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R&D policy

1.5

1. Introduction

A critical step in reducing greenhouse gas (GHG) emissions is the introduction of new technologies for energy supply and use. This chapter deals with the question of what policies would be required to stimulate the kinds of R&D that would raise the odds of developing those technologies. This question is not as simple as it appears.

'Getting the price right' on GHG emissions is a necessary condition. Doing so provides a broad and appropriate incentive for reducing emissions, and adopting available technologies that are neglected because their ability to reduce emissions is only valuable when emissions are priced. Thus a price on emissions can correct what we may call the 'climate change market failure'.

However, R&D is itself subject to market failure in that it is impossible for researchers and innovators to capture themselves the full value of the information that their activities provide to society. This spillover effect is a positive externality, but it also implies that without active government intervention there will be less R&D than is socially optimal.

R&D is a critical part of climate policy because of the nature of the climate change phenomenon and the radical transformation of the energy system required to stabilise global temperatures. Climate change is driven by the concentration of GHG in the atmosphere, making climate change what economists call a 'stock externality'. Concentrations of GHG do not respond to changes in emissions over short periods of time, but depend mostly on cumulative emissions over long time periods. Therefore, there is a choice of many different paths for emissions over time and can lead to identical outcomes in global average temperatures. If R&D can reduce the cost of technologies that replace fossil fuels and other sources of GHG emissions, with alternatives that have lower or zero GHG emissions, then timing emissions reductions in order to take advantage of innovations that lower cost and introduce new opportunities can reduce the cost of meeting climate goals. By reducing the cost of moving to a low or zero carbon economy a worldwide agreement to reduce GHG emissions can become more likely. Although these propositions about the nature of the climate problem are widely accepted, relationships between concentrations and temperature increases, and the potential consequences of increased temperatures are highly uncertain. Therefore the amount of action required to avoid temperature increases above some level, for example 2°C, is also highly uncertain. This leads many to characterise climate policy as an exercise in risk management rather than straightforward planning or cost-benefit analysis.

The need to develop and adopt new technologies as part of this risk management process is widely accepted. The policy problem is how to create incentives for the appropriate kind of innovation, and how much and what kinds of R&D to support. Answering these questions begins with an appreciation for the scale of emissions reductions required over time, and the radical changes in energy supply and use that this entails. Fundamental breakthroughs to make the use of new energy sources feasible, both technically and economically, are necessary to achieve changes of this scale at costs that are acceptable globally. Achieving those breakthroughs requires in turn a comprehensive and effective program of support and incentives for R&D, invention and innovation. Designing such a program will be very difficult, both because of the complex and unpredictable nature of the R&D process, and the political economy of support for new technologies. Nevertheless, failure to embark rapidly on such a program could leave the costs of stabilising GHG concentrations prohibitively high and make adaptation or geoengineering a much larger part of the risk management strategy.

1.1 R&D defined

Policy prescriptions about R&D can appear ambiguous or inconsistent without an explicit definition of R&D. The definition used by the National Science Foundation to collect data on R&D is:

> *Research* is systematic study directed toward fuller knowledge or understanding of the subject studied. Research is classified as either basic or applied, according to the objectives of the investigator.
>
> *Development* is systematic use of the knowledge or understanding gained from research, directed toward the production of useful materials, devices, systems, or methods, including design and development of prototypes and processes.
>
> R&D is part of an innovation process, often depicted as in Figure 1, in which *demonstration, deployment and commercialisation* are different activities, that follow R&D in bringing a new product or improved process into use.

This linear conception does not correspond to case studies on how the innovation process actually works, and greatly oversimplifies the complex relationships between different activities and the institutions in which they are carried out (Nelson et al 1982a). The process of technology development sometimes leads from a researcher's curiosity, for example research at Bell Laboratories on solid state physics, to an innovation that transforms industries and society: the transistor. At other times the desire for a product, for example nylon, leads to directed R&D that ultimately finds exactly what it was looking for. The more accurate 'linked chain' conception and its implications for design of R&D policy are described later in this paper. But the simple linear conception and the distinctions it draws between R&D and other activities involved in further developing and deploying an application that passes out from the R&D stage is useful for delineating the subject of this paper.

1.2 Policy for R&D versus policy for technology deployment

Diverse institutional roles

Successful innovation also entails a social activity in which the new technique, product or knowledge is applied, marketed or disseminated. The profit motive is often assumed to dominate at this level of activity, and in many instances, it is influential. At the same time, creative work is actually done by individuals, who may be subject to complex motives. Then too, a firm seeking to profit from technological advance may often find itself dealing with many non-profit organisations. Innovation can, therefore, entail exceptional institutional complexities (Nelson 2005). See Figure 2.

In the United States (US), a diverse mix of institutions fund R&D and there is comparable diversity in the mix of those that conduct it. The US innovation system includes governments, various private sector entities and universities. It comprises federal and state

FIGURE 1:
THE 'R, D, D, AND CONTINUUM' (RDD&C)

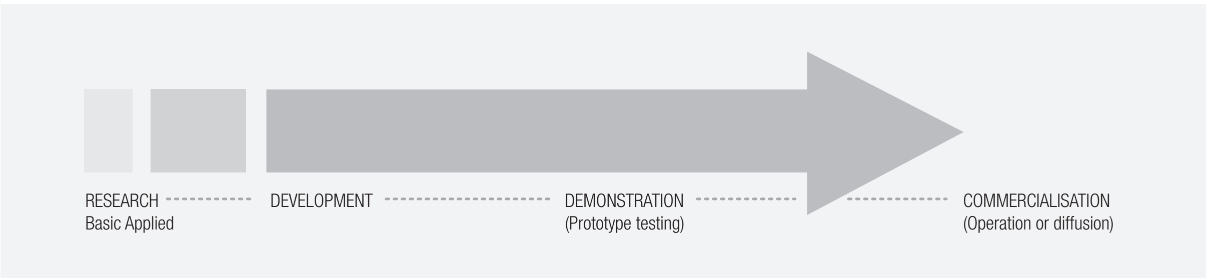


FIGURE 2:
INSTITUTIONS AND INCENTIVES IN TECHNOLOGY DEVELOPMENT

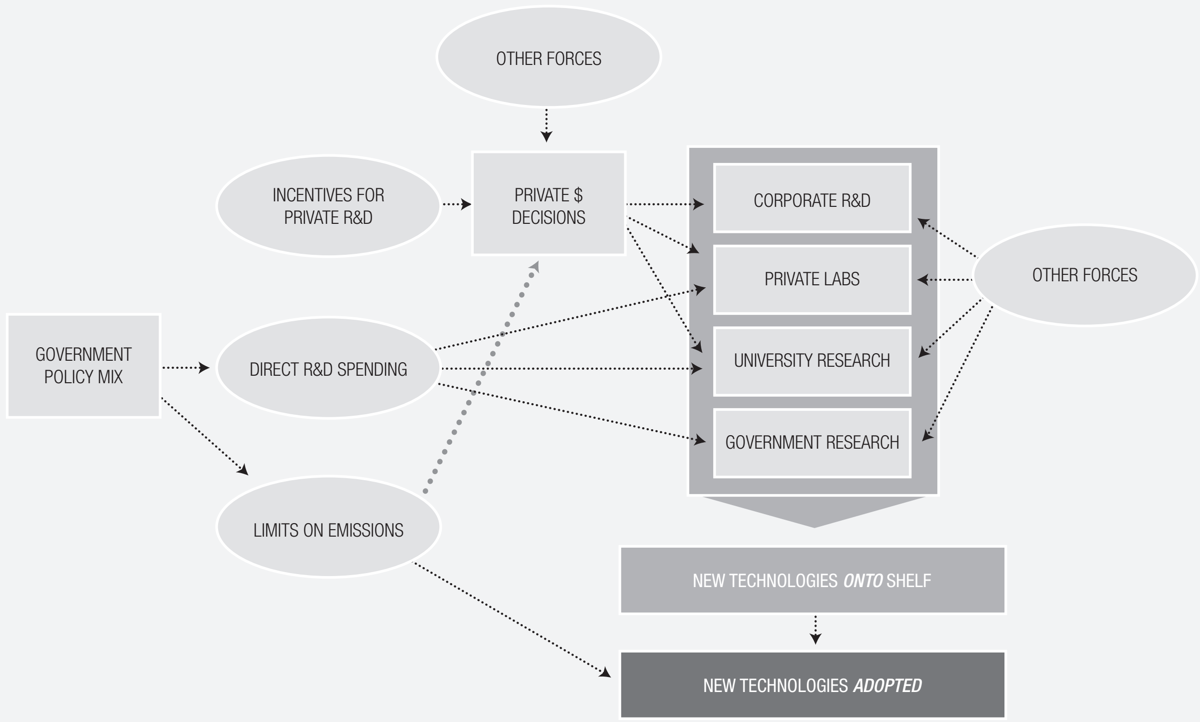


TABLE 1:
AGGREGATE R&D SPENDING

	BASIC RESEARCH	APPLIED RESEARCH	DEVELOPMENT	TOTAL
Industry	5%	20%	76%	US$223.4 B
Government	59%	33%	16%	US$94.2 B
Total	US$61.5 B	US$74.7 B	US$204.3 B	US$340.4 B

Source: National Science Foundation, Division of Science Resources Statistics, National Patterns of R&D Resources (annual series).

governments, for-profit and not-for-profit entities, and national and multinational institutions. These institutions perform a wide variety of R&D and is illustrated in Table 1.

This suggests, as will be discussed further, that the problem of appropriability is greatest in basic research, important in applied research, and smaller in development and later stages of demonstration, commercialisation and deployment.

There is little question that a clear, credible, consistent and stable policy that puts a price on CO_2 emissions will lead to cost-effective technology deployment and provide a demand-driven inducement to innovation. Credibility is greatest with policies addressing the climate externality that are economy wide, permanent, based on long-term goals, but with flexibility and cost containment, so that the policy can be expected to survive the inevitable unexpected shocks. The decision for any large-scale investment to deploy a new technology is certainly complex, depending on many factors not easily reduced to a simple rate-of-return calculation.

What should be equally clear is that a series of temporary, politically unstable, targeted subsidies, financial incentives, or even mandates for deploying specific GHG-reducing technologies will not provide adequate incentives for basic and applied R&D. This paper addresses the design of an R&D policy to get innovation started, and is therefore focused on an area where the need for government action is clear, but the appropriate mechanism is not.

1.3 R&D and the role of developing countries

The design of R&D policy must also take into account the major role of developing countries. That is, the opportunity to bring down costs and make action more attractive; different institutional, technical capacities; R&D networks – linking practice and research; and international networks to combine resources, create capabilities and exchange information, and provide practice-led R&D.

2. Nature and importance of the problem

Something more than a price on carbon is required to stimulate this kind of innovation. R&D investments directed at finding technologies that will reduce GHG emissions are subject to two important, but quite distinct kinds of market failure. One of these failures relates to the nature of R&D as an economic activity. The second relates to private markets' failure to reflect in prices the social costs of the climate change that is associated with GHG emissions (Newell 2005, Edmonds et al 2003). Because of climate market failure, there are no incentives to reduce CO_2 emissions below levels implied by weighing private fuel costs, and private costs and the benefits of energy efficiency.

Thus there is insufficient market pull for innovations to produce fuels with lower carbon content or new technologies for energy efficiency. However, remedying this market failure through, for example, a carbon tax does not address the R&D market failure. Theoretical reasoning and empirical evidence on the social rate of return to R&D establish that the impossibility of appropriating the full rewards of R&D also leads to insufficient incentives for R&D (Nordhaus 2007). A number of policies, including patent protection, special tax treatment of private R&D and government funding of research have been adopted to restore these incentives, but clear evidence of the remaining differences between the social rate of return on R&D and the private return establish that incentives for R&D remain deficient. Therefore, in addition to putting a price on carbon, climate policy must include additional policy instruments to increase the amount of R&D directed toward climate-related technologies.

In response to R&D market failure, government policy has long sought to encourage innovation. The challenge posed by climate change adds another dimension: how shall government encourage the development and adoption of technologies for which, absent policy, no demand would exist?

2.1 The two market failures

The 'inappropriability' of the benefits of R&D

Several features of the economics of R&D cause investments in producing innovation to fall well short of the levels that would be socially optimal. For example, it is often impossible to exclude others from the benefits of the discovery of new knowledge. In the discovery of new knowledge, large returns to scale are commonplace (Arrow 1962). Arrow points out that the fundamental returns-to-scale problem arises because R&D creates information, which has a fixed cost to create but near-zero marginal cost to transfer. Imitators can often copy a product or process based on the discovery of new useful knowledge. Therefore, in competitive markets, anticipated future prices may fall short of levels needed to recoup an innovator's R&D costs. At a minimum, the cost and uncertainty of exclusion reduces the net returns and therefore, weakens incentives for R&D (Arrow 1962).

Despite this problem, ownership of assets whose value is increased by innovation may call for some level of for-profit R&D, but that ownership is unlikely to provide an incentive equal to the entire marginal social value of the R&D (Hirshleifer 1971). It is also true that new knowledge may sometimes create monopoly power in the hands of the innovator, either through first mover advantages or through the operation of intellectual property rules, and this monopoly power may create incentives to invest in R&D. However, the use of this monopoly power will, itself, diminish the social benefits of the innovation.

Further, the production function of R&D is often unknown and sometimes unknowable. It depends, in part on the difficulty of the scientific problem being tackled, but the latter is uncertain until the problem and the nature of the solution are well understood (Arrow 1962). These uncertainties entail a high risk of failure. Knightian uncertainty, defined as the impossibility of assigning meaningful probabilities to outcomes, also implies limited or no opportunities for spreading risk or diversifying in order to reduce risk aversion. That risk may dissuade for-profit R&D. Depending on the comparison of private and social benefits, the Arrow-Lind argument for different social (risk-free) and private discount rates in the presence of non-diversifiable risks may apply and justify government intervention even when rewards are appropriable.

Uncertainties may create very large asymmetries of information. The information that an innovator or researcher obtains may be difficult to convey credibly to potential buyers or investors, and making that information available to potential buyers risks its appropriation by others. The latter difficulties may, among other things, degrade the efficiency of the capital market as well as the efficiency of the market for sale or license of innovations. This asymmetry clearly has something to do with the structure of innovative industries, and the structure of some industries may inhibit innovation.

The R&D process is also characterised by network externalities such that the outcome of one strand of R&D may turn out to be the key link in some other process (Edmonds et al 2003). Thus, the value of any individual piece of research can only be established by tracing its influence through a number of other research projects and technologies. The difficulty of establishing the role of specific breakthroughs, and the chilling effect that hiding all research (so as to have a claim on all its value) would have on the research enterprise, again makes the financial reward to a useful result less than its full social value. Failures may convey as much information as success, in particular that a particular approach does not work, and incentives to disseminate information about failures may be very weak.

University research may be subject to another form of externality. University research often generates valuable information about the otherwise hard to gauge scientific talent of researchers. This information can be quite valuable to for-profit firms wishing to acquire expertise through hiring employees or retaining consultants. This information is, in effect, an external benefit of university science (Dasgupta *et al* 1994).

The climate damage externality

Because the harmful effects of climate change are not incorporated into the price of many activities that contribute to GHG emissions, the market will under-reward those who develop technologies that reduce such discharges. This external cost market failure stands in addition to the external benefit problem that plagues R&D (Edmonds et al 2003).

Two externalities require two instruments

The lengthy time scales involved in both climate change and technology development imply that expectations of future policies motivate current investments. Expected future prices for GHG emissions are especially important. The credibility of a government's commitment to future policies is vital as an incentive to invest in R&D. Uncertainties about future policies will motivate delays in investment decisions if additional, timely information is expected to become available (Blyth 2007). Policy uncertainty is not necessarily fatal. However, any time inconsistencies that bias government *ex post* decisions against high carbon prices will weaken private sector incentives to invest in the relevant R&D.

Time inconsistency arises because the carbon price required to provide an adequate return on the R&D investment is higher than the price required to motivate adoption of an innovation after it is discovered. Thus, what is optimal for a government to announce as a carbon price in advance of a discovery is greater than what is optimal for a government to announce, post-discovery.

This policy failure would persist even if current policy projects a high price on future carbon emissions (Montgomery *et al* 2007). Indeed, existing policy mandates that imply very high future carbon prices may actually fuel doubts about the commitment of future governments to those mandates.

2.2 Why R&D is critical in climate policy

Halting increases in global average temperature at some level demands that at some time in the future, annual emissions of GHG from human sources must be not exceed the amount removed by natural processes. This goal of zero net emissions implies that global emissions must shrink to roughly 20 per cent of business-as-usual projections by mid- to late-century, if the goal is stabilising GHG concentrations at 550 ppm CO_2, and lower if a more ambitious goal is chosen (Clarke *et al* 2007).

For example, Figure 4 below shows the results from three models that analysed stabilisation scenarios for the US Climate Change Science Program. All three models found that for global emissions to stay at 550 ppm or less, emissions would have to remain 80 per cent below projected levels in 2100, a level at which each year's emissions would no longer exceed the amount of CO_2 naturally removed from the atmosphere.

The speed with which this emissions rate is achieved will determine the GHG concentration at which the atmosphere stabilises, and therefore global average temperature. Thereafter net zero emissions must be maintained to prevent further increases in concentrations. Recent economic trends foresee global energy consumption doubling, or even tripling, by the end of this century. Without policies to change the choice of energy sources, this could lead to roughly similar increases in GHG emissions.

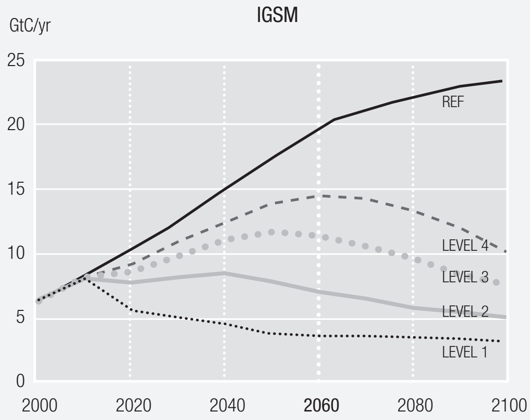
2.3 Need for fundamentally new technologies

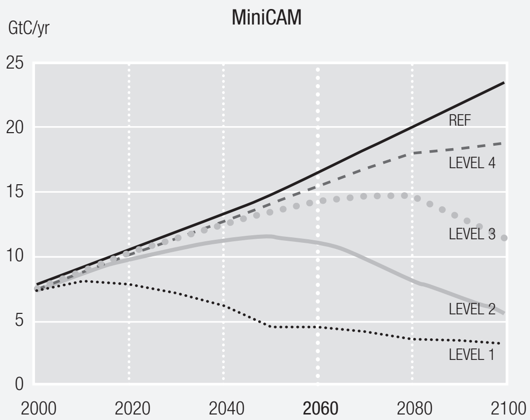
Reaching the goal of zero net emissions with existing energy technologies, and incremental improvements to them, would require high costs (Hoffert et al 2002). Currently, the high cost of curtailing GHG discharges limits the size of emissions cuts that are cost beneficial. Indeed, with only incremental improvements to current technologies, achieving the emissions levels needed to hold temperature increases to 2°C or less, the marginal cost of abatement would exceed current estimates of the marginal damages from CO_2 emissions (Tol 2007).

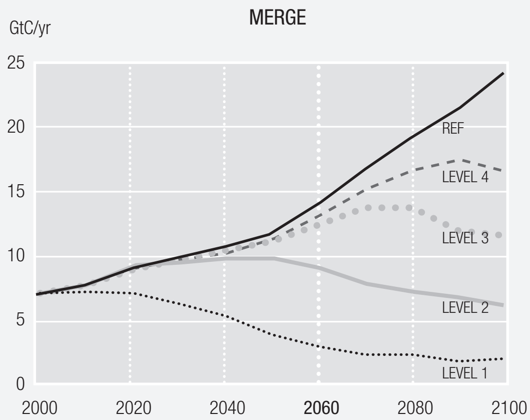
Thus, for steeper GHG reductions to become cost-beneficial, technological progress must drive down the costs of abatement. Existing technologies and incremental improvements to them seem unlikely to produce cost reductions that would be large enough for this purpose (Hoffert *et al* 2002). Most projections of scenarios that achieve stable concentrations of GHG in the atmosphere are constructed from technologies that are not available today.

FIGURE 4:
FOSSIL FUEL AND INDUSTRIAL CO_2 EMISSIONS ACROSS SCENARIOS (GTC/YR)

Fossil fuel CO_2 emissions vary among the reference scenarios, but the three differing emissions trajectories lead to emissions in 2100 in the range of 22.5 GtC/yr to 24.0 GtC/yr. The timing of emissions reductions varies substantially across the stabilisation levels. In the Level 1 scenarios, global emission begin to decline soon after the stabilisation policy is put in place (as the scenarios were designed, after 2012), and emissions are below current levels by 2100 in all of the Level 1 and Level 2 scenarios. Emissions peak sometimes around the mid-century to early in the next century in the Level 3 and Level 4 scenarios and then begin to a decline that would continue beyond 2100.







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For example, in its 'Sustainable Mobility Project' the World Business Council on Sustainable Development (2009) concluded that the bulk of emissions reductions for personal transportation by 2050 would have to come from biofuels and fuel cell technologies not known today. This is presented in Figure 5.

The most plausible route to these more substantial cost reductions appears to depend on achieving multiple breakthroughs in basic science, as well as creating incentives for invention and innovation based on known science. Thus, a strategy for improving GHG-control technologies is not a pretext for delay. Rather, it is central to managing climate risks in a way that produces expected net economic benefits.

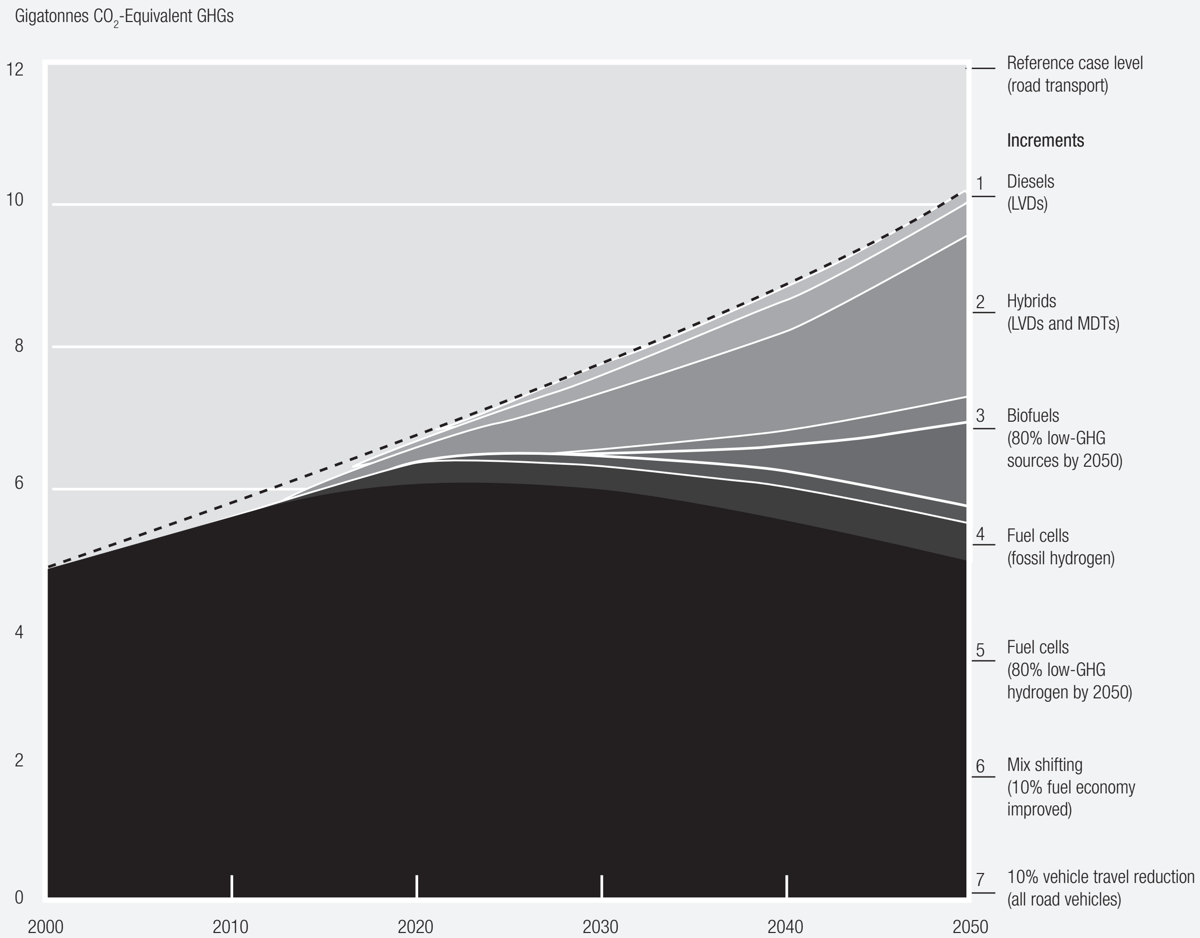
3. The nature of low-carbon R&D

3.1 An iterative model of the process

By now, though, the notion of a linear progression as a description of the innovation process has been thoroughly discredited (Rosenberg 1994). Descriptive contributions to the literature on R&D suggest a very different paradigm. The picture of a straight line is replaced by one of a linked chain with interactions and loops back and forth between basic science, product development and marketing occurring repeatedly until a successful (or unsuccessful) outcome is reached (Nelson et al 1982a). Interactions also occur across chains, as discoveries in the pursuit of one application turn out to be useful for another development activity.

Typically, the effort to develop a discovery's practical application will lead to further questions that themselves, require basic or fundamental research to resolve (Nelson YEAR). For example, pilot plants for production

FIGURE 5:
EMISSIONS REDUCTION – PERSONAL TRANSPORTATION



Source: Sustainable Mobility Project calculations

of alcohol from biomass reveal that the limiting factor on yields and costs is the proportion of lignin to cellulose in the feedstock. Lignin is a woody material that holds stalks up, and cellulose is the required input to fermentation. This observation led back to research in plant genomes to discover the genetic code that controlled this proportion. This step led in turn to the genetic engineering to create new variants, and finally, according to the National Renewable Energy Laboratory (NREL) plant research to determine which will grow .

The other way of looking at this example is that the questions raised in practice can themselves provide a motivation for a particular form of basic research, such as the recent interest in carbon nanotubes as a result of the focus on cost-effective batteries for electric vehicles.

Unpredictability also characterises this process, which then becomes highly path dependent. Several historical studies establish that the scientists responsible for key breakthroughs (eg Shockley and the transistor) had no idea that their discoveries would be put to the uses that made them famous, and in many cases explicitly predicted that their discoveries would have no such use. Thus the notion of planning backward from a technology goal to the basic research required to reach it seems contrary to much of the history of innovation.

New knowledge about the regularities of the natural world enables discovery of new useful knowledge. New techniques often pose fruitful subjects for scientific inquiry or supply novel tools for measurement and observation (Mokyr 2004). History illustrates countless examples of new technology producing advances in science (Rosenberg 1994). These examples, of course, suggest some causal flows in the opposite direction of that suggested by the older linear model.

Further, most innovation implies the novel application of ‘old’ knowledge. Nelson offers a more inclusive perspective. He defines innovation as ‘...the processes by which firms master and get into practice product designs that are new to them, whether or not they are new to the universe, or even to the nation.’ (Nelson 1992, p. 349). ‘Invention’ involves the development of new knowledge. Cumulatively, the novel application of existing knowledge produces much economic value. This fact underscores the importance of the accessibility of 'old' scientific knowledge (Mokyr 2004). At the same time, though, unless the existing knowledge base is refreshed and expanded, diminishing marginal returns are likely eventually to set in (Mokyr 2004).

In Mokyr's view, inventions vary greatly in their significance. Incremental advances in knowledge yield micro-inventions. Large breakthroughs, sometimes referred to as macro-inventions, lead to new lines of technological development. The two types of inventions are synergistic. 'Door opening' macro-inventions are needed to avoid the onset of diminishing returns to innovative activity. The far more numerous 'filling in' micro-inventions are often required to reap the economic benefits that may be only implicit in macro-inventions (Mokyr 2004).

3.2 Implications of the iterative nature of the process

In the linked chain model, however, activities characterised by inappropriability and uncertainty may occur at any point in the innovation process, for example, if a pilot plant reveals a challenge that can only be overcome by going back to investigating some fundamental properties of matter. A highly proprietary (and potentially quite profitable) process being developed in a company may then need basic research that can only be carried out in some other institution, under conditions of inappropriability and uncertainty.

Therefore, just as the iterative nature of the innovation process complicates the task of defining the optimal IP rules; it also poses problems for government-funded R&D (Nelson *et al* 1982a). The difficulties may be especially acute for government-funded R&D intended for private sector adoption. In this case, government-funded basic research might have to address problems that arise at the 'later' stages of the R&D process. These reverse flows may involve the private sector trying to get the attention of government funding and perhaps university researchers for basic research problems that arise in development or commercialisation phases. In other cases, the work flow may remain within the public sector.

In either case, there is a challenge for the basic researchers to be responsive. Culturally, this may not be an easy challenge for them to meet. And there are some signs that the federal appropriations process has a very hard time in shifting funds up and down the process to match the changes in the location of the work's center of gravity.

This feature of the process would appear to imply that support (subsidies, demand pull from carbon pricing) for technology demonstration is likely to be prone to failure, unless there are also mechanisms to provide adequate incentives for all the linked research efforts that may be needed to overcome obstacles (efficiently, without duplication of research effort or attempts to solve problems best addressed in the lab as part of large scale construction project).

3.3 Time scales for diffusion of technology

The diffusion of macro-inventions can be especially time consuming with the pace likely shaped by institutions. Economic history indicates that institutional change was often a necessary prelude to technological change (North 1990). This generalisation will almost certainly apply to GHG reducing innovations. In many instances, adoption of such technologies will depend on disincentives for GHG discharges, created and enforced by government. Yet some governments may prefer to eschew GHG reduction strategies for sound political and economic reasons (Schelling 2005).

There are often very good economic reasons why old technologies remain in use for extraordinary lengths of time. For example, a long process of adaptation to local conditions may make seemingly primitive technologies formidable competitors (Edgerton 2007).

Because climate policy is, by its nature, a global concern, climate-related technology policy must also confront the international dimension. Cost-effective GHG reductions depend crucially on reducing emissions from all major national sources. Any important country's failure to participate in a control regime will cause a rapid increase in the costs of any given abatement goal (Nordhaus 2007).

With China already the globe's biggest emitter and India the sixth largest, these countries must participate or a GHG control regime will be doomed to fail. Currently these countries' economies are much more GHG-intensive than is that of the US, let alone of Europe or Japan. Although new investment in China is more GHG efficient than its installed capital plant, even the newer capital stock still trails that of the US in this regard. Substantial gains in GHG control, could, therefore, occur if China and India were merely to adopt US technology (Montgomery *et al* 2006).

Since even technologies that are currently economically new are not in use, the demand for improved low-carbon technologies will depend on institutional reform. To move beyond this goal, governments would have to adopt pricing or other policies to internalise the climate externality. However, the position taken by these governments in current climate negotiations suggests that they are disinclined to take this step. Absent such policies, no incentive exists to pull GHG reducing technology into these markets.

The successful transfer of technology, however, presents challenges. Economic history has often shown that institutional change can be a necessary prelude to technological change (North 1990). Currently, many institutional distortions in the Chinese and Indian economies discourage investment in more energy-efficient technologies. Such distortions include poor protection for intellectual property, energy price controls and a failure to internalise environmental externalities. (Montgomery *et al* 2006). Further, at least in China, a whole suite of policies effectively subsidise the expansion of energy-intensive heavy industries (Rosen *et al* 2007). By inference, the successful diffusion of less GHG-intensive processes and products is likely to depend in part on institutional change within China and India (Montgomery *et al* 2006).

4. Why has low-carbon R&D policy failed and can anything be done?

4.1 The sources of energy R&D failure

Gaining and holding political power means that lawmakers impose net costs on society in order to secure support. These costs are the inevitable consequence of government, not an aberration (North 1990). A simple example, and one noticed by political observers since Thucydides, is that policies favor concentrated, powerful interests over dispersed, less powerful interests. The beneficiaries of a not-yet-invented technology are, almost by definition, politically silent. The problem is worse if the technology is useful primarily to lower the costs of supplying a global public good.

It is not surprising, therefore, that energy R&D had a long history of waste and failure. Cohen and Noll (1996) describe a dynamic based on incentives by executive agencies and Congressional incumbents that leads to the conclusion that R&D programs will investigate too few risky alternatives in the early stages of research, commit prematurely to large scale demonstration, and continue to fund large scale projects long after their failure has become evident (Cohen *et al* 1991). This is exactly the opposite of the stable, long-term research program required to stimulate breakthrough research and introduce game-changing technologies.

The nature of the electoral process raises the *political* discount rate, especially for members of Congress. Supporting R&D projects that yield large, but diffuse, net benefits and those only after a long time, is a poor re-election strategy. However, when an R&D project reaches a large enough scale, it begins to have distributive significance. At that stage, the project may become politically relevant to legislators interested in re-election (Cohen et al 1991).

In the US, government R&D agencies exhibit an unwillingness to propose a sufficiently wide range of risky alternative approaches to achieve real breakthroughs. High-risk approaches with high potential may not come to their attention, since in the early stage of R&D there are significant agency problems in communicating the nature and potential of an approach (Cohen *et al* 1991). Career advancement is also more likely to come from successful projects rather than accumulation of useful information about approaches that do not work. This limits the set of alternatives considered for funding and leads to far too little risk-taking in government R&D and too narrow a view of possible avenues of approach.

This dynamic introduces a series of perverse incentives.

- First, it encourages officials to move technologies too swiftly to the phase of large-scale demonstration. As a result, these projects often run into technical problems that could have been resolved much more cost-effectively at a smaller scale, and to end up having chosen the wrong route overall.
- Second, congressional involvement has often led to poor projects surviving long after they should have been terminated. Representatives gain electoral credit for continued funding of local facilities and lose almost no electoral credit because the funding is accomplishing nothing.
- Third, the excess resources that demonstration projects consume, either because they are launched prematurely or because they linger too long on political life support, are likely to crowd out more valuable earlier phase research. In effect, projects at the early stage of development are not politically appealing because further work on them is not expensive enough to have distributive significance.
- Fourth, the rush to demonstration may distort the selection of technologies toward those that are more mature rather than toward those that are more promising. Where there is path dependency in technology selection such distortions may have long-term consequences.

In addition to the effects of the high political discount rate on a premature rush to demonstration at high cost, congressional influence on location and design of projects to benefit the most powerful members of Congress and their most influential constituents is unlikely to lead to the choice of the best qualified and most cost-effective organisation to carry out an R&D project, even if it has merit.

The institutional changes that would be required to suppress these tendencies would take away from Congress the ability to use these programs to satisfy constituency demands. It is unclear that there is any way to convince Congress to pass such a 'self-denying ordinance', given opposition to similar reforms such as the line-item veto.

4.2 Recommendations for reform of the climate R&D process

The prevalence of these perverse incentives poses a severe challenge to climate policy. Basic research is essential in the quest for climate solutions and the private sector is unlikely to perform anything like an optimal amount of this work. Hence, government may need to adopt an active research role. The growing evidence that government GHG controls are likely to use relatively cost-ineffective tools reinforces the sense that emissions regulation alone are unlikely to succeed.

However, for the reasons just discussed, creating more direct incentives for R&D entails tackling an inherently very difficult problem. No clear guidelines exist for improving the prospects for a successful search. The task is international by its very nature. And national innovation systems vary greatly. That fact alone ensures that attempts to 'improve' the institutions that will conduct publicly funded R&D are not likely to advance along a single path. That said, a few ideas may merit relatively broad consideration.

Inducement prizes

Among economists, the idea of substituting prizes for research contracts is popular. Prizes have the great advantage of rewarding successful outputs rather than inputs. Thus, the incentives they create can be more closely aligned with the social objectives. Prizes also can stimulate innovation without the disadvantages of creating *ex post* monopoly power, a disadvantage of patents (Newell *et al* 2005).

Government support for generic innovation

One approach, which also fits well with the complex nature of the innovation process stressed by Nelson and others, is to strengthen the R&D supply side and its basic institutions as much as possible. With more resources devoted to R&D, the wide range of signals that technologies which reduce the cost of limiting CO_2 emissions are socially desirable, may then cause some of the results to be climate-relevant.

A much more difficult question is how to create effective economic incentives to shift a large share of R&D resources in that direction. Direct government subsidies designed to boost the supply of scientists, engineers, or research facilities would be one approach. More generous R&D tax credits (or patent protections?) would be others. Such efforts may either aim to increase the total resources committed to RDD&C (the Research, Development, Demonstration and Commercialisation Continuum outlined earlier) or to raise their cost-effectiveness. In either case, even if they are successful in boosting the rate of technological change, these approaches may not yield much in the form of GHG reductions.

In the US, the federal government also provides specialised research facilities at national laboratories that are crucial to many kinds of research. The federal government has modernised several if these facilities and announced plans for further upgrades.

Funding these inputs does not ensure targeting resources towards R&D work relevant to climate change. However, it is also true that some fields produce research skills of very general application despite their relatively low contribution to directly useable discoveries. Thus, Brooks, describing the results of a survey of industrial research executives from 130 industries, observes "…44 industries rated physics high in skill base (second only to materials science, computer science, metallurgy and chemistry, in that order), whereas physics was almost at the bottom of the list in respect to the direct contribution of academic research results to industrial applications"' (1994, p. 480). At the same time, Brooks notes that the need for "defensive science" to deal with various side effects of new technologies also implies that a broad range of disciplinary expertise is required today to bring any new technology to fruition.

At the very least, the potentially high opportunity costs of specialised resources used in R&D suggests that if government makes large increases in climate related R&D expenditures, it should consider the potential supply-side impacts and evaluate possible responses.

Broaden the climate-related research agenda

Substantial global warming is already inevitable, and technological progress seems to offer means by which its costs might be reduced 'adaptation'. Possible examples might include development of drought resistant crops or public health technologies able better to control the spread of tropical diseases. Experts have suggested other possible technological advances.

A substantial amount of climate change is inevitable. Past emissions have locked it into the climate system. Fortunately, much can be done to minimise the net social costs of this change. Many of these adjustments can be left in the hands of the private sector, and state and local governments. They have strong incentives to undertake the needed changes. Today, though, they are hampered by lack of knowledge about how regional climates will change and on what time scale (Repetto 2006). Generating and diffusing this kind of scientific knowledge should be a top priority of federal climate policy. Developing this knowledge will depend on a strong, non-ideological climate science program. New knowledge in this area would clearly boost the nation's long-term economic productivity.

In this policy realm, avoiding the worst outcomes may be more relevant than aiming for the best. This suggests that simply asking whether there are measures that can be counted on to move R&D in the right direction may be more important than designing or modeling optimal policies.

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