEF's emphasis on the innovation and learning benefits of technology cooperation and transfer is similar to the NRC's emphasis of knowledge and options benefits associated with R&D investment; the common implication is that a focus on metrics of direct, realized benefits may miss the most important outcomes.

At the same time, quantified estimates of indirect benefits (e.g. including replication) are based rather subjective assumptions; and should be viewed as significantly more uncertain than estimates of direct benefits. Eberhard et al (2004) note several problems with the analysis of emissions reductions, including the consistency of supporting assumptions across projects, and the rather subjective methodology used to assign a causality factor to replication, and call for the development of a more coherent GEF-wide methodology.

As illustrated in Box 2 below, the AP6 provides an example of international technology collaboration where the future emission benefits have been projected (Maytsek et al, 2006). These projections are based on a series of rather heroic assumptions regarding the linkage between general types of actions (R&D, foreign investment, etc.) and outcomes, rather than on empirically or theoretically-based relationships, such as those discussed in the R&D outcome section above.[54] Such an approach may be reasonable for an illustrative scenario analysis, with suitably caveats. By providing some bounds on the range of possible impacts, and illuminating the assumptions to which those impacts are particularly sensitive, such analyses can possibly help design better policies. However, such analyses are inevitably based on untestable assumptions, in the same manner as other notable scenario analyses of R&D impacts (Schock et al, 1999; Nemet and Kammen, 2007), where judgment-based probabilities are assigned to the likelihood that R&D will succeed at enabling target CO2 concentrations to be achieved.

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[53] GEF management notes that "the most important role for GEF in the climate change focal area is to be a catalytic force—focused on innovation and learning—aimed at assisting developing countries to meet their sustainable development goals while protecting the climate." Management Response in Eberhard et al, 2004

[54] For example, the "collaborative partnership action on technology is assumed to increase the energy efficiency and uptake of advanced technologies in partnership regions…. In the electricity generation sector, collaborative R&D on fossil fuel technologies is assumed to result in improvements to energy efficiency, relative to the reference case." (Maytsek et al, 2006, p.43) Similarly their global scenario assumes that "actions taken by partnership countries to accelerate the development and uptake of advanced energy technologies are assumed to diffuse to nonpartnership countries via trade, foreign direct investment and aid associated with relevant technologies, as well as through mobile capital and labor markets." (Maytsek et al, 2006, p.45-46)

From the GEF and AP6 examples, it is not clear that either *ex post* or *ex ante* analysis of international technology collaboration is rigorous enough to provide outcome metrics that are sufficiently credible to serve as a basis for international climate policy. Given these limitations, it might be preferable to consider effort rather than outcome metrics for international technology cooperation and transfer. As with their energy R&D budgets, many countries also report their spending related to international cooperation. For example, in its fiscal year 2007 climate change budget, the US administration requested about $220 million for international assistance (OMB, 2006). Of this, $17 million was the US contribution to the GEF climate portfolio, about $30 was for the Asia-Pacific Partnership (AP6), and $110 million for USAID "development assistance". The diversity of different budget items labeled international assistance makes it difficult to assess in a standardized way the actual level of effort devoted to climate technology cooperation. While the former two items in the US package might be reasonable labeled climate technology cooperation, it is unclear how much of the USAID portfolio should be included.[55]

Box 2: The Asia-Pacific Partnership: Why common metrics are important:

The Asia-Pacific Partnership on Clean Development and Climate (AP6) represents a multi-lateral effort to address climate change and development through largely voluntary, technology cooperation activities that target "expanding investment and trade in cleaner energy technologies, goods and services in key market sectors." (http://www.asiapacificpartnership.org/)

In keeping with the theme of this paper, then, how might one compare the AP6 to other climate initiatives in terms of effort or outcome? With respect to effort, it is too early to say, since only a few governments have specified and secured their financial contributions and the precise project portfolio is unclear. With respect to outcome, on the other hand, a commissioned analysis provides a scenario analysis to indicate the potential emissions benefits (Maytsek et al, 2006), as illustrated in the figure below.

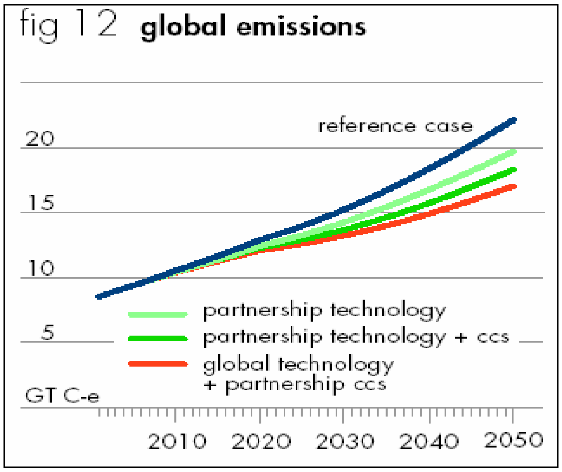

Figure 8. (Maytsek et al, 2006)

While the emissions benefits of partnership scenarios is clearly far from sufficient to achieve the deep reductions needed to avoid dangerous climate change, the chart suggests that partnership efforts – such as increased R&D expenditure, increased technology transfer, capacity building, and technology-oriented goal-setting – could provide significant reductions, on the order of 10 to 25% over the next 40 years. These study results derive from a hypothetical scenario approach, assuming a linkage between actions and outcomes, rather than from an empirical analysis or model of such linkages. The judgment-based methodology is not unreasonable, given the high complexity, large uncertainties and limited understanding of technology development and transfer. However, if the AP6 is to be compared with other climate policies and measures – which it surely will be, even if this is not its stated intent – the metrics and tools used to measure potential outcomes will need to go beyond judgment-based scenario assessments.

For national budget reporting to provide metrics for effort on international climate technology cooperation, reporting standards would need to be developed and agreed upon.[56] An alternative approach, which would sidestep the challenges of developing a common reporting standard, would be to focus on efforts that are conducted through specific internationally vetted channels, such as those directed through common global climate technology programs such as the GEF. (See Table 8 for a comparison of GEF contributions per unit of GDP.)

3.7 GHG Intensive Policies: Fossil fuel subsidies

A category of policies that may have a significant impact on GHG emissions are those relating to the development and deployment of fossil fuel technologies. Metrics intended to reflect the net effort or outcomes of a nation's climate-related actions would have to consider fossil-fuel policies for two reasons: first, because the fossil-fuel policies in place strongly determine the nature of a nation's emissions. No assessment of government effort or outcome related to GHG emissions is complete without addressing the policies that could effectively "undo" benefits of the GHG mitigation efforts described above such as subsidies to fossil fuel R&D, production and use. Second, among the most important steps a government can take to level the playing field for low-carbon technologies is to reform or eliminate existing support for fossil technologies. To be meaningful, metrics should recognize those efforts and their outcomes, as well.

The field of environmental economics contains a rich vein of literature on the impacts of subsidies and subsidy reform, and policies that promote fossil fuel consumption and production feature prominently in nearly all. (Pearce, 2003; Golberg, 2000; Koplow and Dernbach, 2001) By some estimates, globally, subsidies for fossil fuel use and consumption may exceed $150 billion per year, as shown by region in Figure 9 (de Moor, 2001). According to various estimates, reform of fossil fuel subsidies could reduce global CO2 emissions by up top 8% and by up to 20% in selected countries where subsidies for fossil fuels are more pronounced (Pearce, 2003; Koplow and Dernbach, 2001).[57]

Much like the R&D, technology deployment, and international collaboration policies noted above, energy subsidy assessments are notably challenging. As the above, they take various incommensurable forms – among them, tax credits, price controls, depreciation policies, preferential loans or interest rates, direct government spending on energy and/or transport infrastructure, and failure to reflect external costs. But perhaps more difficult is the challenge

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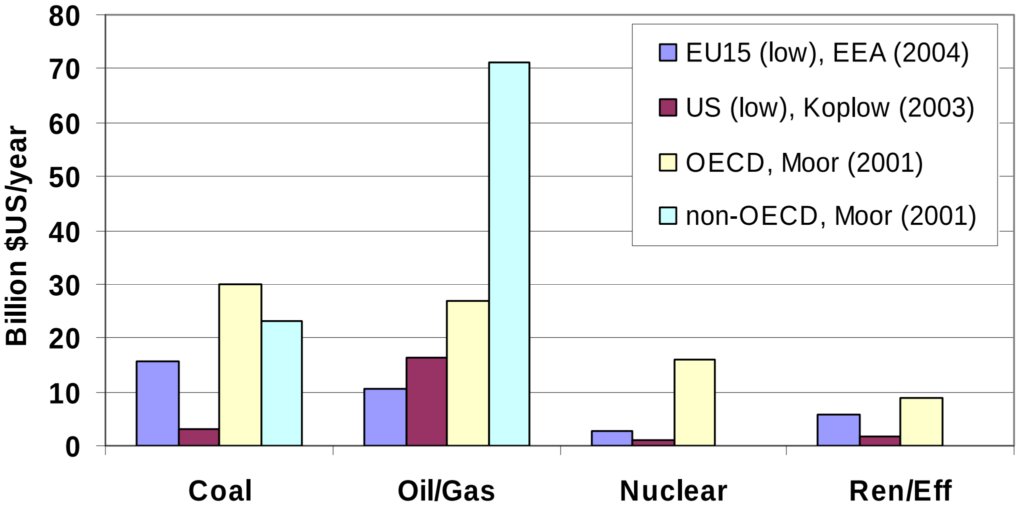
[56] This could entail various challenges, such as identifying which technologies are legitimate targets of climate technology assistance (cooperation to achieve marginal improvements in fossil fuel use?); dealing with cooperation that is broadly shared across climate technology and other development goals (e.g., investments in post-secondary education and technical training); distinguishing efforts that are aimed at climate technology cooperation from efforts that are primarily about export promotion and may happen anyway; and accounting for the effectiveness of resources spent, given that some efforts are intensively focused on cooperation, while others may be more diluted (e.g., tied aid that may have less technology transfer benefits).

[57] "A study by the OECD for example, shows that global carbon dioxide emissions would be reduced by more than 6 per cent and real income increased by 0.1 per cent by 2010 if all subsidies on fossil fuels used in industry and the power sector were removed everywhere in the world." UNEP/IEA, 2002, p.16.

posed by the general lack of transparency of information on subsidy policies (Koplow and Dernbach, 2001).[58]

Figure 9. Estimates of energy subsidies, various sources[59]



In the case of subsidies and subsidy reform, government expenditures and economic cost would be poor, if not perverse, indicators of effort. Efforts to reduce subsidies for fossil fuels would *reduce* government expenditures and societal cost, while improving GHG emissions. The converse is also true: increasing fossil subsidies *increase* cost and expenditure, while worsening GHG emissions. These effects are opposite in direction to those one attempts to capture due to most climate-related policies, such as R&D or support for international cooperation.

Clearly reducing subsidies for fossil fuels would appear to generate clear economic and environmental gains, and could be achieved in many cases with a stroke of the legislative pen. What is, then, the effort associated with subsidy removal? As de Moor (2001) puts it, “there are a number of lock-in mechanisms that create addiction to subsidies and make subsidy reform so extremely difficult to pursue”. Resistance to subsidy reform can result from rent-seeking behavior, regulatory capture, and the fact that apparent losses are often concentrated among a few actors, who might depend on subsidies for survival, while the benefits are dispersed. In some cases, removal of subsidies can have negative social impacts, e.g. on household budgets, unless removal is gradual and “safety nets” are created (Pershing and Mackenzie, 2004). Since

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[58] In their exhaustive review of subsidies to fossil fuels, and studies thereof, Koplow and Dernbach (2001) note that while there is wide agreement that subsidies “represent a transfer of economic resources to market participants that affects either prices or production costs”, there can be sizeable difference is how such definition is interpreted. They cite estimates for annual fossil fuel subsidies in the US that span four orders of magnitude from $200 million to $1.7 trillion. In general, the lower estimates use very narrow definitions of subsidies (e.g. including only on-budget subsidies), whereas higher estimates often consider energy security costs (military costs attributed to maintaining oil supply) and external costs not included in prices.

[59] Both US and EU are "low" estimates by study authors. Estimates do not include government R&D spending. US estimates include $12 billion in defense-related costs for security oil supplies.

subsidies can also provide competitive advantage to national industries, removal can be a prisoners' dilemma problem, and an issue of relevance to international trade negotiations. This makes it particularly important that such measures are reflected in assessment metrics that are intended to be useful for international climate regime.

A common theme of the subsidy reform literature is the critical importance of increasing the transparency of information on the extent, nature, and impact of subsidy policies (Koplow and Dernbach, 2001; Moor, 2001). Koplow and Dernbach (2001) suggest, for example, that the public review procedures used to make environmental regulation more transparent (and to assess their costs and benefits), along with justification and impact assessment methods, could also be applied to subsidy policies. All such efforts could be documented in a qualitative manner (negotiations undertaken; transparency procedures adopted), but quantitative, and particularly economic, indicators would be necessary to create useful metrics for comparison.

Assessment of current subsidies and their reform would arguably be an important component of any meaningful comparison of national climate policies. These policies have a major impact on global emissions. Quantitative assessment of subsidy efforts and outcomes will require significant advances in the transparency of subsidy policies and in the estimation of their impacts, as well as common agreement on what constitutes a subsidy and what efforts are associated with their reform. A handful of studies provide order-of-magnitude guidance on likely subsidy reform impacts or outcomes. However, there is no obvious metric for effort in subsidy reform that could be comparable with other effort metrics discussed in this section.

4. SYNTHESIS AND CONCLUSIONS

This paper has sought to examine how technology development activities might be examined and compared in a systematic manner through the development of metrics for quantifying efforts invested in long-term technology policies and their resulting outcomes. Chapter 2 provided a general rationale for these metrics and framework for investigating them, and Chapter 3 explored the feasibility and implications of their application in a series of case studies. This section distills key findings for effort and outcome metrics, and offers a few suggestions for the way forward.

4.1 Comparing effort metrics

The case studies illustrate that for certain policy types, effort metrics in terms of total government expenditures (R&D, technology cooperation and transfer) or direct incremental costs (technology deployment), can be roughly estimated and compared across countries. Table 8, presents the various findings of the case studies for different policy types in terms of a single value, $/GDP by country/region in selected years. It clearly shows that public R&D investment in low carbon technologies per unit of GDP is, on average, similar level across the EU, Australia and US, with Japan at a significantly higher level. Japan's emphasis on energy R&D reflects its high import dependence and the priority it has given to energy security, as well as to finding ways to meet its Kyoto Protocol commitments (Dooley, 1999).

Table 8. Comparative Effort (incremental costs, subsidies, and expenditures) by policy type ($US/million 2004 $US GDP), selected countries, annual

	Technology Development	**Technology Deployment**		**Int. Technology Coop & Transfer**	**GHG Intensive Policies**
	Public R&D for low-carbon technologies* (2004)	Renewable Electricity Deployment (2001/3)	Renewable Electricity Deployment (2010)	GEF climate change contributions (2002-2006)**	Subsidies for Fossil Fuels (current)
	Expenditure (ex post)	*Incremental cost (ex post)*	*Incremental cost (ex ante)*	*Expenditure (ex post)*	*Various*** (ex post)*
EU15	50	350	1200	6	2100
Australia	30		500	3	
Japan	220		60	6	
US	70	2	100	2	1700

Sources: various, per analysis above. All values indexed to 2004 GDP.
* not including nuclear
** annual average of 2002-2006 GEF3 replenishment, multiplied times the fraction of GEF funding that goes to climate change program (33%)
*** subsidy estimates reflect direct subsidies as well as various fiscal and tax provisions.
n/a = data not available

Comparing across policies, Table 8 also shows that the EU and US fossil fuel subsidies are roughly an order of magnitude greater than direct societal costs implied by renewable energy policies. One would conclude that fossil fuel subsidies, and specifically policies aimed at reforming them, are a critical part of assessing a Party's net effort at reducing emissions. One might also conclude that other efforts might need to be raised to a comparable scale if the climate challenge is to be addressed. Indeed, in the case of the EU, the implied costs of renewable energy deployment by 2010 suggest that this scaling up of effort may be underway.

While it is tempting to think of Table 8 as an attempt to tally up each Party's efforts across the range of policy categories, it should be viewed with a good deal of caution. First, it is far from comprehensive. A major category of activity not included in Table 8 (but shown in Table 2 and Table 3) is direct environmental policy, such as GHG cap and trade or carbon tax mechanisms. These are among the most encompassing climate policies, and a major avenue through which climate-related effort is directed.

Second, the figures for different categories are not comparable. As raised in Chapter 2, it is important to distinguish between metrics that reflect expenditures, i.e., spending directly induced by implementing a climate policy, and broader costs to society, i.e. the full range of economic and social costs and benefits that result directly or indirectly from a given climate policy. The figures shown here include metrics of both government expenditures (R&D spending, GEF contributions, subsidies) and broader societal impacts (renewable energy deployment). However, a given policy can be formulated in such as way as to shift the expenditure burden from the government to private actors (or vice-versa). For example, a given amount of renewable electricity can be induced with a feed-in tariff paid for by the government, or alternatively by a renewable portfolio standard that transfers costs to ratepayers. R&D can be paid for in government budgets, or leveraged through tax credits or matching funds, achieving similar overall spending levels with different levels of government investment.

Whether expenditure or broader socio-economic impact is appropriate for a given metric will likely depend on what policies are being compared, and the objectives of such a comparison. While it may be relevant to compare national budget expenditures on R&D across countries, for the purpose of informing international dialogues on climate technology development, it may make little sense to directly compare expenditures on R&D with expenditures on, or overall societal costs of, implementing a market-based mechanism to reduce GHG emissions, as a measure of overall "fairness". While a metric of broader societal impacts would provide a more comprehensive perspective of the effort involved in a given climate policy, the difficulty, of course, is that assessment of the broader societal impacts is not at all straightforward and entails much greater uncertainty than the relatively straightforward estimation of expenditures.

Third, not all climate mitigation efforts, nor necessarily the most critical ones, can be readily measured in currency units. Some governmental efforts, such as modifying trade rules and relations, the legal treatment of intellectual property rights, or overcoming the barriers to fossil fuel subsidy removal may be more challenging "efforts" to implement than increasing expenditure on R&D or technology deployment. As Koplow (2003) notes "subsidies for energy are usually driven by non-energy objectives and are usually highly politicized and difficult to remove."[60] Furthermore, societal efforts to change consumption levels, urban configurations or

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[60] http://www.earthtrack.net/documents.asp?docURL=Koplow%20Subsidy%20Reform%20Slides.ppt

travel patterns may represent very significant efforts that have no objectively measurable economic cost. As with many metric issues, there is always the risk that one is counting only what is easiest to count. Furthermore, as some have noted, "wheelbarrows of federal money are not sufficient, and may in some cases be counterproductive" (REPP in Goldberg, 2000, p.2), whether in reference to building markets for renewable energy as this quote refers to, or the addressing the overall GHG mitigation challenge.

Fourth, expenditure data, even though it is much more tractable than socio-economic costs, still has a number of limitations. Some, but not all, of these can be addressed through improved and more consistent data collection. Expenditure data is generally tabulated only for national governments, and does not include what may be non-trivial support at the regional, state, or provincial levels. International data compendia, such as IEA energy's R&D database, contain data as reported by member nations, with limited monitoring and review to ensure consistent reporting. In the case of subsidies, where there is typically little incentive for government transparency and definitions vary as to what in fact constitutes a subsidy, developing consistent estimates across countries is a far more challenging task (Koplow and Dernbach, 2001; Pearce, 2003; de Moor, 2001). Finally, expenditures are only a single year snapshot, often accounting for first costs, without fully conveying the commitment to future costs or the potential for future benefits of initial investments.

Even if not all of these challenges can be resolved, efforts to improve the consistency and comprehensiveness of data, both on the side of national governments and the international institutions, should become a higher priority as data related to climate technology development becomes increasing relevant to international discussion. Examples of activities underway include IEA's ongoing work to improve international reporting of R&D expenditures and to compile information on national policies and measures, as well as the UNFCCC process' efforts to improve and standardize national communications.

4.2 Comparing outcome metrics

As the case studies show, methods exist to estimate the emission reduction benefits of certain policy types. For technology deployment and environmental policy (such as cap-and-trade policies), in particular -- these estimates are reasonably well-established and generally able to yield policy-relevant conclusions. However, for technology development (e.g. R&D) and international technology cooperation and transfer, estimates of emissions benefits are far less certain or robust. With further refinements, better empirical grounding, and integration of top-down and bottom-up model strengths, models could grow more reliable at projecting the incremental R&D-driven changes in "known technologies". However, they are likely to remain hard-pressed to anticipate the more radical changes in technological systems and techno-economic paradigms (as witnessed in the classic example of stage coaches to railways) that might ultimately deliver deep emission reductions.

By its very nature, R&D gives uncertain outcomes, since it deals with immature technologies. But it is also subject to the uncertainties about the future world that plague any policy. The impact of any policy are highly dependent on a number of variables and assumptions about the future, such as economic growth patterns, consumer preferences, future fuel prices, and the advancement of competing technologies. For a given technology or policy, different modeling analyses can yield emissions impacts that differ by a factor or two or more, and sometimes differ in sign, depending on what modeling framework is used and which baseline scenario is assumed (see IPCC TAR). As IPCC reports have consistently underlined, comparison of estimated policy impacts is complicated by different baseline assumptions across models and analysts. To some extent this use of common marker SRES scenarios has eased but not overcome this hurdle. If metrics are to be considered credible enough to serve as a basis for international policy, then the inherent uncertainty of (ex ante) projected outcomes might need to be addressed by applying ex post corrections or discounting factors to reflect uncertainty.[61]

Box 3. Trading among technology and emission targets: one possibility

Blok et al (2005) suggest that "'tradability' between technology and short-term emission reduction targets, could be implemented in a protocol as the general possibility to replace short-term action by technology development. No concrete technology agreements need to be made. If countries come up with a proposal on a technology trajectory a procedure should be in place to certify, monitor and verify the alternative pathway (comparable to the procedures now in place for the Clean Development Mechanism). It will not be an easy task to safeguard environmental integrity in this case: the conversion of short-term activity into long-term activity vice versa is far from straightforward. Also, it is difficult to compare technology development and deployment efforts with short-term GHG reduction efforts. A variant of this approach is that the 'trading' is already done during the protocol negotiations: some countries may primarily focus on emission reduction objectives, whereas others exchange part of the commitment in this area by commitments on technology development." (p.101-102)

The authors suggest the possibility of a CDM-like approach of monitoring and verifying technology efforts to estimate "credits", using agreed methodologies. As one might expect, this raises the same questions that arise in the case of crediting CDM projects. How is causality established (particularly in the context of technology efforts which may not have the one-off project nature of CDM activities)? How could double-counting benefits of other policies (e.g. emissions caps) be avoided? Can a crediting procedure span the time frame and spatial boundaries often needed to realize technology benefits?

The authors are suggesting a technology development approach that would be subject to monitoring *ex post*, generating emission reduction credits much as a CDM project does. While this offers the advantage of a simple and commensurate metric for trading purposes and an incentive for technology development efforts, it presents many of the same challenges with respect to outcome metrics that are identified in the case studies here. Not only would a clear causal linkage need to be established between technology development and discrete emissions reductions in a given time frame, but judging technology initiatives on their short-term "realized benefits" may be antithetical to the nature and intent of technology innovation and development initiatives (e.g. option and knowledge benefits). As the authors themselves note, the technology development is a long-term issue, with large uncertainties, and significant spillover effects (to other technologies, companies, and countries in ways not easily measured.)

Attribution, policy synergy, and double-counting[62] present additional challenges to outcome metrics. For instance, the reduction in cost of solar PV could result from multiple innovations

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[61] In fact, a number of CDM methodologies discount estimated emission reductions based on uncertainty using the IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (2000).

[62] Double-counting *among* different options could easily occur, which may not be a problem depending on the context. Imagine a system whereby credit is given to expanded technology R&D efforts as well as to actual emission reductions in a given sector or country subject to a separate tradable allowances system. It could turn out that some of the emissions allowances are in fact generated as the result of the same R&D activity that is separately

arising from several R&D efforts, along with learning-by-doing arising from deployment efforts. Attributing outcomes to specific actions may challenging, if not misleading, since in many cases, progress will derive from a full portfolio of actions across the innovation chain from R&D to deployment. Carbon capture and storage provides a clear example; R&D is needed, so too is the removal of market barriers (regulations, public acceptable), but absent a price signal or regulatory requirement from environmental policies, significant deployment is highly unlikely. The consequence is that distinct attribution of outcomes to individual actions may remain challenging if not unattainable.

4.3 Key challenges

Additionality of actions:

The international climate regime is a burden-sharing arrangement. As such, Parties have negotiated obligations that are some manner commensurate with each Party's responsibilities and respective capabilities. For this reason, it is useful to have metrics that reflect the effort a Party devotes to climate by taking actions above and beyond what it would otherwise be doing purely for reasons of national self-interest. The extent to which countries undertake policies that reduce emissions for climate or for other reasons will always be debatable, as will the question of whether this should matter. The Kyoto Protocol, as with other environmental agreements, have skirted this issue by selecting historical marker years, such as 1990, and similarly effort and outcome could also be reckoned in terms of incremental change since that or another relevant historical year. However, this too is problematic since factors other than climate action "effort" account for many emission declines: reunification in Germany, economic collapse in Russia, and the downfall of coal miners' unions in the UK, for example. Nonetheless, an historical marker year, perhaps adjusted for spurious factors, represents one of the more objective means to benchmark what might be considered "additional" climate effort or outcome. (See for instance, the comparison of R&D budget changes 1990-2004 in Figure 3)

Consistency with underlying principles

The choice of metric can have a subtle relationship to the fundamental principles underlying a climate regime. For example, consider technology R&D investments, for which effort can be presented using several possible units: dollars per capita, dollars per unit of GDP, dollars per ton of carbon emissions, etc. By indexing Parties' efforts to population, GDP, or emissions, it would be implied that the burden of effort should be allocated, respectively, to individuals, according to economic capability, or according to (responsibility for) current or historical emissions. Of course, an obligation of any level of stringency can be expressed in any unit, but there is a strong conceptual link between the units in which obligations are expressed and the perception whether those obligations are fair. This was clearly the case with the Kyoto Protocol obligations, where by expressing emissions reductions obligations in terms of a percent reduction below 1990 levels, the principle that was most strongly conveyed was that it is fair for countries to continue

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credited and "tradable" against these same allowances. If the principal goal of the R&D effort is the development of technologies with respect to their longer-term potential, this double crediting may be of limited concern. However, if the goal is to yield discrete emissions reduction in a given time frame (see Box 2), then the "tradability" of R&D credits should be called into question.

emitting at roughly historic levels, irrespective of capacity to pay for mitigation or responsibility for GHG emissions. The choice of denominator therefore relates to long-debated issues in the burden-sharing literature, such as ability-to-pay or historical responsibility (Bode, 2004; Blanchard et al, 2001). Ultimately, this choice must be informed by the agreed principles upon which climate agreements are made. For the purposes of comparing effort and outcome across countries paper uses economic output (GDP) since it is plausible that the level of effort undertaken by countries may be ultimately viewed as a function of their ability to pay.

4.4 Conclusions

Technology clearly has a place in the international climate regime. Unlike quantifying emissions and emission reductions, for which there are methodologies, processes, and technical constituencies firmly in place, there is no comparable institutional infrastructure in place for quantifying activities aimed at advancing technologies. This paper makes an initial survey of the approaches that might be used for quantifying such efforts, and highlights the implied challenges.

This report draws several main conclusions. The most evident of these is that technology poses much greater quantification challenges than emissions. The quantification apparatus in place now (e.g., R&D budget surveys, technology development modeling tools) provides rough indicators of some aspects of effort and outcomes that can be employed for coarse assessments in support of reporting) on general, non-quantitative technology-related commitments (such as for National Communications). But the apparatus is not nearly mature enough to provide a robust, objective, and credible basis for monitoring effort toward quantitative, legally-binding international commitments. Thus, it is not mature enough to support the implementation of equivalence and tradability between emissions reductions and technology advancement in a dual-track climate regime.

There are some aspects of climate technology development that may be amenable to quantification once additional progress is made on data gathering, methodologies, and common reporting protocols. Public sector investment in R&D is one such aspect. Another may be the (near-term) outcomes of certain straightforward environmental policies such as renewable obligations.

Certain other aspects of technology development might be amenable to quantification if there is not only progress on data, methodologies, and protocols, but also substantial improvements in transparency. Fossil fuel subsidies fall into this category.

Yet other aspects appear to be too rife with uncertainties and subjective decisions to be amenable to rigorous quantification. For instance, ex ante assessment of the long-term impacts of R&D is questionable, owing to the inherently uncertain nature of technology R&D. The more intangible benefits of R&D (option benefits and knowledge benefits) often greatly exceed the concrete (realized) benefits, but quantifying those benefits requires scenario analysis, assumptions, and subjective decisions. Attempts to quantify those intangible impacts can be interesting, indicative exercises, but cannot be considered definitive predictions of future impacts.

Ultimately, even if the goal of rigorous quantification in support of strict tradability is out of reach, there is still much to be gained from further development of metrics and approaches for their quantification. Technological transitions are a critical part of the climate problem, and any steps that help Parties more credibly demonstrate the efforts they are making and the outcomes they are achieving will help to build trust, instill confidence, and motivate more resolute action toward solving the climate problem.

REFERENCES

Alic, J, Mowery, D., Rubin, E. 2003. U.S. Technology and Innovation Policies: Lessons for Climate Change. The Pew Center on Global Climate Change, Arlington, VA.

Athanasiou, T, Kartha, S., Baer, P., 2006. "Greenhouse Development Rights", EcoEquity/Christian Aid, www.ecoequity.org

Babiker, M. and R. Eckaus. Rethinking the Kyoto Targets, MIT Joint Program on the Science and Policy of Global Change, Report No. 65, August 2000.

Barker, T., Qureshi, M., Köhler, J., 2006. The costs of greenhouse-gas mitigation with induced technological change: A Meta-Analysis of estimates in the literature, 4CMR, Cambridge Centre for Climate Change Mitigation Research, Cambridge: University of Cambridge.

Barrett, S., 2003. Environment and Statecraft: The Strategy of Environmental Treaty-Making, Oxford University Press.

Battelle, 2000. Addressing Climate Change: Initial Findings from an International Public-Private Collaboration, http://www.pnl.gov/gtsp/docs/infind/cover.pdf

Berglund, C., Soderholm, P. 2006 Modeling technical change in energy system analysis: analyzing the introduction of learning-by-doing in bottom-up energy models, *Energy Policy* 34, 1344-1356

Blanchard, O., Criqui, P., Trommetter, M., Viguier, L., 2001. Equity and efficiency in climate change negotiations: A scenario for world emission entitlements by 2030, Cahier de Recherche No. 26, Institut d'economie et de politique de l'energie, Grenoble

Blok, K., Höhne N., Torvanger A., Janzic R., 2005. Towards a Post-2012 Climate Change Regime Final Report, Contracted by: European Commission, DG Environment, Directorate C - Air Quality, Climate Change, Chemicals and Biotechnology, http://europa.eu.int/comm/environment/climat/pdf/id_bps098.PDF

Bodansky, D. et al., 2004. International Climate Efforts Beyond 2012: A survey of Approaches, Prepared for the Pew Center on Global Climate Change

Bode, S. 2004. European Climate Policy: Burden Sharing after 2012, Hamburg Institute of International Economics DISCUSSION PAPER 265. http://www.hwwa.de/Publikationen/Discussion_Paper/2004/265.pdf

Brooks, C., Milford, L. and Schumacher, A., 2004. Global Clean Energy Markets: The Strategic Role of Public Investment and Innovation, a report from Clean Energy Group.

CBO (Congressional Budget Office of the United States), 2006. Evaluating the Role of Prices and R&D in Reducing Carbon Dioxide Emissions, Washington, DC, September.

Criqui P., Russ P., Deybe D., 2006. Impacts of multi-gas strategies for greenhouse gas emission abatement: insights from a partial equilibrium model, *Energy Journal*, 27, 251-273

Davis, G., Owens, B., 2003. Optimizing the level of renewable electric R&D expenditures using real options analysis, *Energy Policy* 31, 1589

de Moor, A., 2001. Towards a Grand Deal on subsidies and climate change, *Natural Resources Forum,* 25:2.

Dooley, J. 1999 Energy Research and Development in the United States. PNNL-12188. Washington, DC. http://energytrends.pnl.gov/usa/ustoc.htm

Dooley, J. 2000. A Short Primer on Collecting and Analyzing Energy R&D Statistics. Pacific Northwest National Laboratory, Report PNNL-13158. Washington, DC. February 2000. http://energytrends.pnl.gov/integrat3/integ001.htm

Eberhard, A., Tokle, S., Viggh, A. del Monaco, A., Winkler, H., Danyo, S., 2004. GEF Climate Change Program Study, Global Environment Facility, Office of Monitoring & Evaluation, September.

EC 2005, Energy R&D Statistics in the European Research Area, Final report, Directorate-General for Research Sustainable Energy Systems EUR 21453

Edmonds, J., Roop, J., Scott, M. 2000. *Technology and the economics of climate change policy.* Prepared for the Pew Center on Global Climate Change.

Eurelectric, 2004. A Quantitative Assessment of Direct Support Schemes for Renewables, 1st Edition, Working Group Renewables & Distributed Generation, January 2004, Ref: 2003-030-0741, Union of the Electricity Industry–EURELECTRIC

European Environment Agency. 2004. Energy subsidies in the European Union: A Brief Overview, (Copenhagen, Denmark, 2004). http://reports.eea.eu.int/technical_report_2004_1/en

Gallagher, K. 2005. Limits to leapfrogging in energy technologies? Evidence from the Chinese automobile industry, *Energy Policy* 34, 383

Gallagher, K. Frosch, R., and Holdren, J. 2004. Management of Energy Technology Innovation Activities at the US Department of Energy, September (NCEP)

Gallagher, K., Holdren, J., 2004. U.S. Government Policies Relating to International Cooperation on Energy, November. (NCEP paper)

GEF/ICF, 2005. OPS3: Progressing toward Environmental Results: Third Overall Performance Study of the GEF, Global Environment Facility, Office of Monitoring & Evaluation, June.

Gerard, G., Lave, L. 2005. Case study of technology forcing with catalytic converters, *Technology forecasting and social change* 72 (2005) 761-778

Goldberg, M. 2000. Federal Energy Subsidies: Not All Technologies Are Created Equal. Renewable Energy Policy Project Research Report No. 11. Washington DC. http://www.repp.org/repp_pubs/pdf/subsidies.pdf

Goulder, L, 2004. *Induced Technology Change and Climate Policy*, prepared for the Pew Center on Climate Change.

Goulder, L., Schneider, S., 1999. Induced Technological Change and the Attractiveness of CO2 Abatement Policies, *Resource and Energy Economics* 21: 211-53.

Grubb, M., 2005. Climate, energy and innovation: Moving from theory to practice, in Technology Partnerships for Renewables: Key to Energy Security, Fort, B., Johnson, F., eds. Asia-Europe Environment Forum (ASEF) Third Roundtable, Asia-Europe Foundation

Grubb, M., Steen, N. 1992. Pledge and Review Process: Possible Components of a Climate Convention, Workshop Report, Royal Institute of International Affairs, London.

Hansen, J., M. Sato, R. Ruedy, P. Kharecha, A. Lacis, R. Miller, L. Nazarenko, K. Lo, G. A. Schmidt, G. Russell, I. Aleinov, S. Bauer, E. Baum, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Cohen, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, J. Jonas, M. Kelley, N. Y. Kiang, D. Koch, G. Labow, J. Lerner, S. Menon, T. Novakov, V. Oinas, J. Perlwitz, J. Perlwitz, D. Rind, A. Romanou, R.

Schmunk, D. Shindell, P. Stone, S. Sun, D. Streets, N. Tausnev, D. Thresher, N. Unger, M. Yao, S. Zhang, 2006. Dangerous human-made interference with climate: A GISS modelE study. *Atmos. Chem. Phys. Discuss*., 6, 12549-12610, 2006

Hargadon, A. 2004. Clean Energy & Fuel Cells: Implications for Innovation Strategies from Historic Technology Transitions, by UC Davis.

Haug, M. 2005. Public Support to Hydrogen and Fuel Cells: An International Perspective, Powerpoint Presentation, Director, International Energy Agency

Hoffert, M.. Caldeira, G. Benford, D. R. Criswell, C. Green, H. Herzog, A. K. Jain, H. S. Kheshgi, K. S. Lackner, J. S. Lewis, H. D. Lightfoot, W. Manheimer, J.C. Mankins, G. Marland, M. E. Mauel, L. John Perkins, M.E. Schlesinger, T. Volk, T. M.L. Wigley, 2002. Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet, *Science* , 298, 981-987

International Energy Agency, 2004. Hydrogen and Fuel Cells: A Review of National R&D Programs. Paris

International Energy Agency, 2006. R&D Statistics Database. Paris. http://www.iea.org/Textbase/stats/rd.asp

Jaffe, A., Newell, R. Stavins, R., 2005. A tale of two market failures: Technology and environmental policy. *Ecological Economics (54) 154-164*

Jaffe, A., Newell, R. Stavins, R., 2003. Technological Change and the Environment. in K.G. Maler and J. Vincent, eds., *Handbook of Environmental Economics,* North Holland, pp. 461-516.

Kammen, D., Nemet, G. 2005. Reversing the Incredible Shrinking Energy R&D Budget, *Issues in Science and Technology*, 22: 84-88.

Kobos, P.H. ,Jon D. Erickson ,Thomas E. Drennen, in press. Technological learning and renewable energy costs: implications for US renewable energy policy, *Energy Policy*

Koplow, D. 2003. Obstacles to Subsidy Reform in the Energy Sector, Presentation to *OECD Technical Expert Meeting on Environmentally Harmful Subsidies,* 3-4 November, Paris, France www.earthtrack.net

Koplow, D. 2004. Federal Subsidies to Energy in 2003 - A First Look, Memorandum to the National Commission on Energy Policy, www.earthtrack.net

Koplow, D. and Dernbach, J., 2001. Federal Fossil Fuel Subsidies and Greenhouse Gas Emissions: A Case Study of Increasing Transparency for Fiscal Policy, *Annual Review of Energy and the Environment*,

Kouvaritakis, N., Soria, A., Isoard, S., 2000a. Modeling energy technology dynamics: methodology for adaptive expectations models with learning by doing and learning by searching, *International Journal of Global Energy Issues* 14: 104-115

Kouvaritakis, N., Soria, A., Isoard, S., 2000b. Endogenous learning in world post-kyoto scenarios: application of the POLES model under adaptive expectations, *International Journal of Global Energy Issues* 14: 222–248.

Lane, L. 2005. Reflections on Climate Related R&D, Climate Policy Center. http://www.cpc-inc.org/

Margolis, R.M., and D.M. Kammen, 1999. Evidence of Under-Investment in Energy R&D in the United States and the Impact of Federal Policy, *Energy Policy* 27, 575-84.

Martinot, E. 2005. Renewables 2005 Global Status Report, Worldwatch Institute and Tsinghua University

Matysek, A., Ford, M. Jakeman, G., Gurney, A., Fisher, B. 2006. Technology: Its Role in Economic Development and Climate Change, Australian Bureau of Agricultural and Resource Economics, ABARE Research Report 06.6, July. www.abareresearch.com

Meinshausen., M., Hare, W., Wigley, T., van Vuuren, D., den Elzen, M. Swart, R., 2006. Multi-gas emission pathways to meet climate targets. *Climatic Change* 75, 151–194.

Miketa, A., Schrattenholzer, L., 2004. Experiments with a methodology to model the role of R&D expenditures in energy technology learning processes; first results. Energy Policy 32, 1679–1692.

Montgomery, D. and Smith, A., 2005. Price, Quantity, and Technology Strategies for Climate Change Policy, CRA International, http://www.crai.com/.%5Cpubs%5Cpub_4141.pdf

Natsource, 2003. Review and Comparative Analysis of National Responses to Climate Change, Natsource Tullett Europe

Nemet, G., Kammen, D. 2007. U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion, *Energy Policy* 35: 746–755.

Nishio, K, Asano, H., 2003, The Amount of Renewable Energy and Additional Costs under the Renewable Portfolio Standards in Japan, CRIEPI report, Y02014. English summary at http://criepi.denken.or.jp/en/e_publication/a2003/03seika4.pdf

NRC (National Research Council), 2001. Energy Research at DOE: Was it Worth It? Energy Efficiency and Fossil Energy Research 1978–2000. National Academy Press, Washington, D.C.

OECD/IEA, 2006. Renewable Energy: RD&D Priorities Insights from IEA Technology Programmes

Pacala, S., Socolow, R., 2004. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies, *Science* 305: 968-972

Papineau, M. 2005. An economic perspective on experience curves and dynamic economies in renewable energy technologies *Energy Policy* 34, 422

Pearce, D. 2003. Environmentally Harmful Subsidies: Barriers to Sustainable Development, in *Environmentally Harmful Subsidies: Barriers to Sustainable Development,* OECD, Paris.

Pershing, J., Mackenzie, J., 2004. Removing Subsidies Leveling the Playing Field for Renewable Energy Technologies: Thematic Background Paper, International Conference for Renewable Energies, Bonn

Petersik, 2004. State Renewable Energy Requirements and Goals: Status Through 2003, USDOE, EIA, http://www.eia.doe.gov/oiaf/analysispaper/rps/index.html

Pew Center on Global Climate Change, 2005. International Climate Efforts Beyond 2012 – Report of the Climate Dialogue at Pocantico, November. http://www.pewclimate.org/global-warming-in-depth/all_reports/climate_dialogue_at_pocantico/

Philibert, C., Podkansi, J. 2005. International Energy Technology Collaboration and Climate Change Mitigation: Case Study 4: Clean Coal Technologies, OECD/IEA, Paris www.iea.org

Philibert, C.. 2005. Climate Mitigation: Integrating Approaches for Future International Cooperation, OECD/IEA Information Paper, Paris www.iea.org

Pizer, W. 2007. The Evolution of a Global Climate Change Agreement, Resources for the Future Discussion Paper, December. www.rff.org

Popp, D. 2006. ENTICE-BR: The effects of backstop technology R&D on climate policy models, *Energy Economics* 28 188-222

Popp, D., 2004. ENTICE: endogenous technological change in the DICE model of global warming, *Journal of Environmental Economics and Management* 48, 742–768.

Riahi, K., Rubin, E., Taylor, M., Schrattenholzer, L., Hounshell, D., 2004. Technological learning for carbon capture and sequestration technologies, *Energy Economics* 26, 539– 564

Sagar, A., van der Zwaan, B. 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing, *Energy Policy* 34: 2601-2608.

Sanden, B.A., Azar, C., 2005. Near-term technology policies for long-term climate targets --economy-wide versus technology-specific approaches, *Energy Policy* 33: 1557-1576.

Schelling, T. 2002. What makes greenhouse sense, *Foreign Affairs*, May/June 2002.

Schock, R.N., Fulkerson, W., Brown, M.L., et al.,1999. How much is energy research & development worth as insurance? *Annual Review of Energy and the Environment* 24, 487–512.

Stern, N., S.Peters, V.Bakhshi, A.Bowen, C.Cameron, S.Catovsky, D.Crane, S.Cruickshank, S.Dietz, N.Edmonson, S.-L.Garbett, L.Hamid, G.Hoffman, D.Ingram, B.Jones, N.Patmore, H.Radcliffe, R.Sathiyarajah, M.Stock, C.Taylor, T.Vernon, H.Wanjie, and D.Zenghelis, 2006. Stern Review: The Economics of Climate Change, HM Treasury, London.

US Department of Energy, 2005. Carbon Sequestration: Technology Roadmap and Program Plan www.fossil.energy.gov/programs/sequestration/publications/programplans/2005/sequestration_roadmap_2005.pdf

US Office of Management and Budget, 2006. Federal Climate Change Expenditures Report to Congress, April. www.whitehouse.gov/omb/legislative/fy07_climate_change.pdf

Viellefosse, A. 2005. Note sur technologie et changement climatique: Comment les politiques publiques peuvent-elles accélérer le progrès sur les technologies de lutte contre le changement climatique ? Ministère de l'Ecologie et du Développement Durable, réf. :B2-05-004

Vollebergh, H., Kemfert, C. 2005. The role of technological change for a sustainable development *Ecological Economics,* 54, 133-147

Wigley, T., Richels, R., Edmonds, J. 1996. Economic and Environmental Choices in the Stabilization of Atmospheric CO2 Concentrations, *Nature,* 18, 240-243.

Wing, I.S., 2006. Representing induced technological change in models for climate policy, *Energy Economics,* 28, 539–562