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Innovation and Climate Change

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INTRODUCTION

To a large extent, the study of innovation and technological change has been motivated by a desire to understand and shape the forces that underlie economic development and competitiveness in a market economy. Thus, there is a large literature, contributed mainly by social scientists, examining the many facets of innovation and the factors that contribute to it—ranging from the behavior of individuals and organizations, to the role and effectiveness of government policies aimed at spurring innovation in particular sectors of the economy or targeted areas of technology such as computers, aircraft, or agriculture.

The role of technological innovation in addressing societal problems such as air pollution and water pollution is a more recent development. Unlike innovations in industries such as pharmaceuticals or electronics—where the result is new products that consumers desire (such as more effective or lower-cost medicines, cell phones and internet services)—there is little or no "natural" market for most environmental technologies whose function is to reduce or eliminate a pollutant discharge to the environment. Would you voluntarily pay an extra $1,000 to install air pollution emission controls on your automobile if it were up to each consumer to decide? Most individuals would not, recognizing that their action alone would do little to solve the air pollution problem unless all drivers were required to take the same action.

In cases such as this, the role of government policies and regulations becomes critical, since most environmental problems require collective action to effectively address the problems. Similarly, the nature and extent of innovations that lower the cost and/or improve the efficiency of environmental controls depends heavily on the actions of government agencies at all levels.

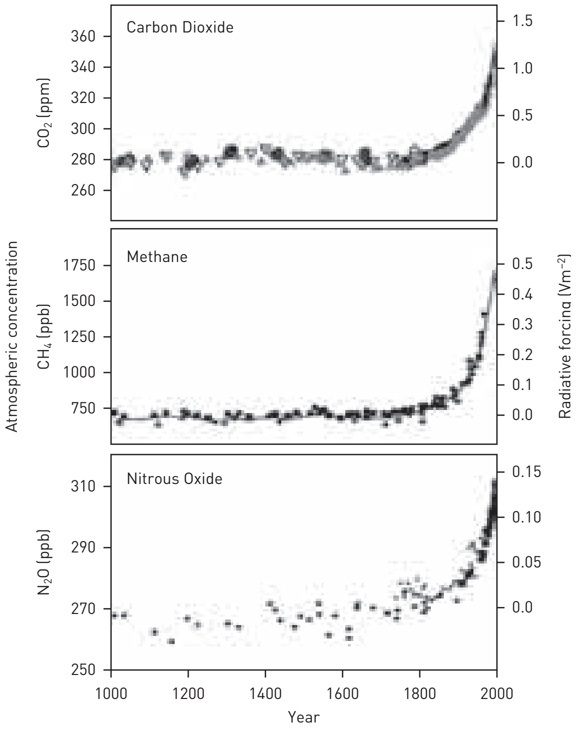
In this paper we focus on the links between technological innovation and global climate change—which is arguably the most far-reaching and formidable environmental challenge facing the world today. First we present a brief overview of the climate change problem and the innovation needs that motivate this paper. Then we examine in greater detail some of the options available to accelerate the innovations needed to address the climate change challenge. While many of the examples cited in this paper are drawn from experience and studies for the United States, the general concepts and approaches that are discussed are widely applicable to all nations faced with the challenges of climate change mitigation.

THE CLIMATE CHANGE PROBLEM

Over the past 150 years, there have been significant increases in the concentration of "greenhouse gases" (GHGs) in the atmosphere, notably carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (see figure 1), as well as a group of industrial GHGs including hydrofluorcarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Greenhouse gases drive climate change by trapping heat in the atmosphere, which tends to raise the average temperature of the planet. This, in turn, alters the patterns and intensity of precipitation as well as the flows of air and ocean currents around the globe—all of which directly or indirectly influence the climate (defined as the average weather in a region over a period of several decades.)

The main sources of increased GHGs in the atmosphere are the GHG emissions from a variety of human activities (table 1).

Figure 1. Historical trend in the atmospheric concentration of major GHGs



Source: IPCC, 2007a

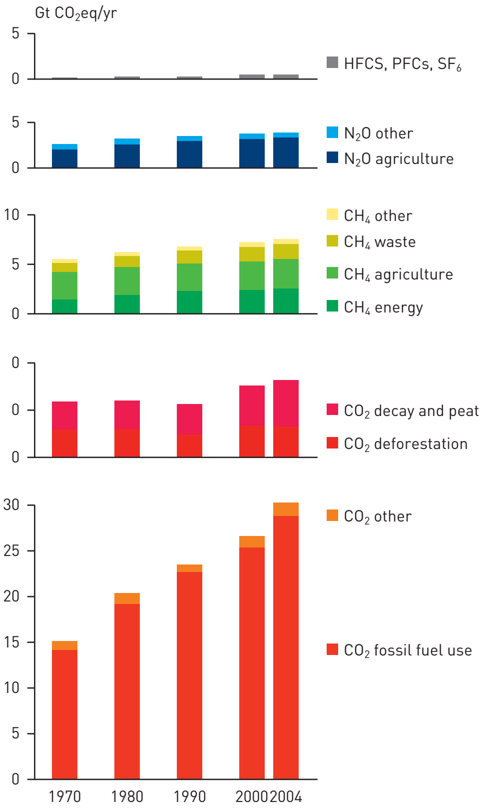
Figure 2 shows the recent growth in global GHG emissions, expressed in terms of "CO_2 equivalent" tonnages, which accounts for differences in the heat-trapping ability of different gases relative to carbon dioxide (see IPCC, 2007 for details). The largest contributor is CO_2 from the combustion of fossil fuels (petroleum, coal, and natural gas,

Table 1. The major greenhouse gases and common sources of emissions

Símbolo	Nombre	Fuentes comunes
CO_2	Carbon Dioxide	Fossil fuel combustion, forest clearing, cement production, etc.
CH_4	Methane	Landfills, production and distribution of natural gas & petroleum, fermetation from the digestive system of livestock, rice cultivation, fossil fuel combustion, etc.
N_2O	Nitrous Oxide	Fossil fuel combustion, fertilizers, nylon production, manure, etc.
HFC's	Hydrofluorocarbons	Refrigeration gases, aluminium smelting, semiconductor manufacturing, etc.
PFC's	Perfluorocarbons	Aluminium production, semiconductor industry, etc.
SF_6	Sulfur Hexafluoride	Electrical transmissions and distribution systems, circuit breakers, magnesium production, etc.

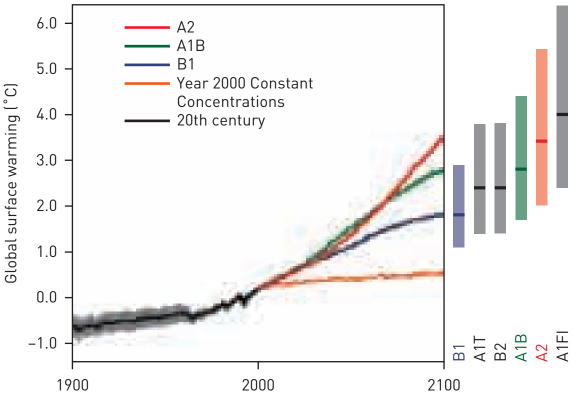
Source: IPCC, 2007b

Figure 2. Recent growth in global emissions of greenhouse gases



Source: IPCC, 2007b

Figure 3. Historical trend and future scenarios of global warming from 1900 to 2100. Ranges shown at the right are for six scenarios (labeled B1 through A1F1) modeled by the IPCC



Source: IPCC, 2007b

composed mainly of carbon and hydrogen). Because our use of energy also releases some non-CO_2 GHGs (primarily CH_4 and N_2O), energy use accounts for roughly 85 percent of all GHG emissions.

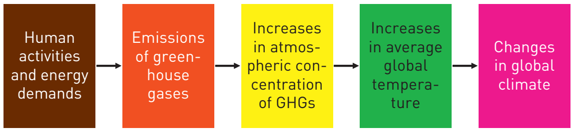
The essence of the climate change problem is that if current trends continue, future global emissions of greenhouse gases will grow significantly in coming decades in response to growth in world population, economic development, and other factors that increase GHG emissions. As a result, the average global temperature is projected to increase by 1.1°C to 6.4°C by the end of this century (IPCC, 2007). While there is considerable uncertainty in such projections (as evidenced by figure 3), the potential impacts of global warming could seriously endanger human health, water supplies, agriculture, and human settlements—especially in coastal areas vulnerable to sea level rise and storms (IPCC, 2007b; NRC, 2010b).

In light of these large uncertainties, why not simply wait until there is stronger empirical evidence about the magnitude and impacts of climate change? A fundamental difference between greenhouse gases and "conventional" air pollutants like sulfur dioxide (SO_2) and particulate matter is that GHGs, once emitted, remain in the atmosphere for very long periods of time—typically decades to millennia. For example, roughly half the CO_2 emitted today will still be in the atmosphere a century from now, still contributing to global warming. Centuries later some of today's CO_2 emissions will still be in the air! In contrast, conventional pollutants like SO_2 stay in the atmosphere for relatively short periods of time—typically days or weeks—before they are removed or washed out by various physical and chemical processes. Thus, if we quickly reduced emissions of conventional pollutants their atmospheric concentrations (and associated impacts) also would fall quickly. Not so for GHGs. Because of their long lifetimes, atmospheric concentrations would continue to rise unless emissions were curtailed dramatically. (Think of a bathtub being filled from a large faucet, with only a slow trickle draining from the bottom; the water level would continue to rise unless the faucet were turned down nearly all the way to match the slow drainage.) Thus, if climate change impacts prove to be as serious as projected, reducing GHG emissions in the future would do little to quickly reduce atmospheric concentrations to mitigate those harmful impacts.

WHAT ACTIONS ARE NEEDED?

International policy goals for global climate change were established in 1992 under the United Nations Framework Convention on Climate Change (UNFCCC). To date, 192 nations have adopted the UNFCCC goal of "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Scientific research has sought to better understand and quantify the links between human activities, GHG emissions, the resulting increases in atmospheric concentration, the consequent changes in global temperature, and the impacts of those changes (figure 4). The largest uncertainties are in the links between global temperature increases and resulting impacts. However, based on current science many policymakers worldwide advocate no more than a 2°C rise in long-term global temperature as the climate policy goal needed to prevent dangerous impacts. Achieving that goal would require actions to stabilize atmospheric GHG concentrations at levels only slightly greater than current levels. That, in turn, would require a reduction in annual global GHG emissions of 50% to 80% below 1990 levels by 2050, according to recent studies (IPCC, 2007b).

Table 2. Key linkages between human activities and global climate change



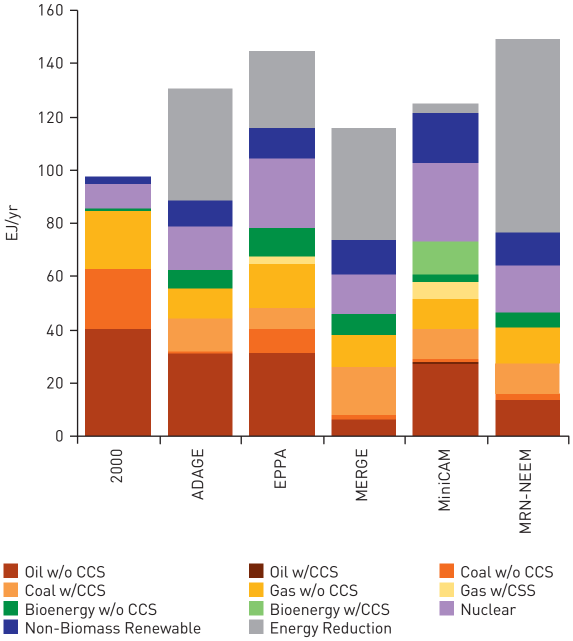
The technological implications and challenges of meeting such a goal are formidable. This is illustrated in figure 5, which shows the results of recent modeling studies for the United States. These results show there is no unique solution or pathway to achieving large reductions in GHG emissions—different models give different solutions based on different assumptions about the future availability and cost of alternative technologies and other factors. What all models show emphatically, however, is that dramatic changes in the energy system will be required, since this is the dominant contributor to climate change.

Today about 85% of the world's energy is provided by fossil fuels. Approximately half of that is in the form of oil (used mainly for transportation), followed by roughly equal amounts of coal (used primarily for electricity generation) and natural gas (used for a variety of domestic and industrial heating applications, and increasingly for electric power generation). The CO_2 released from the combustion of those fuels—primarily from power plants and automobiles—is the key source of GHG emissions. Achieving a transition to a sustainable low-carbon (ideally zero-carbon) energy system is the major challenge we face to avoid potentially dangerous climate change.

THE NEED FOR TECHNOLOGICAL CHANGE

Technological change on a massive scale will be needed to achieve large reductions in global GHG emissions. The results in figure 5 illustrate the four general strategies available to transform the energy system of a country or region: 1. reduce the demands for energy in all major sectors of the economy (buildings, transportation, and industry), thus reducing the demand for fossil fuels; 2. improve the efficiency of energy utilization so that less fossil fuel is required to meet "end use" energy demands, resulting in lower CO_2 emissions; 3. replace high-carbon fossil fuels such as coal and oil with lower-carbon or zero-carbon alternatives such as natural gas, nuclear, and renewable energy sources such as biomass, wind and solar; and, 4. capture and sequester the CO_2 emitted by the combustion of fossil fuels to prevent its release to the atmosphere.

Figure 4. Results from five models showing the least-cost US energy mix in 2050 for a policy scenario requiring an 80% reduction in GHG emissions below 1990 levels. Actual energy use in 2000 is shown for reference. (Note: CCS = carbon capture and storage).



Source: adapted from Fawcett *et al.*, 2009

As illustrated for the scenario in figure 5 (an 80% reduction below 1990 emissions by 2050), all four approaches are needed to reduce emissions at lowest cost. Reductions in energy demand, which include the effects of improved efficiency, play the most prominent role in all but one of the five models shown. The uncontrolled combustion of coal is eliminated or sharply curtailed in all cases, and the direct use of oil and natural gas also is reduced relative to the year 2000 reference case. In contrast, the use of nuclear power, biomass, and non-biomass renewables (mainly wind) increases significantly in these studies. So too does the use of carbon capture and storage (CCS). This technology could make it possible to capture the CO_2 from power plants and other large industrial sources, and then sequester it in deep geologic formations or depleted oil and gas reservoirs. This option has gained substantial worldwide attention in recent years, with efforts now underway to develop and demonstrate the applicability of CCS for climate change mitigation.

The same types of energy system transformations that are illustrated in figure 5 for the United States emerge in other modeling studies at the global level (e.g., IPCC, 2007b; Clark *et al.*, 2009). While energy use is the dominant contributor to GHG emissions, technological change in other sectors will also be needed to deal effectively with climate change. For example, changes in land-use practices, especially deforestation, are needed to reduce or prevent the release of CO_2 from natural "sinks" such as forests

> “The development and adoption of new technology is an essential element of any comprehensive response to global climate change”

and soils. Technological change similarly can reduce or avoid emissions of non-CO_2 GHGs, such as PFCs in the semiconductor industry or nitrous oxide emissions from the agricultural sector. More broadly, at least some adaptation to climate change will almost certainly be necessary, and such adaptations also will require some degree of technological change (NRC, 2010c).

In short, the development and adoption of new technology is an essential element of any comprehensive response to global climate change. But technological change on the scale required cannot happen overnight. To achieve the substantial reduction in CO_2 emissions underlying figure 5, for example, the United States alone would have to retrofit or replace hundreds of electric power plants, tens of millions of vehicles, and hundreds of millions of consumer appliances, building systems (for heating, cooling and lighting), and industrial processes and equipment. Change on this scale will take many decades to achieve.

Many of the technologies needed do not yet exist commercially or are too costly (alternatives to gasoline-powered automobiles is a good example). Some alternatives, such as carbon capture and sequestration technologies for power plants, have yet to gain widespread social and political acceptance. Because the rates of development and adoption of new technologies respond to government policies as well as to market forces such as energy prices, we next look more closely at the processes of technological change and innovation and the factors that influence them.

THE PROCESS OF TECHNOLOGICAL CHANGE

As discussed elsewhere (e.g., NRC, 2010a), the general process of technological change can be characterized as involving a number of steps or stages. Different terms are used in the literature to describe these stages, but four commonly used descriptors are:

Invention: Discovery: the creation of new knowledge or new prototypes;

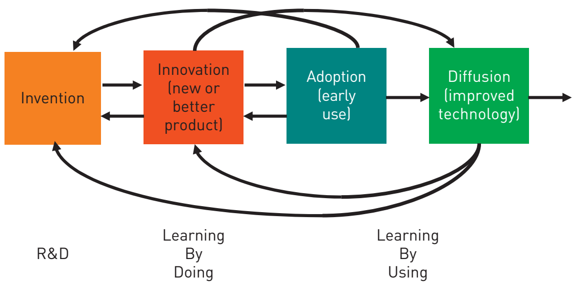
Innovation: Creation of a new or improved commercial product or process;

Adoption: Initial deployment and use of the new technology;

Diffusion: Increasingly widespread adoption and use of the technology.

The first stage—invention—is driven in large part (but not solely) by research and development (R&D), including both basic and applied research. The second stage—innovation—is a term often used colloquially to describe the overall process of technological change. As used here, however, it refers only to the creation of a product or process that is commercially offered; it does not mean the product will be adopted or become widely used. That happens only if the product succeeds in the final two stages—adoption and diffusion, which reflect the commercial success of a technological innovation. Those two stages are the ones that inevitably are most critical to reducing GHG emissions via technological change.

Table 3. Stages of technological change and their interactions



Source: Rubin, 2005

Studies also show that rather than being a simple linear process in which one stage follows another, the four stages of technological change are highly interactive, as depicted in figure 6. Thus, innovation is stimulated not only by R&D, but also by the experience of early adopters, plus added knowledge gained as a technology diffuses more widely into the marketplace. Thus, "learning by doing" (economies in the manufacture of a product) and "learning by using" (economies in the operation of a product) are often (though not always) critical elements that enable the adoption and diffusion of new technologies. Along with sustained R&D (sometimes called "learning by searching"), these stages often help to improve the performance and/or reduce the cost of a new technology—trends that are commonly characterized and modeled as a "learning curve" or "experience curve" (IEA, 2000; McDonald and Schrattenholzer, 2002).

Each stage of the process also requires different types of incentives to promote the overall goal of technological change. An incentive that works well at one stage of the process may be ineffective—or even counterproductive—at another. Large-scale change also must be viewed and considered from a "systems" perspective since the success of any new technology is often dependent upon other technological and non-technological factors. For example, the diffusion of energy-saving technologies that can automatically adjust home appliances like air conditioners and water heaters may depend on the development and dissemination of "smart grid" technology in electrical networks. Similarly, the dissemination of energy-efficient appliances may be inhibited by institutional arrangements, such as landlord-tenant relationships where neither party has an incentive to purchase a more expensive but more energy-efficient appliance. Thus, in addition to technical considerations, the widespread adoption and dissemination of a new technology may require measures to address social and institutional barriers that affect the nature and pace of technological change.

THE IMPORTANCE OF TECHNOLOGICAL INNOVATION

Any successful strategy to reduce GHG emissions significantly will require actions not only to deploy the low-emission technologies that are available today, but also to foster innovation on new technologies that are needed. Accordingly, there has been growing interest in recent years on ways to foster such innovation, in particular, the role that governments can and should play in that process.

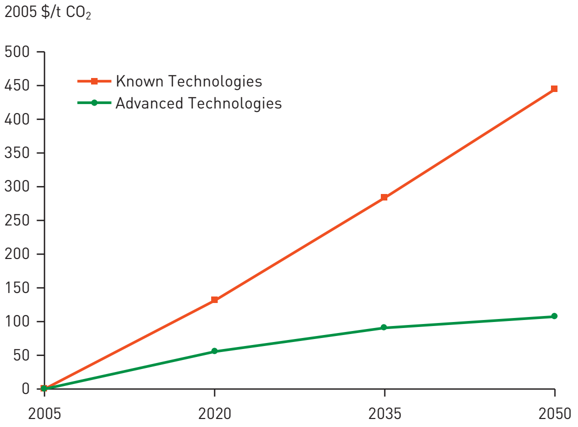
Although research and development is a major element of the innovation process, there is growing recognition that technological innovation is a complex process that commonly involves interactions with other stages of technological change, as depicted in figure 6. Thus, gains from new technologies often are realized only with widespread adoption—a process that usually takes considerable time (often decades) and typically involves a sequence of incremental improvements that enhance performance and reduce costs (Alic *et al.*, 2003).

In the context of this paper, a key question is: what strategies and policies can most effectively foster technological innovations that help reduce GHG emissions? As discussed earlier, GHG emissions depend mainly on the types of energy sources and technologies used to provide the goods and services that society seeks. Thus, technological innovations can help reduce GHG emissions in a variety of ways (NRC, 2010). For example:

- New or improved technologies can enable devices such as vehicles, machinery and appliances to use energy more efficiently, thereby reducing their energy use and GHG emissions per unit of useful product or service (such as a vehicle-mile of travel or a lumen of lighting for illumination).
- New technologies can create or utilize alternative energy carriers and chemicals that emit less GHG per unit of useful product or service (such as renewable energy sources or new low-nitrogen fertilizers).
- New technologies can create alternative ways of providing goods and services that are less GHG-intensive (such as by using substitute products or materials that have lower GHG emissions, or by facilitating larger system-wide changes such as replacing automotive and air travel with teleconferencing and telecommuting).

Technological innovations can facilitate this full spectrum of possibilities. An even broader set of innovations would include social and institutional systems and designs. For example, innovations in urban planning and development could help reduce future energy demands (and associated GHG emissions) for transportation as well as in residential and commercial buildings. Institutional innovations could provide incentives for electric utility companies and others to invest in measures that reduce the demands for energy, as opposed to policies that favor increased energy sales.

Figure 5. Global carbon (CO_2-equiv) prices needed to reduce emissions from fossil fuel use and industrial sources with and without advanced technologies



Source: Kyle *et al.*, 2009.

Figure 7 shows one estimate of how technological innovations can reduce the future cost of reducing GHG emissions. In this modeling study, a "business as usual" case—which includes historical rates of technological improvements—is compared to a case with more rapid technological change. The cost of meeting a stringent emission-reduction scenario is reduced dramatically when "advanced technologies" are available. This reduction in the unit cost of abatement translates into large national and global cost savings, especially as emission-reduction requirements grow more stringent over time.

THE CRITICAL ROLE OF GOVERNMENT POLICY

A major challenge in reducing GHG emissions is that few if any markets exist for many of the more efficient and low-emission technologies that are needed. What electric utility company, for example, would want to spend a large amount of money on carbon capture and storage technology if there is no requirement or incentive to significantly reduce CO_2 emissions? How many individuals would willingly buy an advanced electric vehicle that costs much more than a conventional automobile simply to reduce their carbon footprint? Costly actions by firms or individuals to reduce their GHG emissions provide little or no tangible value to that firm or person. Only by government actions that either require or make it financially worthwhile to reduce GHG emissions are sizeable markets created for the products and services that enable such reductions. Government actions to create or enhance markets for GHG emission-reducing technologies are thus a critical element of the technological innovation process.

Different policy measures influence technological innovation in different ways. In general, policy options can be grouped into two categories: voluntary measures and mandatory requirements ("carrots" and "sticks"). The first group—often called "technology-policy" options—provides incentives of various types to encourage certain actions or technology developments. The second group consists of government actions that impose requirements or limitations on specified activities, facilities, or technologies, typically in the form of regulations and standards. Table 2 lists examples of policy options in each of these two general categories. The discussions below elaborate briefly on policies in each category to illustrate their role in stimulating innovations that reduce GHG emissions.

TECHNOLOGY-POLICY OPTIONS

Technology-policy measures can stimulate innovation and help create markets for GHG-friendly technologies by providing incentives and support for the development

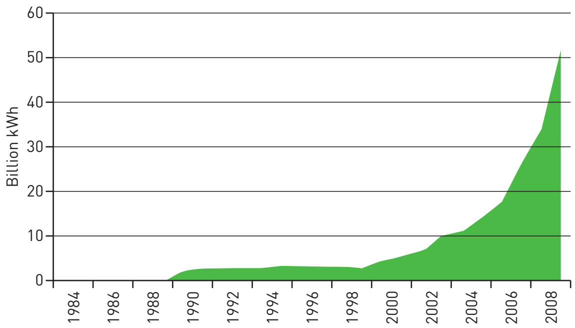
Table 4. Policy options that can foster technology innovations to reduce GHG emissions

"Technology Policy" Options			Regulatory Policy Options
Direct Government Funding of Knowledge Generation	Direct or Indirect Support for Commercialization and Production	Knowledge Dissemination and Learning	Economy-wide Measures and Sector or Technology-specific Regulations and Standards
• R&D contracts with private firms (fully funded or cost shared) • R&D contracts and grants with universities and non-profits • Intramural R&D in government laboratories • R&D contracts with consortia or collaborations	• R&D tax credits • Patents • Production subsidies or tax credits for firms bringing new technologies to market • Tax credits, rebates or payments for purchasers/users of new technologies • Gov. procurement of new or advanced technologies • Demonstration projects • Loan guarantees • Monetary prizes	• Education and training • Codification and dissemination of technical knowledge (e.g., via interpretation and validation of R&D results; screening; support for databases) • Technical standards • Technology/Industry extension programs • Publicity, persuasion and consumer information	• Emissions tax • Cap-and-trade program • Performance standards (for emission rates, efficiency or other measures of performance) • Fuels tax • Portfolio standards

Source: NRC, 2010a

> “Studies have documented the ability of energy and environmental regulatory policies to influence the development and deployment of major energy-related technologies, and also to stimulate innovations that reduce GHG emissions and other air pollutants”

Figure 6. Growth in electricity generation from wind in the United States



Source: EIA, 2010

and deployment of new technology. Table 2 lists a number of available measures, grouped into three categories. The first is direct government support for R&D to generate new knowledge (including new concepts and technologies). This is the most common form of government support for innovation, and typically involves a variety of public and private organizations (Alic *et al.*, 2003; CATF, 2009).

The second column lists additional policy options that directly or indirectly support the development, deployment and commercialization of new technologies. Such measures have had a major impact on technology development in the past. For example, US government procurement of jet aircraft and computers during their early stages of commercialization following World War II was critical to their subsequent development and widespread deployment in the marketplace (Alic *et al.*, 2003). More recently, government support in the form of investment tax credits and production tax credits (or feed-in tariffs) have fueled the rapid growth in wind-power systems, as illustrated in figure 8. Additional measures such as loan guarantees and support for demonstration projects are currently being used to stimulate investments in “clean coal” technologies such as coal gasification and carbon capture and storage systems.

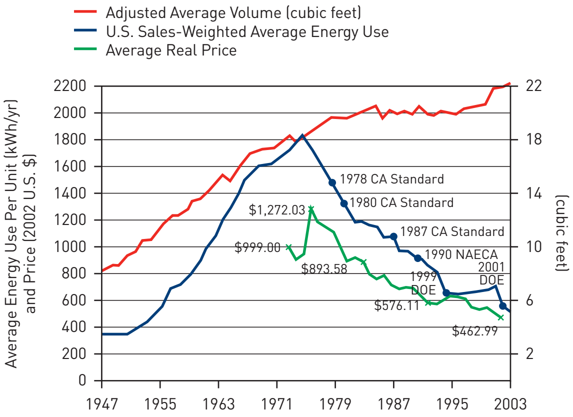
The third group of technology policy options in table 2 reflects measures to stimulate learning and the diffusion of knowledge. These include support for education and training programs, as well as measures such as the development of codes and standards that facilitate the diffusion of new technologies.

REGULATORY POLICY OPTIONS

Energy and environmental regulatory policies respond to “market failures” in which individuals and organizations have little or no economic incentive to curtail activities that adversely affect society as a whole (such as emitting pollutants to the environment), and lack of government intervention. Studies have documented the ability of energy and environmental regulatory policies to influence the development and deployment of major energy-related technologies, and also to stimulate innovations that reduce GHG emissions and other air pollutants. Highly-cited examples include fuel economy and pollutant emission standards for automobiles (Lee *et al.*, 2010), energy efficiency standards for major appliances such as refrigerators (Rosenfeld, 2008), new source performance standards for power-plant air pollutants (Rubin *et al.*, 2004), and market incentives such as the cap-and-trade rules for power plant SO_2 emissions (Popp, 2003).

In 1975, for example, the US government imposed Corporate Average Fuel Economy (CAFE) standards on all new cars sold in the United States in order to reduce US oil consumption in the wake of the 1973 Arab oil embargo. The standards called for roughly a doubling of the average 1973 fuel economy of approximately 13 miles per gallon (mpg) to the CAFE standard of 27.5 mpg for new passenger cars. This provoked a series of technological innovations that affected nearly all aspects of automobile design. In little more than a decade, the US auto fleet became nearly twice as efficient as it had been (EIA, 2010). In 2007, in response to renewed concerns about oil imports, the US adopted more stringent CAFE standards. The new rules call for a fleet-wide average fuel economy (including both passenger cars and trucks) of 34.1 mpg by 2016 (NHTSA, 2010). These standards also will reduce emissions of greenhouse gases (CO_2) from fuel burning. Although the United States has long avoided energy pricing policies and fuel taxes to encourage energy efficiency, evidence from other countries, including many in Western Europe, indicates that a substantial boost in gasoline taxes would also be a powerful stimulus for innovation in automotive technologies.

Figure 7. Trends in average energy use, price and size of new US refrigerators

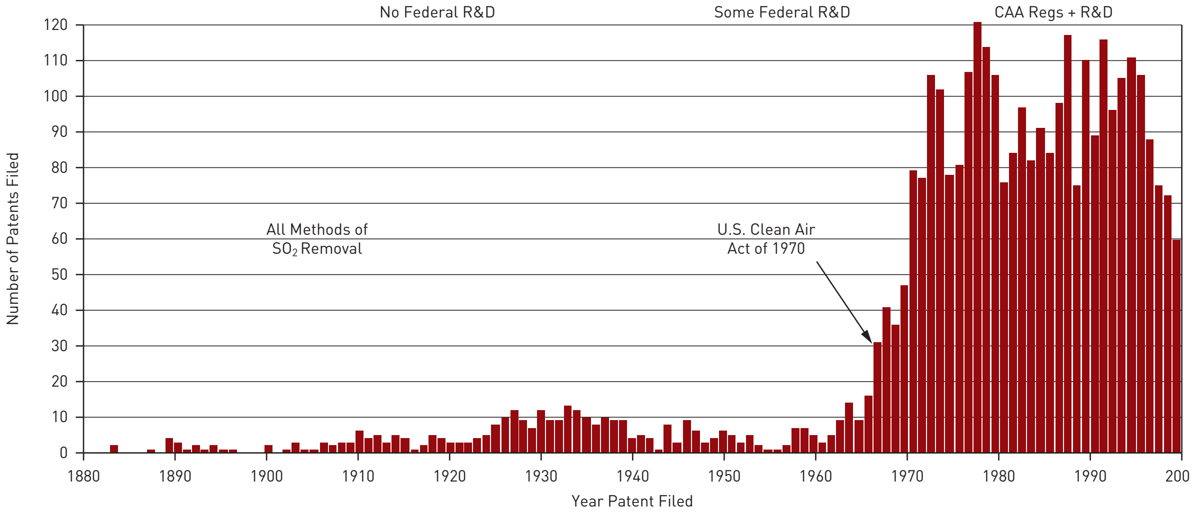


Source: Rosenfeld, 2008

Energy efficiency standards also have reduced the average energy use of major household appliances including refrigerators, dishwashers, and air conditioners. Figure 9, for example, shows the dramatic decrease in the average energy consumption of new refrigerators—then the most energy-intensive home appliance in the US—following the adoption of California state standards beginning in the 1970s, and subsequent national standards beginning in 1990. As a result of technological innovations, the average annual energy use of refrigerators was reduced to a third of its 1975 value. At the same time, the average retail price of a new refrigerator fell by a factor of two, even as the average size of new units increased. The overall savings in electricity demand avoided the need for many new power plants and their associated air pollutant and GHG emissions.

The case of sulfur dioxide (SO_2) emissions from electric power plants further illustrates the potential influence of performance standards on innovation for environmental control technologies. Stringent national limits on SO_2 emissions from new coal-fired plants

Figure 8. US patenting activity in sulfur dioxide removal technologies, 1880-2000



Source: Taylor, *et al.*, 2005

were adopted in the US starting in 1970. The result was a dramatic rise in "inventive activity" as measured by the number of US patents filed (from around the world) in the area of SO_2 control, as seen in figure 10. As post-combustion capture technology became required and more widely implemented, the capital costs of such systems fell by more than half over two decades, while operating costs also declined sharply (Taylor *et al.*, 2005, Rubin *et al.*, 2007). During this time the performance of such systems also improved considerably: in the 1970s SO_2 "scrubbers" typically captured 80% of the potential emissions. By 1990 the norm was about 90% SO_2 removal, climbing to 95% or more just five years later (Rubin, 2001). Today the best systems are up to 99% effective in capturing SO_2. If CO_2 capture and storage technologies are to become a cost-effective option for GHG reductions, similarly sustained cost and performance improvements will likely be needed (Rubin, 2009). This history of post-combustion SO_2 capture suggests that well-crafted regulatory policies can help accomplish that goal.

The regulatory policies illustrated above are examples of what are often referred to as "command-and-control" regulations that compel polluters or manufacturers to meet specified levels of technology performance at individual facilities. The more recent adoption of "market-based" regulations, such as the cap-and-trade systems adopted for compliance with acid rain legislation and summer ozone control (Yeh *et al.*, 2005), gives polluters greater flexibility in complying with national or regional requirements for an overall level of emissions reduction. Such flexibility can significantly lower the cost of compliance.

An economy-wide cap-and-trade program is a regulatory policy approach that has been widely advocated and proposed as the most cost-effective means of greenhouse gas mitigation (e.g., Jaffe *et al.*, 2003). This approach is also the centerpiece of the current Emissions Trading System (ETS) for carbon dioxide emissions in the European Union. Alternatively, many economists advocate a tax on GHG emissions as the preferred market-based approach for

> “Voluntary technology policy measures alone will not be sufficient to stabilize GHG (greenhouse gases) levels. Sufficiently stringent regulatory policies are also needed to limit GHG emissions and to foster technology innovation”

reducing GHG emissions (NRC, 2010a). Both approaches can stimulate innovation by establishing economic incentives and markets for emission-reduction measures. In the case of cap-and-trade, this requires a sufficiently stringent cap, while in the case of an emissions fee, a sufficiently stringent tax. Because there is less historical experience with such market-based regulations, there is limited empirical evidence of their effectiveness in stimulating technology innovations that reduce environmental emissions. However, in the case of SO_2 control, a study of patent data found that the US cap-and-trade program enacted in 1990 fostered innovations that lowered the cost of operating SO_2 capture units and improved their SO_2 removal efficiency (Popp, 2003). Studies also found that the SO_2 cap-and-trade program promoted changes in the internal procedures of regulated firms as well as innovations and investments by upstream suppliers (Burtraw *et al.*, 2005). Strong theoretical grounds also support a major role for market-based policies in an overall strategy for dealing with climate change.

CHOOSING POLICY OPTIONS

The merits and limitations of alternative policies for climate change mitigation is a topic widely discussed in the literature and debated in policy forums. Inevitably, the choice of policies adopted by any nation, either unilaterally or as part of an international accord, will depend on many factors and circumstances, discussion of which is beyond the scope of this paper. Rather, the preceding discussion was intended to illustrate some of the ways in which policy choices can affect technological innovation for GHG mitigation. Similarly, we note that other types of policies, such as patenting and anti-trust enforcement, can also have an indirect influence on innovation, as discussed by Alic *et al.* (2003).

In most cases, the preferred path for climate change mitigation and technology innovation will be a combination of policies that offer both “carrots” and “sticks”. The simple but important message of this section is that voluntary technology policy measures alone will not be sufficient to stabilize GHG levels. Sufficiently stringent regulatory policies are also needed to limit GHG emissions and to foster technology innovation.

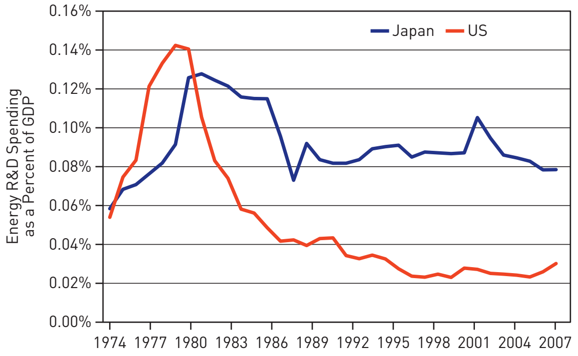
RESOURCE NEEDS FOR TECHNOLOGICAL INNOVATION

Achieving climate change goals will require not only a set of policy drivers, but also an infusion of financial and human resources to support each stage of the technological-change process depicted earlier in figure 6. Such resources are especially critical for the technology-innovation stage. In particular, there are significant needs for increased financial support for R&D and for people with the requisite training, skills and creativity to innovate—not only with regard to technologies for energy supply and demand, but also in other sectors that emit GHGs, including agriculture, forestry, and manufacturing.

The present outlook for a major infusion of such resources is decidedly mixed. In recent years, for example, China—which is now the largest emitter of GHGs in the world—has embarked on a major expansion of investment in "green" energy technologies that has propelled it to become the world's leading manufacturer of photovoltaic solar cells, as well as a dominant force in wind power systems. China is also investing heavily in nuclear power generation, and is developing a number of clean coal technologies, including carbon capture and storage systems.

In contrast, national government funding for energy R&D in the United States has declined sharply over the past three decades. In 2008, such funding was less than a fifth of what it was in 1980, in real terms. While federal energy R&D funding in the US has increased in the past few years—including a sharp rise in 2009 as part of an economic stimulus program—US expenditure for energy R&D remains much lower than for other key areas of science and technology such as space and health (NRC, 2010a). Compared to many other industrialized countries (including Canada, Denmark, Finland, France, Japan, Korea, Norway, and Sweden), the US also spends substantially less on energy R&D as a fraction of gross domestic product (GDP) (IEA, 2009). This is illustrated in figure 11, which compares government spending on energy R&D by the US and Japan as a percentage of GDP. For the past three decades, the US percentage has been considerably lower than that of Japan. While in absolute terms the US spending is higher than in other smaller nations, the normalized data suggest that energy R&D is a lower national priority in the United States than in many other industrialized countries.

Figure 9. Government spending on energy R&D in Japan and the United States, 1974–2008



Source: NRC, 2010a

Ultimately, the private sector must play the major role in technology innovation if the climate change problem is to be dealt with successfully. Reliable data on private-sector funding of energy-related R&D is less readily available. Estimates by the International Energy Agency (IEA) and others suggest that the current rate of R&D spending by the energy industry is far below that of industries such as pharmaceuticals, biotechnology, and software and computer services—industries whose profitability depends more strongly on the ability to create new or improved products. Within the energy sector, the electric-power industry tends to have the lowest rate of R&D spending as a percentage of sales (a widely-used indicator) (NRC, 2010a). This suggests that a significant increase in private-sector investment in R&D will be needed to develop and commercialize new low-emission technologies to address climate change. In turn, government policies must provide the signals and potential markets needed to stimulate private-sector investment in R&D to reduce greenhouse gas emissions.

Technology innovations to reduce GHG emissions will also require increased numbers of skilled workers, especially engineers and scientists in a wide variety of disciplines (including the social sciences). Limited data for the US suggests that the energy industry currently has far fewer R&D workers as a percentage of the total workforce than the average for all US industries. Over the past two decades the percentage of US college graduates in engineering fields has also declined significantly (NRC, 2010a). While other countries exhibit more favorable trends, increased efforts will be needed to direct human resources and talent to focus on innovations that support climate change mitigation.

CONCLUSION

While the study of technological innovation historically has been motivated by a focus on economic development and competitiveness in a market economy, the links between innovation and the attainment of environmental quality goals has become a subject of growing interest. This paper has discussed the critical role of technology innovation in addressing the problem of global climate change—arguably the most pressing environmental challenge we presently face.

As elaborated in this paper, technological change on a massive scale will be needed over the coming decades to achieve the international goal of stabilizing atmospheric levels of greenhouse gases (GHGs) at levels that avoid dangerous impacts. This will require replacing current GHG-intensive technologies—especially energy technologies based on fossil fuels (oil, gas and coal)—with newer technologies that emit fewer or no greenhouse gases. In many cases this will require advanced technologies that have not yet been developed or adopted on a significant commercial scale, or which have not yet been invented.

> “Technological change on a massive scale will be needed over the coming decades to achieve the international goal of stabilizing atmospheric levels of greenhouse gases (GHGs) at levels that avoid dangerous impacts”

Studies of technological change show that it is a complex process involving interactions among all stages of the process (invention, innovation, adoption, and diffusion of new technology into the marketplace). In general, gains from new technologies are realized only with their widespread adoption, a process that usually takes considerable time.

Government policies influence outcomes at each stage of this process. The stage of technological innovation—which leads to the development of new processes and technologies—is especially uncertain because development pathways and the likelihood of success cannot be predicted with confidence. Nor does the development of a new technology guarantee its commercial viability.

The role of government policies is especially critical in fostering innovations that address the problem of climate change. In the absence of government mandates or incentives to mitigate the problem, there are few if any markets for new technologies whose sole purpose is to reduce emissions to the environment (air, water or land). Thus, to achieve the large reductions in greenhouse gas emissions needed to reduce the risks of climate change, a broad portfolio of policies is required—not only to foster technological innovation, but also the subsequent adoption of new technologies by a large range of actors including individuals, governments, and firms of all size.

The policy portfolio to foster innovation should include a combination of "sticks" in the form of regulatory policies that directly or indirectly set limits on GHG emissions (such as through market-based mechanisms, technology performance standards, or a combination of measures), together with "carrots" in the form of technology policies that provide voluntary incentives to encourage technology innovation and deployment (such as through support for R&D, tax credits, loan guarantees, government procurement programs and other measures). To realize the full benefits of technological innovation, the policy portfolio also should support diffusion of knowledge, such as through financial support for education and training, along with other measures.

Although R&D alone is not sufficient to achieve widespread technological change, it is nonetheless a critical element of the policy portfolio needed to foster innovations that reduce GHG emissions. As discussed in this paper, substantial increases in government support for energy-related R&D are required to address the challenges of climate change. Large increases are also needed in private-sector support for R&D, especially in energy-related industries. Government policies again play a vital role by establishing the requirements and market signals needed by the private sector to justify R&D investments.

Finally, reducing GHG emissions through innovations in technology and institutions will require increased numbers of skilled workers, especially engineers and scientists across a wide variety of disciplines, including the social sciences. At the end of the day, it is people who innovate. Both government and the private sector have critical roles to play in attracting and retaining the best and brightest people worldwide to address the challenges and invent the opportunities for mitigating global climate change.

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