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NESTA Making Innovation Flourish

Technology policy and global warming

Why new policy models are needed (or why putting new wine in old bottles won’t work)

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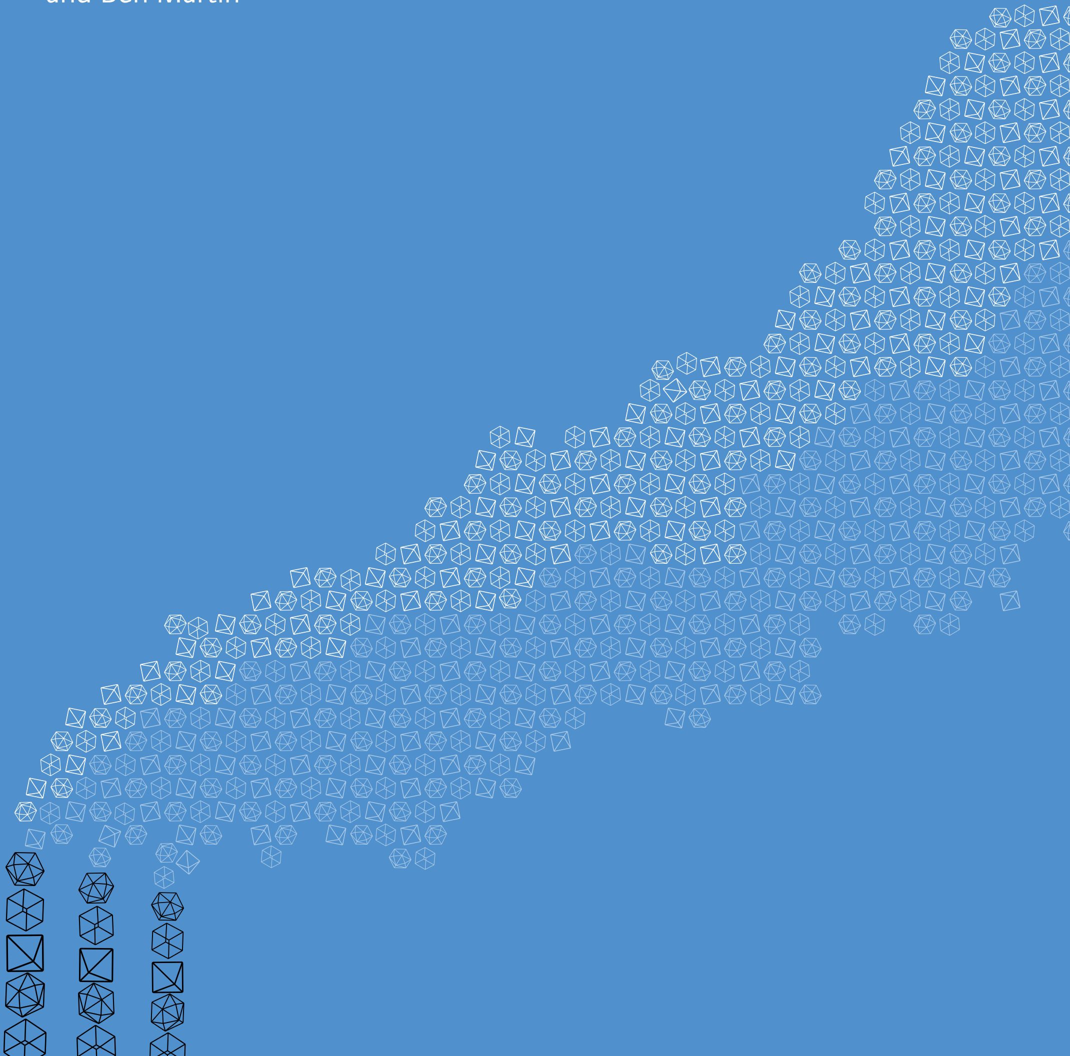

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Introduction

The growing urgency of the global climate challenge has triggered a lively debate in Washington DC, London, and other national capitals over the design of policies to reduce greenhouse gas emissions. While there is no consensus on this, informed participants in the policy debate believe that success in this effort will require the development of new technologies, and that strong governmental technology policy is an essential component of any portfolio of policies aiming to stop and reverse global warming. Many supporters of government action argue that the problem is so great, the need for new environmentally friendly technologies so urgent, and the time remaining for implementation of solutions so limited, that a 'Manhattan Project' or an 'Apollo Program' is needed.

One of the first researchers in the field to invoke the Manhattan Project model was Michaelson (1998), who called for "a Climate Change Manhattan Project". This model was subsequently taken up by others in the academic community such as Amidon (2005), Read and Lermit (2005), and Somerville (2006).[1] An early mention of the Apollo Program model came at the 2000 HYFORUM (International Hydrogen Forum) conference in a reference to the US hydrogen programme (Dunn, 2002, p.257). The Apollo analogy also was discussed by Jacobson *et al.* (2005)[2] and Talbot (2006). Similar arguments in favor of a 'Manhattan' or 'Apollo' model for climate change research and development (R&D) have since been articulated by politicians[3] and others.[4] Most recently, a third policy model, the 'Green New Deal', has been discussed by a leading US journalist.[5] But can one put the new policies required to combat climate change in the 'old bottles' of the Manhattan or Apollo projects?

We emphasise at the outset that we share the broad concern about the risks of global climate change, and we agree that strong government technology policy is part of the solution. Proposals to model such a policy on the Manhattan or Apollo projects, however, are wrongheaded, and if adopted could waste resources and limit the prospects for success.[6] Although the prospect of global warming raises technical and economic issues that are if anything even more daunting than those posed by a lunar landing or the crash wartime programme to develop an atomic bomb, the nature of these challenges is quite different. Most importantly, both the Apollo and Manhattan projects were designed, funded, and managed by federal agencies to achieve a specific technological solution for which the government was effectively the sole 'customer'.

By contrast, technological solutions to global climate change must be deployed throughout the world by many different actors, and these deployment decisions will require huge outlays of private as well as public funds. Both the industries developing and producing these solutions and the sectors in which the technologies will be deployed comprise a very heterogeneous group, ranging from wind power to internal combustion and from electric power generation to dairy farming. Rather than being deployed for a demanding but limited period of operation, technological solutions for global warming must demonstrate their cost-effectiveness, ease of operation, and reliability in systems that may be in operation for decades. Moreover, the long operating lives of numerous installations of these technologies, as well as the embryonic state of development of many of the technologies, mean that these technologies will continue to evolve and improve for decades to come.

Another point of contrast between the R&D programmes that will be needed to combat global warming and these earlier federal 'models' is the relatively high degree of administrative centralisation in both the Manhattan and Apollo projects. As we note below, the tension between centralisation and decentralisation in large-scale R&D programmes is an important issue in programme design for which broad prescriptions are likely to be unrealistic or vacuous. But government R&D programmes to combat global warming will involve numerous organisations, and consequently mechanisms for the coordination of priorities, resource allocation, and performance evaluation will be essential.

This essay focuses on the public programmes needed to develop and adopt new, more environmentally friendly technologies, which we view as a vital part of the broader task of dealing with global warming.[7] We nonetheless recognise that much more than technology policies are needed to address this challenge. Indeed, some observers argue that nothing less than a 'Green New Deal' is needed to support the full range of policies needed to deal with global warming. We agree with this characterisation of the problem and the necessary policy responses. But this analogy should not be carried too far, recognising that the New Deal of the 1930s in the United States did not rely on governmental technology policy to any significant degree, in contrast to the proposed 'Green New Deal'.

Public policies to support the development and deployment of technological solutions to global warming are urgently needed, but these programmes must differ in design from the 'big push' programmes exemplified by the Manhattan or Apollo projects. The next section elaborates on the characteristics of the policy context that call for a different kind of technology policy. We then discuss the political environment within which climate change policies are developed and implemented, highlighting the ways in which this environment contrasts with those of the atomic bomb and lunar landing programmes. Government technology development and deployment programmes in the United States and United Kingdom that provide more useful guidance for policy design are discussed in the next sections, and the final section elaborates on the implications of our discussion for the design of policies supporting technology development and deployment to address global climate change.

The economics of innovation for climate change

The majority of the human activities that generate greenhouse gases and hence contribute to global warming involve the generation and use of energy, and these activities almost certainly will be the focus of climate change technology policies, as has been the case in the United States under President Obama.[8] As we noted earlier, these targeted technologies are numerous and diverse. So are the industries that will produce and sell equipment embodying them, as well as their users. Nevertheless, in virtually all cases, as Newell (2008) has pointed out, technology policies aimed at the climate change problem must address two central challenges.

First, the full social costs of greenhouse gas emissions are not reflected in current market prices for fossil fuels, meaning that these fuels are consumed in greater quantities than is desirable. The 'mispricing' of fossil fuels also suppresses the demand for technological substitutes for fossil fuel technologies. Private funds to develop substitutes will be in short supply, in part because of the expectation that demand for such substitutes will not be forthcoming from private parties. In such an environment, the willingness of private firms and households to purchase and utilise more environmentally friendly technologies developed with public funds will be similarly repressed. Any policy to address global warming must address this failure of prices to accurately reflect social costs, preferably through a tax on carbon or a 'cap and trade' system of emissions targets.

Second, private investors in R&D on alternative-energy technologies in many cases will be able to appropriate only a small portion of the value of the results of their R&D investments. At the same time, however, policies that seek to enhance the private appropriability of these returns by limiting the diffusion of the knowledge resulting from R&D are inadvisable in technology development programmes to combat global climate change. The global nature of the problem and the necessary efforts to address it mean that wherever possible, programmes of support for technology development should include support for dissemination of the knowledge and technologies resulting from these public investments.

The development and improvement of the relevant technologies will be a continuous process that involves the efforts of many actors. It is especially important that restrictive policies toward the sharing of publicly funded intellectual property do not constrain the ability of different domestic and international actors to contribute to these learning and improvement processes. In the United States, energy R&D programmes that emphasise 'public-private partnerships' (e.g. Cooperative Research and Development Agreements, CRADAs) often grant the rights to the intellectual property resulting from such programmes to the private partners. The scope of the global climate challenge and the necessary responses to it nonetheless are sufficiently great that R&D policy in this area should favour broader licensing and dissemination of IP, rather than allowing private actors to employ restrictive licensing policies for any patented results that they may obtain from publicly funded programmes.

As we noted above, the fact that extensive adoption of alternative-energy technologies is essential in order to combat global warming has important implications for programme design in this area. This ‘technology adoption’ challenge was not an issue in the Manhattan or Apollo projects, since the adopter of the technologies was also their developer, and since the technologies developed within these programmes were most definitely not intended for widespread adoption by non-governmental entities. Moreover, and in contrast to the Manhattan and Apollo projects, widespread adoption of alternative-energy technologies requires the replacement of existing technologies for energy production in a diverse array of sectors.

The fact that adoption of alternative-energy technologies is largely a case of replacement means that many would-be adopters of alternative energy technologies are evaluating a new technology with limited deployment history, uncertain reliability, and unpredictable capital and operating costs. Potential adopters must compare this unproven technology against established technologies that have been deployed, for which extensive operating experience has reduced uncertainties about performance and reliability, and where learning in use has reduced operation and maintenance costs. The slow adoption of electric vehicles for personal transportation during the last decade illustrates these challenges.

In most cases, the earliest versions of significant technological innovations are characterised by limited reliability and high capital and operating expenses – compare the mainframe computers of the 1950s with 21st century desktop systems with similar or greater capabilities. Computing technologies, like virtually all complex innovations, have experienced a prolonged period of incremental improvement that has dramatically enhanced their functionality and reduced their costs. In addition, the widespread adoption of computers has accelerated learning in use, further reducing their costs of operation and maintenance.

As a result of these characteristics of innovation, even if the social costs of greenhouse gas emissions were fully reflected in prices and private costs, the early versions of most alternative-energy technologies would be handicapped in direct comparisons with existing technologies by prospective adopters. This characteristic of the technology adoption process not only underscores the critical importance of policies that send the ‘right’ price signals to would-be adopters, but also highlights the possibility that the adoption of the initial versions of more environmentally friendly technologies may require subsidies or other forms of public support for early adopters of these technologies (as in the case, for example, of generous German subsidies for the installation of photovoltaic roof panels – see Reiche and Bechberger, 2004, p.847).

The importance of learning in use also means that broader adoption and more extensive operating experience will feed back into improvements in these alternative-energy technologies. Adoption and technological improvement can thus reinforce one another. These closely linked processes of adoption and technological improvement may benefit from public information dissemination programmes that link early adopters with one another and with major producers and R&D organisations engaged in developing and improving these technologies.

Two other features of alternative-energy technology development and deployment that render the Manhattan/Apollo Project analogy inappropriate are the heterogeneity within the energy technology development and technology adoption communities, and the fact that both of these communities are global in scope. The energy-related technologies that are involved in any solution to global warming are extraordinarily diverse and will be developed and produced by firms in many different industrial sectors. The same characterisation applies to would-be adopters, who span sectors ranging from automobiles to electric power production. Moreover, any portfolio of technology-based 'solutions' to global warming must be adopted and deployed on a global scale. Both the development and deployment of these technologies will therefore involve producers, adopters, and national innovation systems in countries around the world. And the importance of local knowledge of applications and operating environments means that rather than North-South 'technology transfer', feasible technological solutions that are widely adopted will almost certainly involve North-South collaboration in technology development and deployment.

Since alternative-energy technologies are deployed as replacements for existing technologies that initially may be more reliable and/or less costly, and given the importance of information dissemination about the operation, maintenance, and opportunities for incremental improvement of alternative-energy technologies, there is strong justification for public support of early-stage deployment and demonstration of the feasibility and operation of at least some of these technologies. The case for such 'adoption subsidies' is further strengthened by the high probability that prices on fossil fuel carbon emissions will be set too low to reflect the full social costs of these pollutants.

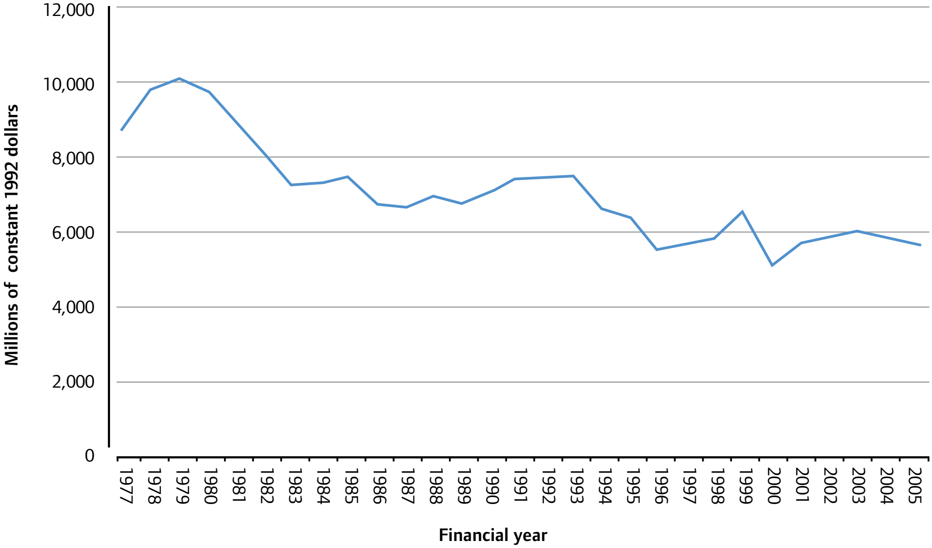
The problematic political economy of technology policy for global warming

The political environment within which technology policy to combat global warming is developed and implemented highlights another contrast with the Manhattan and Apollo projects. The fact that technological solutions to global warming involve the replacement of some technologies and energy sources in widespread use has significant distributional consequences, notably among long-established industries and firms producing various fossil fuels and other forms of energy. The scale of these distributional effects dwarfs any that were present in the Manhattan or Apollo projects. These distributional effects also complicate the politics of alternative-energy technology programmes.

One such complication that we have pointed out already is the reluctance (understandable yet unfortunate) of policymakers to adopt pricing or tax policies that would set a price for carbon-based emissions at or near their full social cost. This failure to intervene more forcefully on the demand side has long been a hallmark of US energy policy. Repeated calls by Presidents from Richard Nixon to George W. Bush to achieve ʻenergy independenceʼ have run aground on the unwillingness of policymakers in the Executive Branch and Congress to impose significant taxes on oil and related products, an important first step towards discouraging the consumption of imported oil and encouraging private investment in the development and adoption of alternative-fuel technologies. US energy policy has failed to stabilise oil prices at levels that reflect the asserted geopolitical and environmental costs of US addiction to foreign oil imports, and the resulting wide swings in oil prices have paralysed private investment in the development and deployment of alternative technologies. In the United Kingdom, public investment in the development of alternative energy sources has also been impeded by swings in political mood, financial priorities and changes in government. The 1970s oil crisis prompted a UK programme to investigate such alternatives, but this was cut a few years later by the government headed by Margaret Thatcher.

Fluctuations in energy prices have tended to produce comparably wide swings in government investment in energy R&D, which typically is ramped up in response to a ʻcrisisʼ of high prices and then declines in parallel with reductions in energy prices (See Figure 1). The chilling effects on private investment in R&D and technology deployment of these wide swings in fossil-fuel energy prices thus have been exacerbated by the synchronous swings in government energy R&D investments in the United States, the United Kingdom and elsewhere. The very political saliency of energy policy and R&D have for the past 35 years contributed to policy instability, which in turn has stunted private investment in alternative technologies.

Figure 1: DOE obligations for R&D and R&D Plant, financial year 1977 – 2005



Source: Science and Engineering Indicators: 2000 (National Science Board), Table 2-36; National Science Foundation, Federal Funds for Research and Development: FY 2003 – 2005 (National Science Foundation), Table 103.

Where and why has US technology policy been effective?

Although the track record of the US government's postwar innovation policies in the energy sector is relatively undistinguished, federal programmes in a number of other sectors have proven effective in supporting the development and deployment of innovative technologies. Here, we briefly summarise the development and effects of US R&D policies in agriculture, the biomedical sciences, and information technology. The subsequent section discusses UK technology policies in the biomedical and agricultural sectors.

Agriculture

In 1940, support for agricultural research accounted for 39 per cent of the R&D spending of the federal government (Mowery & Rosenberg, 1989). Public funding of agricultural research in the United States has long been a joint Federal-State responsibility, with a decentralised structure of funding sources, priority-setting, and R&D performance. The growth of industries supplying inputs to agriculture ranging from agricultural equipment to fertiliser and seeds has been associated with increased industry-funded R&D investment, which accounted for at least 50 per cent of total R&D spending relevant to agriculture by the 1970s (Evenson, 1982).

The growth in industry-funded R&D spending in agriculture reflects the fact that in addition to benefits for farmers, publicly funded R&D in agriculture has yielded knowledge and technologies that have proven useful to agriculture-related industries. Numerous studies have measured the public rate of return on government agricultural R&D investments, and all of these studies have found the return to be high (see Evenson, 1982). Public R&D investments have contributed to the remarkable decline in the real prices of agricultural products that has occurred over the last century as well as to the ability of the United States to expand agricultural output in the face of a considerable reduction in the fraction of the nation's workforce engaged directly in agriculture.

The geographically decentralised structure of the state and federal public agricultural R&D system and the shared responsibility for its financial support gives state agriculture departments, universities, and research stations considerable influence over the R&D agenda of this system. Its decentralised structure also enables the public agricultural R&D system to address the significant differences in climate, crop mix, and soil types among regions of the United States. At the same time, however, the strong influence of 'local' interests within public agricultural R&D has tended to favour a short-term research agenda that is relevant to dominant producer concerns and economic interests, rather than an R&D strategy primarily directed at the development of a strong agriculture-related science base. Nevertheless, the activities of the public US agricultural research system have supported both incremental innovation and the development of new technologies and inputs, including new farming techniques and seed varieties, from which farmers could choose.

An important feature of the US public agricultural R&D system is the agricultural extension programmes that work with farmers in a given growing region to make them aware of research and technological advances relevant to their crops and growing conditions. The United States Department of Agriculture first sponsored such activities in the early 20th century in response to a boll weevil infestation that devastated cotton crops in the South. Like the agricultural research system, the operation and governance of the extension system has been largely decentralised and under state control. As Evenson pointed out (1982), the combination of agricultural R&D and extension activities has proven especially valuable in farmers' adaptation to new environmental and other regulatory mandates in crop production. Inasmuch as a similar regime of regulatory mandates is likely to be an important part of the global response to global warming, these characteristics of agricultural R&D seem especially relevant to climate change R&D policies.

Many agricultural research stations are affiliated with public universities, which have built up strong programmes of research and teaching in the sciences that underpin agricultural research. Management and researchers at the agricultural research stations (some of whom also serve as faculty in the affiliated universities) have benefited from these linkages with academic research. Nevertheless, the focus of the agricultural research stations on applied R&D with clear short-term payoffs appears to have weakened their ability to stay up-to-date with and exploit advances in fundamental science. The publicly funded agricultural research system was slow to recognise the relevance of the revolution in biotechnology that occurred in the 1970s and 1980s, and only gradually expanded its employment of scientists trained in those fields. The US Department of Agriculture has recently pressed the agricultural research stations to strengthen their scientific capabilities, linking a larger share of their federal funding to competitive research grants.[9]

The long history of the US agricultural R&D system highlights the tension within any publicly funded R&D programme between responsiveness to 'user needs', where these 'needs' tend to be those of established producers, and research that seeks to develop new technologies or practices that potentially threaten the interests of those producers. This tension is inevitable and by no means undesirable in an R&D programme with strong links to users. Energy R&D, like agricultural R&D, must balance the objectives of advancing current practice (including supporting technology deployment) and supporting long-term research that aims to bring new technologies into practice. It is essential, however, that this balance be monitored carefully and sustained by a central organisation such as the USDA that is committed to the long-run performance of the system.

The objectives and the conditions that have moulded US agricultural research programmes of course differ in significant ways from those that will orient and constrain government programmes in climate change R&D. Nevertheless, several aspects of the agricultural research programme are relevant for the design of R&D programmes to combat global warming.

First, these programmes must incorporate a considerable degree of decentralisation, reflecting their objective of advancing a wide range of different technologies that serve the needs of diverse users. Second, as in US agricultural research, mechanisms that both reach out to users, thereby developing a sophisticated understanding of user needs, and at the same time inform users of new developments and help them to adopt those new developments, are critical.

But the US experience with its agricultural R&D support programmes also suggests that close attention to the perceived needs of user communities has a downside, especially in skewing resources towards short-term parochial interests. An effective long-term R&D programme in energy must also support the development of promising new technologies that may nevertheless lack a user or industrial constituency.

Biomedical research

The research supported by the National Institutes of Health has been an important factor behind the innovative and commercial success of American pharmaceutical and biotechnology firms during the postwar period. A substantial majority (80 per cent) of the annual research budget of the NIH supports research performed in laboratories at universities, generally in medical schools. The NIH supports half of all federal non-defence R&D and over 60 per cent of federally funded research in American universities.[10] As a result, NIH funding supports the training of a substantial annual cohort of MDs and PhDs, expanding the pool of human capital for fundamental and applied research in biomedical fields, and contributing to advances in clinical practice.

In contrast with publicly funded research in agriculture, much of which has focused on improving practice, most NIH-supported research seeks to advance the state of scientific knowledge of diseases and potential treatments, rather than focusing on improvements in healthcare delivery. With a few exceptions, private firms have assumed primary responsibility for the development of new drugs and medical devices. Rapid growth in federally funded biomedical R&D (which grew from slightly more than $8 billion in 1984 to almost $29 billion by 2008) has been more than matched by growth in privately funded R&D investment in the US pharmaceuticals industry since 1990. By the early 21st century, federally funded

R&D accounted for less than 40 per cent of overall R&D spending in this sector.[11]

The focus of the NIH on basic research is based on the premise that the key to dealing with diseases is better scientific understanding. This premise is broadly accepted within Congress as well as within the biomedical science community, and has influenced the organisation and budgeting for NIH. Currently, the NIH is made up of 27 Institutes and Centers, most of which are dedicated to a broad disease category or categories (e.g., cancer, infectious diseases), and the majority of the NIH budget is divided among these Institutes and Centers.

This structure facilitates lobbying by interest groups organised around specific diseases, an activity that has contributed to the creation of seven new Institutes and Centers since 1987. Although decisions on the establishment of new Institutes and Centers, as well as decisions on the allocation of the total NIH budget among these entities, involve considerable political as well as scientific influence, decisions on funding research projects within disease fields are controlled primarily by peer review and competitive evaluation of proposals from researchers in universities and other academic medical centers. The biomedical research community thus exercises considerable influence over NIH research funding decisions within disease areas.

Although peer review is the primary mechanism for making decisions among individual grant proposals within disease areas, Congressional involvement in allocating research funds among Institutes and research areas assuredly does affect research priorities. And in several major NIH programmes focused on ‘cures’ or specific applications, for example, Congress has pressed NIH administrators to use contracts, which stipulate ‘deliverables’ and timetables for their achievement, rather than research grants, which support fundamental research where the objectives are less easily defined in advance. Both the ‘War on Cancer’, which was launched in 1971, and the artificial heart project imposed clear, if broad, constraints on the types of research that could be supported and made greater use of research contracts.[12] NIH research funding also has been affected by the regional political influences that have been significant within both US agricultural research programmes and the DOE R&D programmes performed within that agency’s laboratories (Hegde and Mowery, 2008). The remarkable success of the NIH in maintaining strong Congressional support is highlighted by the doubling of this research agency’s budget during 1998-2003, an initiative begun under President William Clinton and completed during the Presidency of George W. Bush.[13]

In contrast to federal investments in IT, which we discuss next, US R&D policy in the biomedical sector did not include any direct government ‘demand-pull’ with its R&D investments. For a variety of reasons, however, such as the dominance of third party payment (from both public and private sources) for much of US health care, the US health care system has been insensitive to cost, and relatively quick to adopt new technologies, even where their cost-effectiveness is uncertain. Although it is a costly and inefficient mechanism for supporting healthcare delivery, this payment system may have encouraged private investments in R&D that complemented public funding and accelerated innovation and adoption.

The objectives and the conditions moulding the US government biomedical research programmes, like those of its agricultural R&D programmes, differ from those that will guide energy R&D programmes. But we highlight several features of US government biomedical R&D programmes that provide useful guidelines for the design of energy R&D programmes.

First, federal biomedical R&D programmes illustrate the value of programmes dedicated to advancing the scientific understanding that can lay the base for the development of significant new technologies. Unlike the US agricultural research support programme, which arguably has been oriented too closely to perceived needs of the existing user community, the biomedical research support programme has from its inception largely focused on creating the knowledge needed for the development of new technologies. Second, US biomedical R&D programmes have played a major and successful role in the training of the biomedical research community. The creation of a pool of trained scientists and engineers in fields relevant to climate change innovation should be another important objective of any government programme in this area. The case of US biomedical R&D also highlights the role of demand in the development of incentives for industry R&D investment and rapid adoption by users of the results of public and private R&D investment.

Information technology

Postwar US military R&D programmes in information technology provided a powerful impetus to the development of at least three important 'new industries' within the post-1945 US economy: semiconductors; computer hardware; and computer software. These three industries subsequently combined to give birth to the Internet, a 'general purpose technology' spanning many industrial sectors. The US IT sector has long been a global leader in innovation and competitiveness, and its strong performance has benefited from federal R&D investments that date back to the 1940s. Although a number of federal agencies, including the National Science Foundation, the National Aeronautics and Space Administration, and the National Bureau of Standards, supported R&D programmes in IT during the 1940s, 1950s, and 1960s, the majority of the federal R&D investment in these technologies during this period flowed from US military and defence-related agencies, including the Department of Defense, as well as the National Security Agency and the Atomic Energy Commission.

In contrast to the agricultural and biomedical R&D programmes discussed earlier, a large share of federal R&D

investments in IT was motivated by the need to improve and apply these technologies to national defence missions. Since federal defence agencies were among the first users of semiconductor and computer technologies, military procurement dominated early markets for products based on these technologies. The 'user needs' that drove the R&D agenda during the early years of large-scale federal investment were those of federal agencies, rather than civilian users. Although the US scientific and engineering research community, much of which had been mobilised for World War II and was 'remobilised' for the Cold War, played a key role in advising federal agencies on priorities and research opportunities, the structure of federal R&D programmes in IT during the first three decades of the industry more closely resembled that of the 'War on Cancer', emphasising the use of research and development contracts, than that of fundamental research programmes elsewhere within the NIH.

The involvement of numerous military and civilian federal agencies in IT-related R&D during the three decades following 1945 meant that the structure of these programmes was relatively decentralised – no single federal agency had sole responsibility for overall R&D 'strategy' in IT. The embryonic state of the relevant technologies meant that federal R&D programmes supported activities ranging from fundamental research in academic and industrial laboratories, applied and development activities in academia and industry, and early-stage production of new semiconductor devices by industrial firms. This pluralistic structure of R&D funding sources, along with the investment of public funds in a diverse array of R&D and production-related activities, supported the exploration of numerous alternative technological solutions in the early years of development of technologies characterised by high levels of uncertainty concerning the feasibility of specific solutions and applications.

Although consistent in their broad objectives, federal R&D programmes displayed considerable flexibility and structural change during their first 25 years, a point highlighted by the changing roles of industrial and academic research institutions during the early evolution of semiconductor and computer technologies. US universities played a prominent role in the early years of development work on electronic computers, a role that by the late 1950s had been assumed mainly by industry. Federally supported R&D projects for military applications of computer technology during the early 1950s, notably in strategic air defence and the development of computers for nuclear weapons design, challenged the state of the art within industry and made important contributions to the technological capabilities of firms such as IBM. The contributions by US universities to fundamental research and training of researchers in IT-related disciplines benefited significantly from the support of the US National Science Foundation for research in the new discipline of computer science during the 1950s, including NSF funding for purchases of early mainframe computers by a number of US universities.

The national-security motives for much of the R&D spending meant that federal R&D investments for IT were complemented by federal military procurement expenditures. US military agencies served as ‘lead users’ for technological advances in semiconductors and computer hardware, able and willing to pay premium prices for products meeting their demanding performance requirements. This early-stage federal demand supported the growth of new firms and enabled them to benefit from learning economies and incremental improvement in their products.

Defence-related R&D programmes and procurement produced important advances in civilian technological applications through the ‘spillovers’ of knowledge and technology from military to civilian applications. In addition to the technological knowledge produced by R&D investments in industry and academia, large-scale military procurement of these technologies enhanced their reliability and ease of use, while reducing their costs. The improved cost-effectiveness of computer and semiconductor technologies supported the growth of civilian applications such as information processing, airline reservation systems, and consumer electronics, and commercial sales of computers and semiconductors (particularly integrated circuits) began to expand by the late 1950s. The share of military sales and federally funded R&D within the IT sector declined as civilian sales grew.

Federal procurement regulations and other federal policies influenced other aspects of the evolving industrial structure of the IT sector. Firms supplying defence agencies with semiconductors frequently had to comply with ‘second-sourcing’ requirements that mandated a second producer for key components. These requirements meant that supplier firms had to share production-related know-how with other suppliers, accelerating inter-firm knowledge diffusion. Federal antitrust policy weakened the potential market power of dominant firms (AT&T in semiconductors; IBM in computers) and mandated relatively liberal licensing of key patents. In computer hardware, computer software, and semiconductors, the early years of industrial development were characterised by relatively weak formal intellectual property rights, which appear to have facilitated significant entry by new firms, strong competition, and rapid technical progress.

The development of computer-networking technology, which benefited from R&D funding from the Defense Department’s Advanced Research Projects Agency (ARPA), illustrates the benefits of public support for early-stage deployment of new technologies. US dominance in computer networking did not result from a first-mover advantage in the invention or even the early development of a packet-switched network, the ARPANET. Although US scientists and engineers made important contributions to packet-switching and computer-networking technologies and protocols, they were by no means alone. French and British computer scientists also contributed important technical advances during this period, and publicly supported prototype computer networks were established in both France and the UK by the early 1970s.

One factor that seems to distinguish US computer-networking projects from those in the UK and France is the scale of the early deployment of the US network that was supported by federal funds. Its size and the inclusion of a diverse array of institutions as members both appear to distinguish the ARPANET from its British and French counterparts, and accelerated the development of supporting technologies and applications. The example of computer networking illustrates one way in which public support for the deployment of early versions of new technologies can accelerate their wider adoption and improvement as a result of learning in use and the contributions of innovative users.

Despite differences between the objectives of the US IT R&D programmes discussed above and those that will orient an energy R&D support programme, some of the structural conditions are similar, notably the importance within these IT programmes of R&D performed by industry. In addition, US IT R&D programmes illustrate the importance for long-term innovative and competitive performance of ensuring that one or a few companies do not dominate a particular field of technology. Just as the early US IT R&D programmes sought to create and preserve a competitive industry structure, so too should government energy R&D programmes. Finally, the importance of federal military procurement in the development of the US IT industry underscores the powerful influence of public 'demand-side' policies in developing new technologies.

UK government R&D programmes in the biomedical sciences and agriculture

Having discussed three American government R&D programmes, we now consider two cases in the UK – biomedical research, and (rather more briefly) research related to agriculture. The biomedical case, like its counterpart in the United States, can be regarded as a success story, and we consider it first. The British experience with support of agricultural research has been much less successful, and our summary of the case suggests some reasons for this limited success.

UK government-funded biomedical research

The history of publicly funded biomedical research in the UK, which predates 1945, has several similarities with the United States, where substantial public funding appeared only during the 1950s. Much UK biomedical research, like its counterpart in the United States, has been conducted in medical schools and universities, in close proximity to the training of students as well as to the treatment of patients (in teaching hospitals, which perform a function similar to the extension service in US agriculture, demonstrating to other hospitals and doctors the potential benefits of new medical treatments). Publicly funded research in the UK has contributed to important advances in medical knowledge and practice as well as providing inputs to numerous medical innovations, especially in the pharmaceutical sector. Indeed, Britain's publicly and philanthropically funded biomedical R&D programmes are an important factor behind the strength of the British pharmaceuticals industry.

For many years the principal organisation responsible for public research funding was the Medical Research Council (MRC),[14] which was set up in 1919 to promote research in the medical field. The orientation of the MRC was influenced by a 1918 report by Lord Haldane on public funding of scientific research, which argued that only scientific freedom could generate rigorous, high quality research. For most of its subsequent history, the MRC largely supported basic research. Since World War II, however, MRC funding for research has been complemented by R&D funding from other government agencies for applied research bearing on medical care. One of these was the Ministry (and later the Department) of Health, which in the 1950s began to support large-scale research activities (e.g. population screening). Another was the National Health Service (NHS), which was founded in 1948 to provide health care for all UK citizens. Although the NHS initially provided little funding for research, its support for such activities gradually expanded. Thus, by the 1960s medical research in the UK was supported by three government agencies.

During the 1960s, the MRC was criticised for its emphasis on basic research and for failing to meet public medical needs (Balmer, 1993, p.74). In 1971, in a reversal of the Haldane Principle, the Rothschild Report on overall UK government support for R&D argued for a 'demand-driven' approach to funding research. The report resulted in the transfer of a substantial portion of MRC funds to the Department of Health and Social Security (as it was then named) so that the Department could commission research from the MRC under the 'customer-contractor' principle emphasised by Rothschild. Within a few years, however, this arrangement came under criticism, because the Department evidently lacked the expertise needed for carrying out its new responsibilities. In particular, it was unable to generate its own research projects, so in 1981, the 'customer-contractor' principle was abandoned (at least for medical research) and the MRC was once again given sole responsibility for funding basic medical research.

Up to the end of the 1980s, the research funded by the NHS consisted of a series of relatively uncoordinated projects. Beginning in 1991, however, a formal NHS R&D Programme was established to coordinate overall research within this large healthcare agency. During the 1990s, various efforts to develop a more coherent NHS R&D strategy had little effect, generally because of a redirection of R&D funds to meet health service targets. Finally, in 2006, NHS R&D funds were brought together under a newly created National Institute of Health Research, the aim of which was to make the NHS a centre of excellence for health research. Its budget was £660 million in 2006/07, which exceeded the budget of just over £500 million for MRC in that same year.[15]

Another key component of the biomedical research system in the UK consists of the medical research charities. The largest is the Wellcome Trust, which currently spends about £600 million a year on biomedical research. Another is Cancer Research UK, which in 2006/07 spent just over £300 million on various forms of cancer research. Numerous other disease-specific charities make significant contributions to the funding of biomedical research.

The last, and arguably the most important, component of the British biomedical research system consists of industry, especially the pharmaceutical industry. During the 20th century, companies such as Wellcome, Boots, Beecham, Glaxo and ICI gave considerable emphasis to research, building up their own R&D laboratories as well as collaborating closely with universities. In 2006, the British pharmaceutical industry spent £3.95 billion on R&D,[16] almost double that spent by government and charities. This large industrial R&D investment ensures a strong interest in and demand for the results of publicly funded research.

This brief summary of a complex history suggests that in contrast to the United States, where the NIH has exercised nearly complete control over federal biomedical research funding since the 1950s, public funding of UK biomedical research has for much of this period involved a more diverse set of agencies and funding sources. One area in which UK policy toward publicly funded biomedical research has changed over time, in many respects similarly to the United States, concerns the changing support by policymakers for intellectual property protection of the results of government-supported research. Until the 1960s, UK policy favored placing the fruits of government-funded research in the public arena; penicillin, for example, was not patented in the 1930s.[17] As late as the 1970s, while patents were routinely being taken out by British (and American) pharmaceuticals companies, the results of government-funded research performed by British academic institutions and nonprofit research establishments rarely were patented. Thus, the discovery of monoclonal antibodies by the MRC Laboratory of Molecular Biology in 1975 did not result in a patent application. More recently, the surge of university patenting in the United States following the passage of the Bayh-Dole act has contributed to a swing in policy in the UK towards the encouragement of patenting of products coming out of government-funded biomedical research.

In summary, the successful development of biomedical research in the UK and its exploitation by industry seem to have been based on a number of factors. These include the existence of leading biomedical researchers in a variety of institutions, including universities and medical schools, MRC units and institutes, NHS hospitals and company R&D laboratories, competing but also collaborating with each other. Second, there has been a wide range of funding sources (MRC, Department of Health, NHS, charities and industry), again with an element of competition among them. Third, the periodic attempts to coordinate or even merge the activities of the various public sector funding bodies have largely been ineffective, leaving the different funders free to pursue their own strategies and ensuring a diversity of approaches. Fourth, as in the US, a large part of the research (especially basic research) has been conducted in universities and medical schools, in close proximity to the training of students as well as to medical practice, affording the best opportunity for mutually beneficial interactions between these various activities. Fifth, British pharmaceutical firms set up their own R&D laboratories and invested heavily in research (including funding university research). This helped to provide a strong ‘demand pull’ for biomedical research as well as ensuring that the firms had the necessary absorptive capacity to exploit the results of research conducted in universities or MRC institutes quickly and effectively. Lastly, the fact that until comparatively recently, researchers in universities and MRC institutes were cautious about patenting research results may have accelerated the flow of scientific knowledge through the wider biomedical research system.

UK Government agriculture R&D programmes

UK agricultural research has a far less successful record than biomedical research in the UK, or agricultural research in the United States. There have been relatively few major scientific advances in agriculture comparable in magnitude and importance to the most significant of those that have come from UK universities, MRC laboratories and British companies in the biomedical area (several of which have resulted in Nobel Prizes). Likewise, it is difficult to point to major British firms that have become world leaders through exploiting agricultural research advances in the same way as occurred in the pharmaceutical sector (although for a period ICI was very prominent in the area of agro-chemicals). This section briefly highlights some reasons for this contrast, and indeed for the differences with agricultural research in the United States, before examining what lessons might be drawn from Britain's experiences regarding the design of policies for meeting the challenge of global climate change.

Agricultural research, like medical research, had its own Research Council (the ARC) by 1931, and a number of agricultural institutes were set up in Britain even earlier. Nonetheless, there were several important differences between ARC (which was replaced by the Biotechnology and Biological Sciences Research Council, BBSRC, in 1994) and MRC. In particular, ARC devoted much of its resources to supporting research in its own institutes, most of which were independent entities rather than being embedded in universities. With a few exceptions (e.g. Reading University, Wye College London), UK universities were much less actively involved in agricultural research than in medical research. As a result, the field lacked the strong links between research and teaching that characterised UK medical research.

Another important difference from the medical sector was that the Ministry of Agriculture in the UK never provided research funding of comparable magnitude to that provided by the Department of Health. Third, there was no agricultural equivalent of the NHS to provide another source of public funding for research. Fourth, UK agricultural research lacked a private philanthropic source of funding similar to the Wellcome Trust and Cancer Research UK. Lastly, and most importantly, there was less emphasis on R&D funding in UK agriculture-related industry, with one or two exceptions (such as seeds and plant breeding, and some food producers). In short, there was nothing like the same diversity of funding sources as in the biomedical area, there were weak links between research, on the one hand, and teaching and 'practice', on the other, and there was a much weaker 'demand pull' from industry.

There are also important differences between the UK and US public agricultural R&D systems. First, the agricultural R&D programmes of the UK Ministry of Agriculture (in its various incarnations) were far smaller than those of the US Department of Agriculture. Second, there were no regional sources of funding for agricultural R&D equivalent to those of individual US states. Third, extension service activities in the UK were never developed on the same scale as in the US. Fourth, with one or two exceptions, there were few agricultural research stations attached to British universities, and therefore far less interaction between research, teaching and agricultural practice than in American universities. Lastly, industry funding of agricultural R&D has lagged well behind that in the US (where, as we saw above, it has accounted for perhaps half of total agricultural R&D spending).

What lessons can be drawn from these British cases that are relevant to the design of policies to address the problems of global climate change? One principle for programme design that British biomedical R&D programmes illustrate, as do US government R&D programmes in the IT, agricultural, and other sectors, is the desirability of establishing a range of public funding sources to ensure diversity and competition. A second is that effective R&D support programmes need to have a balance between support of work focused on specific (typically, near-term) needs and demands, and support of the basic research that yields mainly long-term benefits. Striking and maintaining this balance is difficult in a political environment. Third, the contrasts between the British and American agricultural R&D programmes highlight the importance of performing much of the R&D in universities rather than free-standing research laboratories in order to ensure close interaction between research and training, as well as the importance of close interactions with the user community.

Implications for the design of energy R&D programmes for combating climate change

This concluding section pulls together the strands of our argument concerning the nature of the challenges faced by government R&D programmes on energy-related technologies for combating climate change, and develops some general principles for the design of such programmes that draw on our discussion of US and UK government R&D programmes. Although the Manhattan Project and Apollo Program have been proposed by a number of scientists, journalists, and politicians as relevant models, the challenges faced by a programme designed to develop energy technologies that are less damaging to the environment, while no less formidable, differ fundamentally from those faced in these earlier programmes.

As we noted in the Introduction, the Manhattan and Apollo projects were public programmes undertaken to meet the needs of a single, government 'customer', and their success did not depend on the widespread adoption by individuals and firms of a diverse array of technologies. An effective R&D programme to combat climate change must support the development and deployment of many different technologies that will be employed in a diverse array of sectors in the US, the UK, and throughout the world. Although it is important to begin this effort as soon as possible, the battle to combat climate change will not be won in a single engagement, and public programmes should focus on long-term support for the development and improvement of relevant technologies, rather than seeking a one-time technological breakthrough.

The importance of rapid and widespread adoption of alternative-energy technologies also highlights the role of public policies affecting demand for these technologies. An important reason for the success of the US and UK government R&D support programmes discussed earlier was the strong demand by potential users for the technologies that these programmes helped develop. In at least some of these programmes, public policies directly or indirectly supported the demand for the new technologies.

Successful development and adoption of climate-friendly energy technologies almost certainly will require public policies to catalyse and support demand. Government will be an important user of some of the new energy technologies, and public procurement policies can be used to promote certain technologies or applications, an issue that we discuss at more length below. Specific regulatory requirements (e.g. emission or performance targets) or targeted financial incentives (tax credits), may spur the adoption of specific technologies. But rapid adoption of the broad portfolio of new alternative energy technologies by a wider spectrum of users will require that private costs and benefits reflect far more accurately than they do now the full social costs of current energy technologies and the benefits of alternatives. Public programmes to support the development of better energy technologies are therefore not substitutes for policies, such as a 'cap and trade' programme or a carbon emissions tax, that alter prices to reflect more adequately the environmental costs. Supportive price and regulatory policies can significantly enhance the effectiveness of government R&D programmes in this area.

As in the UK and US government R&D programmes discussed above, public R&D investments in the development of new energy technologies must be complemented by private investments in energy R&D; indeed, if the initiative is to be successful, private investments in energy R&D are likely to exceed public investments. This reality means that an important challenge for the design of government R&D programmes in energy technologies is the development of criteria and processes for identifying where and how public investments can catalyse, complement, and usefully augment private sector investment in energy technology R&D.

One guideline for public support for R&D in industry and elsewhere is that such funding is appropriate for projects in which the value to society of the expected returns to R&D is high but private firms' willingness to invest at that stage is low. An important class of such work focuses on the creation of new knowledge and techniques that are some distance from commercial application but that are nevertheless important to future problem solving and design. Such projects include many types of basic research, where the nature and range of potential applications is uncertain and the ability of private investors to capture the returns is likely to be limited even if the research is successful.

This type of R&D also includes research focused on overcoming specific roadblocks to the development of new or improved technologies, where the success of particular efforts is highly uncertain. Work of this type also may involve the design, development, and testing of prototypes of new technologies, particularly when the results of such prototype tests are placed in the public domain. Much of the government R&D in agriculture, IT and the biomedical fields that we described earlier included such projects, which focused on solving practical problems where the social returns to such solutions were high and the private returns were low.

The social returns to R&D that yields results of wide applicability are likely to be greater when those results are broadly available than when they are restricted. For this reason, it is important that governments structure their R&D programmes to support and encourage broad dissemination of the scientific and technological knowledge produced by their R&D investments in the relevant fields. We believe that patenting should be reserved for results that are close to practical application and that patenting of research results whose use is primarily as an input to further research should be minimised. Moreover, licences to these patents generally should be available to all parties, conditional on paying reasonable royalties.

Our earlier discussion of US government R&D programmes noted that the US Defense Department and antitrust policies supported the development of a relatively 'open' industry-wide knowledge base in the early semiconductor industry, accelerating firm entry and innovation. In a similar vein, funding of the Human Genome programme by NIH, MRC, the Wellcome Trust and others helped keep an important new knowledge base open and available to a wide range of firms who sought to make use of it. By supporting work to create lines of seeds that bred constant and true, and making these seed lines broadly available to seed companies, the US Department of Agriculture supported entry into the nascent hybrid seed industry. In all of these areas, the support provided by public R&D programmes for the broad dissemination of fundamental knowledge neither discouraged industry R&D investment nor does it appear to have discouraged privately funded innovation.

The government R&D support programmes that we have discussed earlier differed in the extent to which they supported R&D in industry. As was the case with US IT, a significant portion of government R&D funding for the development of climate-friendly energy technologies is likely to support R&D performed by industrial firms. Industry will play an especially important role as a performer of publicly funded R&D in prototype development and testing. It is important that public funds do not enable industrial performers of such R&D to establish monopoly positions in important technological fields. More generally, it is essential to maintain a 'pro-dissemination' posture towards this type of R&D. Where public funds support R&D performed by industry, wide dissemination of and access to results generated by others should be supported by policy.

Any successful programme of energy R&D that seeks to combat climate change will need to enlist many different organisations, private as well as public, as R&D investors and performers; it also is likely that the mix of R&D funders and performers will change over time. As a technology advances, a transition from research to development and commercialisation will occur, and this transition will be reflected in a shift from public to private funding. The timing of these transitions will be specific to individual technologies and very uncertain, making it difficult if not impossible to plan or predict the structure of the overall R&D effort in any detail, which can be frustrating to those responsible for monitoring the overall effort. Yet this complexity is a strength rather than a weakness. Not only are many different technological advances needed to combat climate change; in many areas the most promising paths towards those advances are highly uncertain, and different experts will make different judgments on this. Given the uncertainties, it is important that public R&D programmes encourage diversity and competition in R&D, as well as in the industries that will be developing and using the new technologies.

A number of US government agencies recently have instituted prize competitions to reward the achievement of technological objectives (see National Research Council, 2007, for a summary).[18] Prizes also have been recommended as a complement to other instruments of government policy, including public R&D funding, in supporting the development of climate-friendly energy technologies (see Newell and Wilson, 2005; Newell, 2008). Advocates argue that prizes provide an instrument that rewards the achievement of an objective, rather than subsidising the costs of R&D through grants or tax credits.

Although prizes may indeed serve a useful role, their utility should not be exaggerated, especially in this field. There are significant limitations to the use of prizes in the field of alternative energy technologies. These reflect both the wide range of technological advances that can contribute to progress in this area and the uncertainties involved in both technologies and applications. In order for a prize competition to be effective, and judged as fair, precise output or performance targets must be specified, and the ability of entries in any competition to meet these targets must be readily verifiable. Targets of this sort may be feasible for some fields of climate-friendly technologies. But the sheer diversity of technologies and (equally important) applications means that *ex ante* specification of such targets on a broad front will be difficult if not impossible.

In addition, the achievement of a technical goal in the field of alternative-energy technologies is only the beginning of a long process of learning, incremental improvement, and monitoring of the performance of these technologies in a wide array of complex operating environments. Prizes are best-suited to the ‘technological breakthrough’ characterisation of innovation that we previously argued is likely to be of limited relevance to climate-change R&D. As a result, if prize competitions are to be used at all in this area, they should be used selectively and their effectiveness should not be exaggerated.

On the other hand, the case study of government R&D policy in the US IT sector illustrates the power of other ‘output-oriented’ incentive mechanisms to spark innovation. Federal procurement contracts for semiconductors and other electronics-based innovations effectively served the same function as a ‘prize’, inducing considerable innovative effort by firms such as Texas Instruments and others. Moreover, the management by the Defense Department of these procurement programmes supported competition by mandating that the ‘winner’ of a procurement competition share technology with other firms to establish a second source of innovative components.

Rather than emphasising prizes for the first to achieve a specific technological goal, governments might be better advised to use procurement competitions to encourage the development of climate-friendly energy technologies that could be implemented in public applications. Moreover, the ‘winning entries’ in these competitions could be operated on an experimental basis for a sustained period of time by government or other research performers with a view to learning more about their operating characteristics, safety, and opportunities for improvement. Indeed, there may be considerable benefit from combining procurement competitions and demonstration projects, a policy tool that we discuss below.

It is important that public R&D programmes maintain good communications with users of the technologies that the programmes seek to help develop or improve. This principle nevertheless should not be carried too far – the example of agricultural research in the United States illustrates the possibility of ‘capture’ of public R&D programmes by powerful user groups. Indeed, at least some previous energy US R&D programmes in the areas of automobiles (USCAR) and coal (‘clean coal’) have experienced similar problems. When established firms or user groups are able to exert a dominant influence over the agenda of public R&D programmes (which is particularly likely in public-private consortia enlisting established firms within an industry), these programmes are likely to focus on near-term improvements in existing technologies. Our discussion above of the research areas in which publicly funded R&D is likely to be most productive suggests that public funding for marginal improvements of existing technologies is misdirected. Instead, public support should focus on advancing the technological frontiers.

There are strong complementarities among the various processes involved in the development, deployment, and continuing improvement of energy-related technologies that address global warming. Research and development obviously are central activities in innovation and the improvement of established technologies. Learning in use, however, is another important source of advance in these technologies, and as we noted earlier, this form of learning will be especially important for decades to come in technology-based programmes to combat global warming. Complex new technological systems of the sort likely to be developed for these purposes typically undergo prolonged processes of incremental improvement that over time produce dramatic advances in overall performance, reliability, and cost-effectiveness. The knowledge resulting from this ‘learning in use’ needs to be disseminated among prospective users and should feed back into the R&D processes that promote additional modifications and improvements in these technologies.

Although we argued earlier that public R&D support should focus on significant new technological opportunities, another important public sector role is selective support of demonstration projects. Demonstration projects provide a bridge between R&D and use of a technology in the environment of actual practice. They can provide information to potential users or developers about a given technology’s performance in actual practice, and may highlight the features of a given technology that are most in need of improvement for commercial success. As such, demonstration projects can provide important information for future R&D investment.

There are a number of examples of demonstration projects in the government R&D programmes discussed earlier in this paper. An important component of the agricultural research programmes in the US and the UK is field trials of new methods, which provided valuable information to farmers and guidance to technology developers regarding further research. Government biomedical R&D programmes in both the US and the UK have supported clinical trials of new medical practices. And much of the prototype development associated with the military procurement programmes that contributed to technological development of the IT industry in the US similarly served to demonstrate the feasibility of new design concepts and applications. We believe that effective public programmes to support the development of alternative energy technologies should also include mechanisms for the support and encouragement of early trial use of new technologies so that their promise can be evaluated and the necessary improvements identified.

An important issue of programme design concerns the balance between decentralisation and centralisation in programme structure and governance. A considerable amount of decentralisation is desirable or even essential in an energy R&D programme that spans such a diverse array of technologies, industries, countries, users, and applications, and which involves such a wide range of activities. Nonetheless, a centralised administrative structure for setting broad priorities, monitoring overall progress, and evaluating performance is a necessary complement to a decentralised programme structure. In the United States, the United Kingdom, and other nations, support for the development of new energy technologies almost certainly will involve multiple agencies, regardless of whether or not a clear 'lead agency' is designated with overall responsibility. The needed coordination mechanisms will therefore have to operate effectively between as well as within agencies.

Whatever the particular organisation of the programme, it is very important that its broad orientation and funding be relatively stable and credible. As we pointed out earlier, a crucial weakness of US energy R&D policy historically has been the instability of programme goals and funding, and the same can be said about UK efforts in this field. The effects of such instability are detrimental not only to the public programmes involved. In a field such as energy, large-scale private investments in R&D and technology deployment are essential, yet are discouraged by perceptions that funding and other policy commitments are fleeting rather than sustained and credible. Stability and credibility are therefore important goals for the design of energy R&D programmes, as well as for the demand-side policies that create incentives (and disincentives) for private-sector investors in R&D and technology deployment.

Finally, an element of programme design on which the historical discussion of previous public R&D programmes provides limited guidance is the need for any national energy R&D programme seeking solutions to global warming to accommodate the global scope of the problem and the necessary responses to it. Combating global warming, as we noted earlier, requires that technological solutions be deployed on a global scale as soon as possible. Moreover, the global nature of technological solutions means that the institutional, economic, and/or industrial settings within which these solutions are deployed will be enormously diverse, requiring a great deal of 'localised' adaptation of these solutions to the regional context. Although US investments in technological solutions to global warming ultimately are likely to exceed the scale of investments by other governments, it is critically important to work out an appropriate division of labour among national governments and to create effective mechanisms for cooperation and coordination. Much more than 'technology transfer' will be required, although support for the global dissemination of information and, potentially, subsidies for other nations to stimulate the adoption of technological solutions may be important parts of the international scope of such a programme.

The track record of multilateral collaboration in R&D programmes is mixed. Successful multilateral efforts in some key fields of agricultural technology (e.g., the development of new rice strains) and medicine (e.g. penicillin) contrast sharply with the less happy record of cross-national collaboration in projects such as the International Space Station or the Superconducting Supercollider. At this point it may suffice simply to underscore the importance of international cooperation, as well as the multidimensional nature of such cooperation, as additional important design requirements for energy R&D programmes in this area.

The scope and scale of the global climate change challenge for government innovation policies are unprecedented in peacetime. We have argued in this essay that the popular analogies of the Manhattan and Apollo projects are at best inaccurate and at worst misleading models for the design of public R&D programmes in this area. Nevertheless, government R&D programmes in both the United States and the United Kingdom have effectively supported innovation on a broad front, and in many cases these programmes also have aided the adoption of new technologies. A number of central design principles from these programmes are relevant to the more ambitious and international R&D programmes that public and private investment will have to support in dealing with the challenges of global climate change. A final challenge for these programmes is to develop a sustained and credible policy structure, while at the same time retaining flexibility and the ability to both monitor and learn from mistakes and successes by adapting programme structures and policies.
These challenges are formidable, but the consequences of failure or inaction are even more forbidding.

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Endnotes

1. A more critical view of the appropriateness of this model can be found in Yang and Oppenheimer (2007).
2. See in particular the accompanying press release, in which Jacobson set forward "an 'Apollo Program' for generating electricity from wind and producing hydrogen using wind-generated electricity." See http://www.eurekalert.org/pub_releases/2005-06/su-pf062305.php [Accessed 4 June 2009].
3. Congressman Randy Forbes of Virginia introduced H.R. 6260, which he described as a 'New Manhattan Project for Energy Independence', on June 18, 2008, a year after Congressman Jay Inslee of Washington State had introduced the 'New Apollo Energy Act' in July 2007 (H.R. 2809).
4. For example, New York Times columnist, Thomas Friedman, has written in support of an energy-related 'Manhattan Project' (e.g. Bush's Waterlogged Halo. 'The New York Times.' 21 September 2005), while advocates of an 'Apollo Program for energy independence' have formed the 'Apollo Alliance'. See http://apolloalliance.org/
5. See A Warning from the Garden. 'The New York Times.' 19 January 2007; and The Power of Green. 'The New York Times.' 15 April 2007.
6. The Manhattan project has been invoked as a possible R&D model in other cases, such as the search for an HIV vaccine. However, as Wilson *et al.* (2007, p.3) argue, such a "mission mode is appropriate only when the way forward is relatively clear and when the necessary development work is intrinsically large in scale. In contrast, when the best path to success is not clear, centralized decision-making can suppress innovation and the development of new strategies. There is therefore a trade-off between the efficiency of mission mode and the greater innovative potential of a more dispersed, less structured organization of R&D".
7. See the references to T.L. Friedman cited in note 4 above; also Barbier (2009); and DiPeso (2009). Proponents of this idea have formed 'The Green New Deal Group' with a website at http://www.greennewdealgroup.org/
8. In order to simplify the terminology below, we use the terms 'energy', or 'alternative energy' or 'energy related' to denote the technologies that are the targets of such policies.
9. The shift within the US agricultural R&D system to a competitive allocation system has been slow. As of 1990, according to Huffman and Evenson (1993), competitive state experiment station grants administered by the USDA accounted for less than 10 per cent of USDA funding of these experiment stations. This modest role for peer review within the US agricultural system is one aspect in which the system differs from the R&D funding systems operated by the National Institutes of Health or the National Science Foundation.
10. National Science Foundation/Division of Science Resources Statistics (2006) 'Survey of Research and Development Expenditures at Universities and Colleges, FY 2006.' Available at: http://www.nsf.gov/statistics/nsf08300/pdf/nsf08300.pdf
11. The US Pharmaceutical Manufacturers Association estimated that foreign and US pharmaceuticals firms invested more than $26 billion in R&D in the United States in 2002, substantially above the $16 billion R&D investment by the National Institutes of Health in the same year (see Pharmaceutical Manufacturers Association, 2003, for both estimates).
12. A 1991 review of the artificial heart programme of the National Heart, Lung and Blood Institute (NHLBI) by the Institute of Medicine observed that:

    > "As with other components of the National Institutes of Health (NIH), the principal mechanism for achieving NHLBI's overall mission is the funding of extramural research through investigator-initiated, non-targeted ("R01") grants. Most of the institutes that make up the NIH do not fund later developmental stages of medical technologies, focusing instead on fundamental or basic research.
    >
    > The NHLBI artificial heart program is, however, a notable exception to this generalization. Historically, the funding mechanism for R&D with MCSSs [mechanical circulatory support systems] has been targeted contracts, issued following requests for proposals. From the first appropriation of funds in 1964, one of the program's major goals has been to produce, through focused development, devices for long-term clinical use…" (IOM, 1991, pp. 22-23).

    Rettig (1977) highlights the debate in the drafting of the legislation that authorised the 'War on Cancer' over the proposal to assign responsibility for the 'War' to a National Cancer Authority, independent of the NIH and reporting directly to the

White House. Rettig's account also discusses the debate within Congress and the US biomedical research community over the expanded use of contracts in the 'War on Cancer'.

13. This surge in federal funding was followed by a decline in NIH funding of more than 10 per cent during 2004-2008. Just as instability in US energy R&D funding has been counterproductive at best, Freeman and van Reenen (2008) point out that the 'boom and bust' cycle of NIH funding has produced significant problems in US biomedical researcher labour markets, as students attracted to the research and funding opportunities during the funding boom complete their PhD degree and enter a labour market in which funding and job openings have declined.

14. This history draws heavily on Balmer (1993) and Shergold & Grant (2008).

15. These two UK government agencies together, however, accounted for less than 10 per cent of the NIH budget during 2006-07, which reached nearly US$30 billion.

16. According to the Association of the British Pharmaceutical Industry – see http://www.abpi.org.uk/statistics/section.asp?sect=3#13 [Accessed 4 June 2009].

17. Paradoxically, the decision not to patent penicillin meant that British companies subsequently had to pay royalties to Merck (an American company) for their use of Merck's patented deep fermentation process for the production of penicillin (Quirke, 2005).

18. Examples include ARPA's competition in robot-controlled land vehicles and NASA's prize competition in aerospace technologies.

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