Launching a Technology Revolution

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Abstract

Despite the huge technological transformation of the global economy in the 20th Century, stabilization of greenhouse gas emissions will require a comparable revolutionary technological change in the 21st Century. While projections of future greenhouse gas (GHG) emissions show large increases in the coming century, the scenarios that underpin these projections already include major improvements in energy technology, including large penetration of renewable technology. However, the low cost and convenience of fossil fuels will lead to their continued use over the next century, unless there are significant changes in the nature of energy technology. These changes require both new technology and a method for fairly valuing society's interest in stabilizing GHG concentrations. If the costs are appropriate, technologies like carbon capture and storage, hydrogen energy systems and biotechnology offer considerable hope for stabilizing concentrations near the end of this century. However, current global investments in energy R&D are modest in comparison to the challenge. Further, widespread deployment of these technologies, likely to be largely developed by a combination of public and private investment, must be demonstrated to be not only technologically feasible but also commercially feasible. The public–private energy R&D partnership must work to avoid the "muddle in the middle" which can arise when the two sectors cannot resolve their respective roles, leaving promising technologies stranded by the market. Considerations of the "end-game", the actual stabilization of GHG concentrations, suggest that the products of the technological revolution may have to penetrate faster than planning would suggest, and that countries interested in stabilization may need to bring their own emissions of greenhouse gases close to zero by the end of this century or shortly thereafter.

How Big a Technology Revolution?

An amazing technological transformation of society took place in the twentieth century, a transformation very much driven by energy. The rise of the automobile, the global diffusion of electricity, and the development of massive energy-intensive industrial processes dominated this transformation. Given that history, it may appear presumptuous to suggest a technological revolution in the very next century, but there will be a revolution.

That revolution will be fomented and shaped by large-scale trends in human history. One such trend is the inexorable growth in the scale of human activities, driven in turn by the expansion of the human population and, more importantly, the growing circle of economic development. This implies a concurrent expansion in the technological infrastructure in such key services as food, water, housing, transportation and energy. As a consequence, the global energy system as we know it cannot continue. It must evolve, because the limited resources of conventional oil and gas imply a transformation in the supply of energy either toward unconventional oil and gas, coal, and/or nuclear and renewable energy forms.

At the same time income growth will lead to increased demands for environmental quality, while at the same time the unintended byproducts of that very same income growth will exert increasing pressure on that environment. That pressure will be acutely felt in the realm of climate change. Fossil fuels are the most important source of emissions of the most important greenhouse gas, carbon dioxide (CO_2). And fossil fuels are the backbone of the global energy system, the engine driving the growth in global incomes.

There is a wide and deep literature that has examined potential futures in the areas of economic development, energy production and use, and associated greenhouse gas emissions.[1] That literature reflects the potential variety of economic and technical developments that could occur over the course of the twenty-first century. While there is enormous variety in potential futures, most foresee a twenty-first century that is at the same time richer and with an expanded scale of human activities.

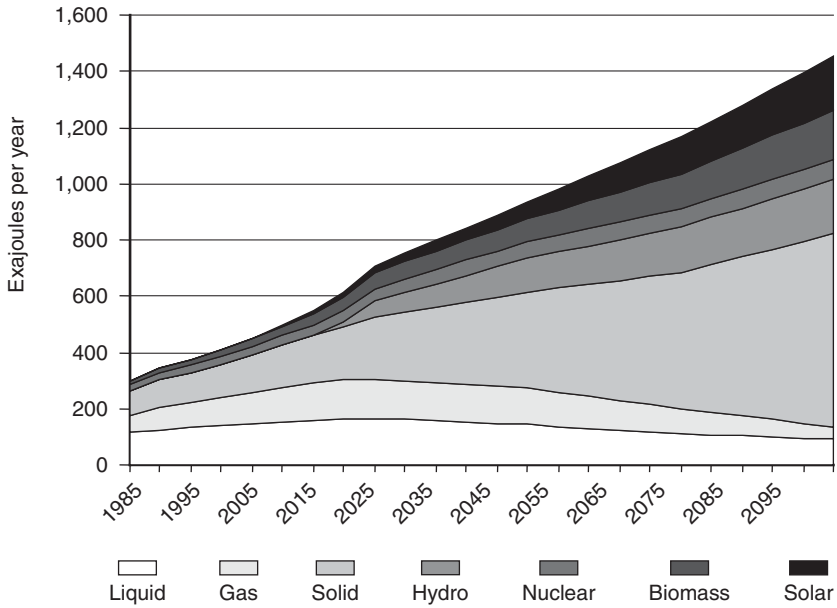
Underpinning this growth is an increasing energy demand, similar to that shown in Figure 1. This figure represents a scenario referred to

as the IS92a scenario.[2] The IS92a scenario has been used frequently because it reflects the central focus of the research literature. The global energy system for IS92a is depicted in Figure 1. Figure 1 clearly illustrates the potential growth in scale of the global energy system, and the potential magnitude of the attendant system changes. There is a tripling of global energy demand, and most of the demand growth comes from the developing world.

The IS92a scenario also has an interesting energy mix. While energy supply is still dominated by fossil fuels, by the year 2100 biomass has grown to exceed the 1990 global use of oil and natural gas. However, this fossil fuel world that will persist in the interim is precisely the one that raises concerns about climate change.

Many other scenarios exist. Some suppose less growth in the global energy system. Some assume more growth. Some exhibit a mix of technologies that contains more renewables. Some exhibit a mix of technologies that contains more fossil fuels. Some of that variety is displayed in Table 1. Table 1 shows population, scale of economic

Figure 1 The IS92a Energy Scenario



Source: Leggett, et al., 1992.

Table 1 SRES Scenarios

Scenario	Indictor	1990	2020	2050	2100
A1	Population (10^9)	5.3	7.4	8.7	8.1
	Gross World Product (10^{12} 1990 US$)	21	56	181	529
	Ratio OECD GDP/ROW GDP	16.1	6.4	2.8	1.6
A2	Population (10^9)	5.3	8.2	11.3	15.1
	Gross World Product (10^{12} 1990 US$)	21	41	82	243
	Ratio OECD GDP/ROW GDP	16.1	9.4	2.8	4.2
B1	Population (10^9)	5.3	7.6	8.7	7
	Gross World Product (10^{12} 1990 US$)	21	53	136	328
	Ratio OECD GDP/ROW GDP	16.1	8.4	3.6	1.8
B2	Population (10^9)	5.3	7.6	9.3	10.4
	Gross World Product (10^{12} 1990 US$)	21	51	110	235
	Ratio OECD GDP/ROW GDP	16.1	7.7	4.0	3.0

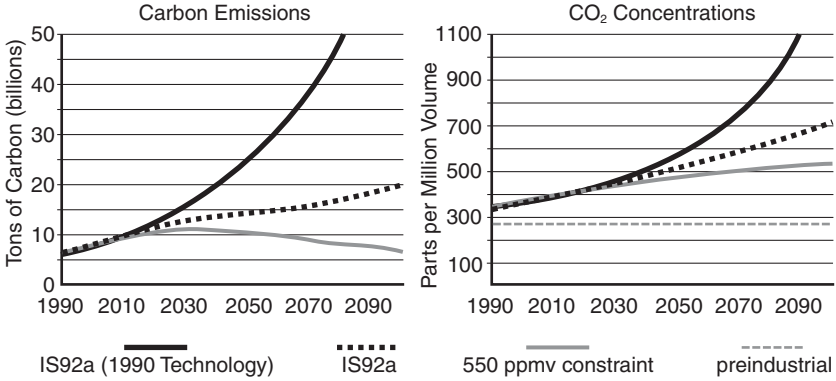
Notes: GDP=Gross Domestic Product; ROW=Rest of World; Scenarios are taken from Nakicenovic et al. (2000).

activity, and the ratio of the gross domestic product of the OECD developed nations to the rest of the world, for the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Emissions Scenarios (SRES)[3]. In all of the SRES scenarios the transitions are dramatic.

In Figure 2 we have translated the energy use of Figure 1 into carbon emissions (shown as the dashed line on the left) and the corresponding impact on the atmospheric carbon dioxide concentration on the right. The left hand central curve is in fact consistent with the continuing and growing fossil fuel use seen in Figure 2. There is, however, a much deeper story contained in Figure 2. The first story is found in the upper "black" curve. This curve shows the emissions profile that could be expected if the requirements for energy in the driving scenario were met with existing energy technology. While neither the emissions profile, nor the resulting concentrations, could really happen, this mental experiment illustrates the extent to which assumptions about 'natural' technological evolution are expected to alter the energy systems of the globe. The difference in total global emissions in moving from the "black" curve to the dashed curve is approximately 1500 billion tons of carbon—slightly less than double the current total carbon content of the entire atmosphere.

The second story involves understanding the changes required to reduce emissions from the dashed curve, a baseline scenario, to the

Figure 2 Emissions of CO_2 and Attendant Concentrations for IS92a, the IS92a Scenario with 1990 Technology, and an Emissions Trajectory that Stabilizes the Concentration of CO_2 at 550 parts per million.



"gray" curve, an emissions trajectory that would stabilize the global atmospheric carbon dioxide burden at 550 ppm, roughly double the pre-industrial value and 50 percent higher than current concentrations. The selection of 550 ppmv is purely arbitrary. At present, there is no scientific consensus as to what concentration would avoid "dangerous anthropogenic interference with the climate system."[4] Cases with concentrations ranging from 450 ppmv to 1000 ppmv have been examined. All stabilization trajectories have one crucial feature in common. They all require that cumulative global emissions be limited, and this in turn implies that annual emissions must eventually peak and begin a long-term decline that then continues indefinitely. Stabilizing emissions does not stabilize concentrations. Emissions must peak and then decline thereafter, eventually falling to virtually zero.

The higher the desired concentration, the later and higher global emissions can peak, but all stabilization requires global carbon emissions to peak and then decline. Affecting that change requires going far beyond the energy-technology suite associated with even the IS92a scenario.

We find it useful to think of the emissions reductions relative to the reference case as the emissions "gap" that must be filled through the deployment of technologies. Just as the suite of technologies deployed in the reference case was broad, the suite of technologies likely to be

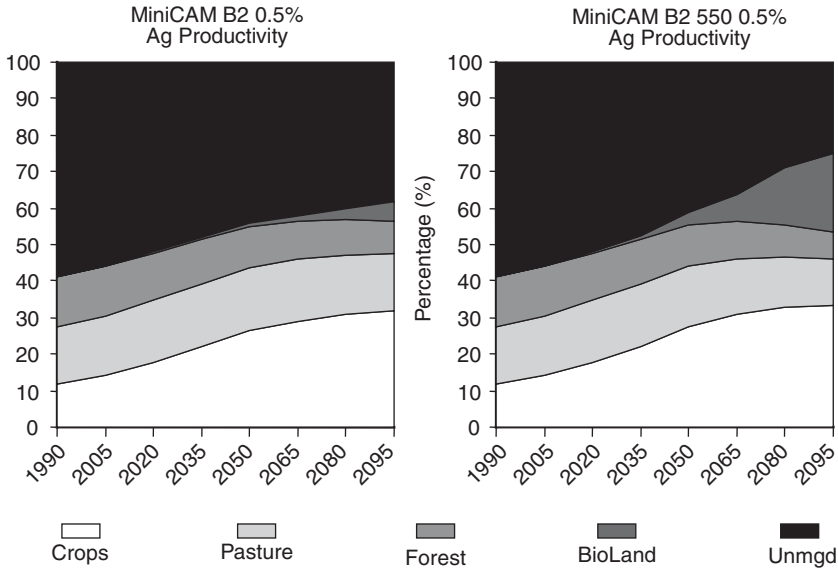
needed beyond the reference case is likely to be similarly broad. Expanding the role of technologies that play a role in the reference case can help close the gap. These include improvements in energy intensity, beyond that assumed in IS92a, as well as expanded deployments of nuclear, renewables, and biomass. Beyond this, advanced technologies such as carbon capture and storage, hydrogen and advanced transportation systems, and biotechnology also have potential to contribute to closing the gap.[5]

Having set some of the basic parameters of the problem we can now put the 'revolution' in context. The key issue is that the combustion of fossil fuels generates a waste stream that contains more than 6.5 gigatonnes of carbon (approx 24 gigatonnes of carbon dioxide). By comparison, the global production of steel in 2002 was just over 0.9 gigatonnes. The sources of the carbon, coming from electricity generation, transportation, and industrial processes suggest that the fossil fuel combustion infrastructure is one of the largest industrial systems in the world, so its replacement or transformation is a major challenge. There are several examples that highlight the scale of this transformation.

Take for example the issue of carbon capture and storage (CCS). Currently available and improving technologies permit CO_2 to be stripped from the emissions streams of power plants and other industrial facilities. The captured carbon can then be sequestered in underground geologic formations such as saline aquifers and depleted oil and gas wells.[6] The potential implications of deployment are enormous. To stabilize atmospheric carbon levels at the lower end of the potential concentration spectrum by capture and storage alone, perhaps hundreds of billions of tons of carbon would need to be sequestered by the end of the twenty-first century. Present capture and disposal is denominated in millions of tons per year. The change in scale covers three orders of magnitude. One implication of this scale of deployment is the importance of CO_2 retention in the reservoirs. Monitoring and verifying the carbon is a significant undertaking. Some losses from reservoirs can be nothing more than a minor annoyance, of no significant global concern.[7] But, significant losses can be a matter of global concern. The critical point here is not that leakage is an issue, but that the magnitude of the storage process is huge.

If we look at the systems associated with fuels that might possibly become alternative transportation fuels, we see similar issues arising from the shear scale of the system involved. For example, the creation and deployment of commercial biomass plantations as a major source of energy carries with it tremendous implications for the energy system as well as agriculture and land use. The present scale of modern commercial biomass is small. Biomass is generally derived from waste streams where it is economical to capture and employ a byproduct of some other process. For example, the pulp and paper industry generates about an Exajoule of energy in the United States from biomass. But moving from the present system scale to one in which hundreds of Exajoules would be produced and consumed each year is quite another matter. That system scale requires more than waste streams. Crops must be grown primarily for their energy content. At a scale of hundreds of Exajoules per year, commercial biomass would be the largest crop grown in the world. This in turn carries implications for deforestation, rural welfare, and energy security. Figure 3 shows land use

Figure 3 Global Land Use Under Two Alternative Cases-Reference (left panel) and Stabilization of Atmospheric CO_2 (right panel).



Source: Edmonds et al. (2003).

under two alternative cases, a reference case and an alternative case in which the concentration of CO_2 is stabilized at 550 parts per million.

Will this constitute a revolution? It could be argued that the improvement expected in Figure 2, to move from the purple curve to the red, is largely incremental. The outcomes are profound, but the process is evolutionary rather than revolutionary. The next step, however, is much more difficult. Filling the "gap" between the Reference Case world and emissions trajectories consistent with CO_2 stabilization are shown to require greater market penetration of both energy intensity reducing technologies and non-greenhouse emitting supply technologies, as well as the introduction of advanced technologies such as carbon capture and disposal, hydrogen systems, and biotechnology.

The scale of deployment of non-emitting "core" technologies and advanced technologies to fill the "gap" is large. Since most of these technologies are not yet deployed at scale, careful consideration needs to be given to crafting the requisite development and deployment paths. Issues that are trivial at small scale can become critical at large scale. It is this massive deployment of technologies not yet demonstrated at scale that argues for a revolution.

Technology and Policy

In creating a technology revolution we must first deal with two popular hypotheses as to how such a revolution might be fomented. They are:

> Myth #1: The revolution is simply a technological one and technology development alone will be sufficient to address climate change.
>
> Myth #2: The revolution can be launched by getting the prices right, and getting the value of carbon "right" will generate the technological change required to meet an environmental goal at minimum cost.

Myth #1: Technology availability alone may not reduce carbon emissions, even if the technology is dramatically better than that currently available. The effect of technology advances on carbon emis-

sions depends strongly on the type of technology, how it fits into the energy-economy system, and its interactions with the rest of the world. Edmonds, Clarke, Dooley, Kim and Smith report results from an experiment in which advanced technologies in the areas of carbon capture and storage, hydrogen, and transportation systems are assumed to become widely available.[8] While these technologies penetrate dramatically, carbon emissions are largely unaffected. The reason is that without a value for carbon, carbon is never captured. It adds an incremental cost to all fossil energy technologies compared with the cost of not capturing and disposing. And, without the economic or regulatory incentive to deploy, that technology simply remains on the shelf.

Carbon capture and storage is the power plant equivalent of a tailpipe technology for vehicles. That is, the fundamental process that generates energy is not changed, but the undesirable by-products of that process are treated before the final waste stream reaches the environment. In the case of an internal combustion engine, the end of pipe treatment is a catalytic converter that enhances the further oxidation of the undesirable pollutants, carbon monoxide, volatile organic compounds, and nitrogen oxides, limiting their release into the environment. In the case of CCS, the generation of energy through the combustion of carbon and hydrogen remains the base process, but the carbon dioxide is somehow removed from the flue gas, compressed into a liquid form and, in the case of geologic sequestration injected into a deep geologic formation (saline aquifer, coal seam or basalt formation) for permanent storage.

Both catalytic converters and carbon capture and storage add cost to the service being provided. In the case of the catalytic converter the added cost came from the device itself and the added cost of the fuel that had to be reformulated to remove the lead based additives, which would otherwise poison the converter. For carbon capture and storage, there would be the capital cost of the capture and disposal system, as well as the energy penalty paid to run the entire process—since stripping carbon from the plant flue gases itself requires an energy input. The added cost of vehicle ownership or the increase in electricity cost for carbon capture and storage would not allow either technology to compete in the market without some additional incentive for adoption. Catalytic converters were a response to regulated tailpipe emission standards. By the same token, CCS technologies will

not compete without some cost being imposed on the free venting of carbon dioxide to the atmosphere, or regulation mandating its use.

Carbon capture and geologic storage technology is also strongly complementary with other energy technologies such as hydrogen production and biomass energy. In the case of hydrogen, the problem is that hydrogen is an end-use energy carrier, not a primary energy form. It is derived either from electrolysis or from hydrocarbons such as fossil fuels or biomass. To the extent that hydrocarbons provide an inexpensive feedstock of hydrogen, the deployment of hydrogen-using technologies implies added use of hydrocarbons, with inefficiency in transformation, and the carbon being vented to the atmosphere. Thus, we are left with the irony that lacking a value attached to carbon, the advent of a hydrogen economy merely pushes the emissions back from the tailpipe of the vehicle to the hydrogen refinery, or, in the case in which electrolysis is employed, to the electric power plant.

A similar set of insights can be derived by looking at commercial biomass. Consider a world in which commercial biomass technology deploys, but in which all of the carbon stored on land is not brought under a system that values carbon. Even if carbon emissions are valued, failure to value the stocks of carbon existent in standing biomass and soils may lead to very dramatic, unintended emissions. Edmonds, Clarke, Dooley, Kim, Izaurralde, Rosenberg, and Stokes show that the deployment of commercial biomass implies competition for land.[9] This competition for land can lead to increased deforestation rates, which depending on the productivity of other crops, pastures, forest, and livestock can yield net carbon emissions as large as those arising from fossil fuel use over the first half of the twenty-first century.

The existence of the technology itself does not bring about its adoption without some market or regulatory incentive that internalizes the value society places on the benefit of the technology, unless the technology can compete economically with the alternatives.

Myth #2: Because price may provide an incentive for adoption of a technology like carbon capture and storage, perhaps by getting the price right, the market can 'solve' the problem and achieve the desired result. Under this scenario, which has been employed in the United States for some power plant emissions, rather than mandate a single approach, individual firms are free to find their own 'least-cost' solutions to handling the additional cost. In the case of carbon dioxide

emissions, the idea has been either to impose a carbon tax on emissions, i.e., a regulated price, or to establish a system of tradable permits in which the market so created would find its own price. If carbon capture and storage therefore becomes part of the 'least-cost' solution, then the technology will be developed and adopted.

For technologies that are "on the shelf" or technologies that are near commercialization, this argument is largely undisputed.[10] But putting technologies on the shelf is another matter. That requires R&D and R&D suffers from the problem of inappropriability. That is, private actors cannot capture the full economic benefits of the R&D they conduct and therefore there is a systematic underinvestment in that activity.[11] Moreover, the more basic the R&D, the harder its fruits are to appropriate. The difficulty then lies in getting the technologies to the point where they can be put on the shelf. At the very least, there is a problem in laying down the foundations upon which new technologies can be built. All of this speaks to the problem of the public-private interface in the creation of a climate policy. There is a clear need for R&D that goes beyond that which even the best market economies would foster in the private sector.

Setting socially optimal values for carbon, both for the moment and across future time, would go a long way toward providing incentives to develop and deploy technology. However, that in turn implies knowledge of the "right" concentration at which to stabilize, the ability to send a credible signal about future carbon values to everyone in all countries and in all occupations, and an ability to estimate the present value of carbon. In addition, climate change is not the only issue for which getting the prices right is a problem. Other commodities are public goods for which market alone cannot be relied upon to set the socially desirable price. National defense is one example, and local and regional environmental amenities another. Much has been made of the idea of ancillary benefits of climate policy. That is, limiting greenhouse gas emissions may simultaneously reduce non-CO_2 environmental emissions. This interconnectedness works at many levels, and the control of greenhouse gas emissions may not only reduce the production of undesirable emissions, but also increase others. Getting the prices right is therefore a matter of simultaneously addressing local, regional, and global environmental problems. The breadth of time, spatial and technical scales is so great that no models currently exist that can credibly estimate the joint solution. Given the real-world

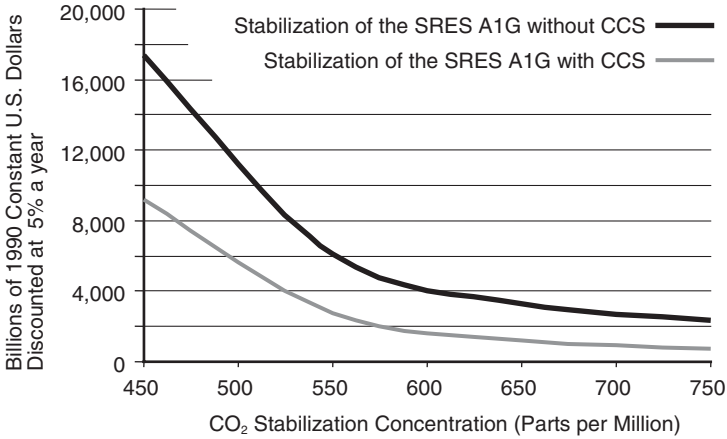
difficulties with getting the prices right for an intergenerational, global public good, it is worth noting that climate policy will, and should be developed on the basis of "act, then learn, then act again".

Technology and Stabilization: Addressing the question of climate change is only one competing end for individuals and society. Unlike most environmental problems, climate change suffers from both a "free rider" problem and an intergenerational allocation problem. The "free rider" problem stems from the fact that it is global emissions that matter, not national emissions. Therefore, an efficient allocation of resources can only be obtained if all of the economies of the world act in concert. Since no individual nation can control the concentration of greenhouse gases in the atmosphere, it is in every nation's interest to encourage others to control the concentration and to "free ride". Since any individual nation contributes only marginally to the total, it can be better off by doing something less than its share, as long as others are acting in the global interest. Of course, this is a recipe for global deadlock.

The intergenerational resource allocation problem is just as sticky. Most of the benefits to emissions mitigation are bestowed on future generations. And therefore, the behavior of present generations is largely altruistic. That is, the fruits of those efforts cannot be captured by the current generation. But, climate change is only one of a number of potential venues for altruistic investments. It must compete for resources with health, water, and regional and local environmental quality, to say nothing of the direct consumer options of the present generation.

Cost is therefore a critical concern. And, technology is therefore of paramount importance, as it affects the cost of reaching any goal. Consider again carbon capture and geologic storage. The value of adding this option to the technology mix can be estimated using an economic model against a reference case world (SRES A1G in this case).[12] Of course, the economic model we have employed has computed the minimum cost of stabilizing the concentration of greenhouse gases. This implies a number of simplifying assumptions that would not be met in the real world. It assumes that all nations fully participate in the stabilization regime from the start. It assumes that all nations have efficient markets. And, finally, it assumes that all nations face the same, "correct" price of carbon everywhere and at all times. Given so many unrealistic assumptions, the numerical values

Figure 4 Minimum Cost for Stabilizing the Concentration of CO_2 at Various Levels With and Without Carbon Capture and Geologic Storage Technology



shown in Figure 4 are interesting for the qualitative insights they yield rather than for any specific numerical values. Nevertheless, some useful insights can be drawn from the figure.

Figure 4 shows the minimum cost for stabilizing the concentration of CO_2 at various levels with and without CCS technology. The first thing worth noting is the unit of measure, trillions of 1990 U.S. dollars. The second thing worth noting is that the difference in cost between the cases with and without CCS technologies is also denominated in trillions of 1990 U.S. dollars. And, these are minimum costs.

The difference between stabilizing the concentration of CO_2 at 650 parts per million with and without CCS technology amounts to two trillion 1990 US dollars (present discounted at 5 percent). Of course, science cannot determine which concentrations avoid dangerous anthropogenic interference with the climate system. But regardless of the concentration, the rewards to the successful development and deployment of cost-effective CCS technologies are great. Those resources thus conserved could be put to other valued uses such as health, environment, and economic development.

Another way to view this information is through the lens of concentrations. Consider fixing a budget for stabilization of CO_2 concen-

trations. For an allocation of the same resources as were required to stabilize the concentration of CO_2 at 710 ppm without CCS, the CO_2 concentration could be stabilized at 550 ppm with CCS. For the same present discounted cost of stabilizing the concentration of CO_2 at 520 ppm without CCS, the concentration of CO_2 could be stabilized at 450 ppm. Thus, the increase in environmental benefits associated with a fixed environmental expenditure—with and without CCS technology—range from 70 ppm upward to 180 ppm, depending on the expenditure level.

Both economically and environmentally, there is a lot riding on the success of the technological revolution.

Launching a Revolution

All revolutions are inherently messy and unpredictable affairs. A technological revolution is no exception.

Intrinsic technological change, which arises out the creative genius of individuals and naturally finds a place in the market, like the automobile or the electric light, is an inherently unpredictable, dynamic phenomenon. In general, it has its roots in R&D, but many other factors shape its success in the market. The rise of the automobile is a good case in point. To be sure, there has been a remarkable series of innovations and improvements in the basic technology of the vehicle. Yet the emergence of the automobile as the dominant mode of personal transportation in much of the world has been aided by both public investment and the early availability of fuel resources.

Public investment in highways that were increasingly compatible with the automobile allowed the vehicles to reach speeds that rivaled train travel and began to make the technology more convenient. In the last half of the 20th Century, the Interstate Highway system constructed across the US, and the associated dense network of freeways that grew out of urban areas, enabled the development of suburbs and transformed the automobile from a convenient conveyance into a necessity.

The early phase of this transformation, particularly in the United States, was aided by what at the time appeared to be an abundant supply of domestic petroleum. By the time that the limits of these reserves were realized and we became dependent on foreign supplies of fuel, the

transformation of society into one that depended on the automobile was firmly in place. These same two factors of highway infrastructure and cheap fuel also enabled the development of long-haul trucking as an effective competitor to rail transport, the darling of public investment in the late 19th century. Understanding that the public investment in infrastructure and domestic resources may have been just as important for the rise of the automobile as Henry Ford's assembly line, which made the vehicles broadly affordable, is an important lesson as we look to guide a similar technological transformation.

Looking now at the R&D that drives basic technology, we know that directed R&D can increase the likelihood of a technology being developed and improved to the point that it achieves a defensible position in the marketplace. But it can guarantee the neither the existence and timing nor the widespread deployment of a particular technology. In the best of circumstances, R&D can rush on as one break-through leads to the next. The heady transformation of the semi-conductor industry, characterized by the now iconic rate of transformation identified by Moore's law, is one such success.

We also know that technological advances can be fueled by learning, serendipity, and discoveries in unrelated fields and distant lands. In energy, for example, many important innovations have come from non-energy related R&D. The combined cycle gas power turbine was the unintended byproduct of military research to improve the performance of military aircraft. Nuclear power, too, was the unintended byproduct of military technology research. In the case of nuclear power, the widespread use of nuclear propulsion for naval vessels also created a cadre of trained professionals that could staff commercial nuclear power plants.

Looking specifically at energy R&D, what we expect to be the wellspring of the technological revolution, it is important to note that it is in no way the sole province of either the public or private sectors. While public sector enterprise has produced important breakthroughs, it is the private sector that has tuned technology to the many needs for energy services and deployed the present global energy system.

Defining a flexible, working relationship between the public and private sectors will be essential to the success of the revolution. The

boundary between the public's role and the private sector is vague and ill defined. Horror stories abound in which that boundary was poorly honored. At the extremes, each sector's claim to contribute is clear. At the boundary the public sector can inappropriately intrude in areas better served by the private sector and market forces. On the other hand, if the public and private sector withdraw too far toward their traditional strengths the result is the infamous 'valley of death,' which strands what may be significant technological advances short of the market.

The public sector's traditional role lies in maintaining the basic research enterprise and in developing the ability to monitor and verify where that is needed. The same perspective describes the private sector's role in deploying technologies in the market. Private sector R&D to develop a hydrogen transportation system dwarfs the public sector enterprise. The middle is muddled. As a result, defining a research agenda that introduces a climate technology motivation to an energy-security agenda, an environment, health and safety agenda, and an inexpensive-energy agenda will doubtless prove challenging.

Before wading into the muddled middle, we must face the fact that at present, energy R&D is in decline in both the public and private sectors throughout the world. This is in sharp contrast to R&D in general in the United States, which is growing.

There are good reasons that may explain this decline. Energy prices have been falling, reducing the expected profitability of energy R&D investments. Energy deregulation has created an incentive to compete on near-term price and reduced the ability of firms to make long-term investments in future technology. Government around the world have come under increasing pressure to balance their budgets, or at least to rein in their deficits. Energy R&D, particularly long-term energy R&D, has been a victim of all these pressures.

Laying the foundations for a revolution will eventually require energy R&D investments. Without such investment, declining R&D in both the public and private sectors threatens not only the development of "gap" filling technologies, but also the productivity of "core" technologies.

If the R&D investments are to be effective it is important that we be clear about what that R&D needs to accomplish, which requires that we address the "muddle in the middle" noted above. A good starting point is the definition of energy R&D from U.S. President's Committee of Advisors on Science and Technology.[13]

- Energy R&D refers to a series of linked processes by which technologies for energy supply, end use, or carbon management move from theoretical conceptualization to feasibility testing and, ultimately, to small-scale deployment.

- Energy R&D encompasses both basic and applied research, technology development, and demonstration associated with each phase of the energy lifecycle including: production (e.g., mining and drilling), energy conversion and power generation (e.g., nuclear fission and fusion, fossil and renewable energy systems, bioenergy, and hydrogen production), transmission, distribution, energy storage, end-use and energy efficiency, and carbon management.

- Energy R&D includes efforts to develop carbon management technologies to manage anthropogenic releases of greenhouse gases such as those associated with the combustion of fossil fuel use, in an effort to mitigate the potential impacts of these emissions on climate systems. Carbon management technologies include advanced agro forestry practices aiming to enhance the capacity of soils, trees, and other standing biomass to absorb atmospheric carbon dioxide; engineered pre- and post-combustion carbon capture systems and technologies for geologic and ocean carbon sequestration.

This definition is very broad, and in fact covers activities that are, or could be, funded by both the public and private sector. Against this definition, it is important to remember what achieving the technological revolution requires. If there is indeed a technological revolution to meet the challenge of climate change, the technologies must not only be shown to be technologically feasible, but commercially feasible as well. Commercial feasibility implies that the technology can be successfully operated with a reasonable return on investment. This means operation at reasonably predictable cost with adequate personnel to manage the facility on a day-to-day basis, minimal likelihood of opera-

tional or regulatory surprises, and widespread public acceptance of the technology. These criteria are not only important to the operator of the facility, but also for those financial institutions providing investment capital to construct the facilities.

Without continued demonstration of commercial viability, it is unlikely that a new technology will reach the level of deployment necessary to make a significant contribution to the stabilization of greenhouse gas concentrations. A case could be made that the emergence of increased operational costs, operational and regulatory surprises, and a failure of public confidence cost the nascent nuclear industry its commercial viability in the US and many other countries around the world.

One of the responses of the US utility industry to handle these surprises was to fund R&D to deal with them. The nuclear R&D program at the Electric Power Research Institute (EPRI) was a key institution in trying to maintain the commercial viability of nuclear-fueled electricity generation. R&D is in fact a critical part of a continuous improvement process for technology. R&D in support of what is often called "technology insertion" at the Defense Department has enabled aircraft like the B-52 to remain a part of the Air Force arsenal for more than 50 years.

As noted above, there has been a steady decline in energy R&D, and programs like those at EPRI and comparable institutions for the gas industry, for instance, have been particularly hard-hit. The realities confronting the energy sector are quite stark. In 1999, the latest year for which data are available, private energy R&D as a percentage of net energy sales was 0.33%. This is in contrast to the all industry average of almost 4%. Further, the energy sector has the lowest R&D/sales ratio of any industry in National Science Foundation survey of R&D. In the utilities industry, the R&D/sales ratio was 0.1%. These are not the levels of investment likely to turn a small scale deployment, the end-point of the PCAST definition of energy R&D, into a widely deployable, commercially viable technology.

It is instructive to look at some of the issues associated with three specific classes of technology expected to be part of the technology revolution and consider the transformation that might make them commercially viable. The three are carbon capture and storage,

hydrogen transportation fuels, and biotechnology. These three are interesting not just because of their potential for widespread deployment, but also because of the different R&D and deployment traditions from which they are expected to emerge.

Carbon Capture and Storage: This technology has several distinct technological components and for this discussion we will focus on the technologies as they relate to electricity production. For the sake of simplicity, it is easiest to focus on the particular case of a coal-fired power plant capturing CO_2 for deep geologic disposal. The first technology that supports this process separates carbon dioxide from other gases. This separation can occur either in the gasification process, for units that use coal as a feedstock for gasification, or in the power plant's exhaust stream. A variety of technologies exist to accomplish this, although none has been deployed on the scale that would be required to demonstrate how they would operate in a commercially viable fashion.

The second stage transforms the resulting carbon dioxide stream into a super-critical fluid and moves it to the injection site. Again this is a known technology that has been operated around the world. There are thousands of miles of carbon dioxide pipelines in the United States already. Operations like the Sleipner project in the North Sea—where Norway's Statoil extracts natural gas from the Sleipner West field, reduces the gas's CO_2 content for commercial sale from 9 percent to 2.5 percent by amine scrubbing, and then injects the carbon dioxide into a saline reservoir 800 meters under the sea bed—illustrate the processes both of preparing carbon dioxide for injection and injection itself.[14]

Finally, the carbon dioxide needs to be injected into a geologic formation capable of long-term retention of the gas. While there are a number of operations and experiments, such as Sleipner and enhanced oil recovery operations, that demonstrate the methods that would be used for injection, there are no certified repositories for long term carbon dioxide storage, and the entire process has never been demonstrated in an operational electricity generating facility.

The basic technologies that support carbon capture and storage are not those normally associated with the electrical generation industry. The separation technology comes out of the bulk chemical industry

and the post-separation technology arose from the oil industry. The environment in which these facilities will be operated is the electrical generation industry. There are several issues associated with the demonstration of commercial viability of these facilities: repository certification and management, water requirements, operational experience, cost, and public acceptance. The two that will drive the demonstration of commercial viability are probably repository certification and water.

In order to succeed as a climate change mitigation technology, the deployment of carbon capture and storage will need to be widespread. The cost and siting of pipelines and the distributed nature of power plants means that local repositories will be preferred. This implies that there will need to be a system of repositories in those countries that wish to deploy the technology. The process of siting and certifying repositories will furnish the framework for gaining and legitimizing public acceptance for the technology and, if the certification process is connected to the use of real flue gas streams from real power plants, valuable operational experience will be gained.

Water is a more complicated issue. The demand for water will arise from the need to cool the carbon dioxide stream for compression and injection. There are already demands on water supplies that affect both the operation of current power plants and the siting of new power plants. Just as repository availability may affect the selection of power plant sites, so will water availability. Processes underway, such as several regional carbon sequestration partnerships, will help address many of these issues and allow systematic examination and planning for everything from siting and certification to water and public acceptance. A well-run process can address many of these questions. A failure in any one of the attempts to address these issues will impact efforts elsewhere. The susceptibility to single point failure early in the process is high.

All this leads to the question of cost. Cost emerges as an issue both in terms of the predictability of the eventual operational costs and as a matter of who will be responsible for the costs associated with the key steps toward commercial viability. Is the network of certified repositories a matter of national interest, like the Interstate Highway System, or is it a regulated private enterprise like many hazardous waste management systems? In the former case public investment needs to be

high, while in the latter the private sector would be expected to make the investment. One can imagine that either choice, particularly when tied to public acceptance, could create a "muddle in the middle" and inhibit the widespread deployment of the technology.

Hydrogen as a transportation fuel: The development of the hydrogen economy is widely anticipated to be another pervasive climate change technology. Like carbon capture and storage, it has several key technological components that need to work together to create the eventual infrastructure and end uses for hydrogen. These components are a source of hydrogen, a distribution network, and the end-use technology itself. Also like carbon capture and storage, each of these components arises out of different R&D and deployment traditions. Hydrogen, like electricity, is an energy carrier rather than an energy source. There are no natural sources of hydrogen. Like electricity, there are many possible methods for generating hydrogen and the key to its eventual use lies in the effectiveness and reliability of the distribution network that supports its use.

The two basic sources of hydrogen currently being considered are hydrocarbons and the decomposition of water using electricity or sunlight. Both approaches are reasonably well understood, but improvable, technologies. Again, like electricity, there exist a range of generation strategies for hydrogen, including both central generation and varying degrees of distributed generation. With one notable exception, it is very likely that the emerging hydrogen market will sort these options out through spirited competition, as long as the distribution infrastructure supports that market and the breadth of options. The effect of hydrogen production on carbon emissions depends entirely on the source of the hydrogen. If either electricity from fossil fuels or fossil fuel feedstocks are employed to produce the hydrogen, then, as noted earlier, carbon emissions have simply been displaced from the tail pipe of the vehicle to the power generation facility or refinery, unless the carbon is captured and stored. The emergence of the CCS option depends heavily on the system of carbon repositories, their capacity and geographic distribution, and is contingent on either an explicit or implicit value for carbon. This option too could be caught in the same muddle in the middle.

On the end-use side, the fuel cell is a key technology. Initially a product of the space program, this technology is the subject of intense

public and private sector R&D investment. Some of this is captured in the statistics on energy R&D, but there is a significant investment in automotive R&D, which is crucial to the development of cost-effective mobile fuel cells to meet transportation needs. To make fuel cells tractable as a transportation technology also means that a means of storing hydrogen must be developed that enables the vehicle to provide all of the consumer and social amenities available from vehicles with internal combustion engines, plus new desirable features. This is no small task.

Between the fuel cell and the various sources of hydrogen lies a large infrastructure. Simple estimates of the capital value of the corresponding infrastructure network for petroleum distribution place its value at perhaps $2 trillion globally. The creation of this infrastructure must fulfill two important criteria. First, it needs to be versatile enough to create a competitive hydrogen market. Second, it needs to have a convenient distribution system that allows it to support the relatively diffuse demands of supporting the transportation infrastructure. The muddle in the middle is most likely to arise during the early implementation phase of this infrastructure.

Several significant sticking points loom. One potential issue could be a proliferation of different and perhaps mutually incompatible fueling techniques and approaches, some protected by strong intellectual property rights on the part of the private sector, competing to become the standard for the large-scale deployment of the technology. These could take the form of 'closed system' hydrogen generation and distribution systems designed to lock-in customers and market share, to the detriment of competitive hydrogen generation technologies. Conflicting state or country level regulation of the transportation and distribution systems will slow the broad diffusion of the technology. Finally, public acceptance, which will be sensitive to any early system failures, will affect both siting of the hydrogen equivalent of filling stations and the adoption of the vehicle technology as well.

Public sector involvement in the early stages of deployment is essential. Because transportation technology is an internationally traded commodity, the harmonization of standards and regulations across traditional regulatory boundaries will be very important. More importantly the public sector, through demonstration fleets and fueling systems may be the critical first customer in many locales for the

new technology. This will build operational experience and public confidence.

Biotechnology and Bio-Fuels: The revolution in the biological sciences is producing fundamental knowledge at an unprecedented pace. Yet, the potential application of biotechnology to the climate change issue is largely ignored, and thus one of the great oversights in climate technology analysis. Biotechnology has the potential to be one of the most important components of the climate technology revolution.

Two applications of biotechnology have obvious potential: biotechnology applications to produce hydrocarbons, i.e., biomass; and the use of biotechnology to produce energy directly from such sources as sunlight, thus potentially blurring the distinction between what is solar energy and what is biomass. While both of these technologies use biological processes to capture or generate energy sources, they do so in a very different way and arise from separate R&D traditions. Biotechnology approaches envisage the use of fundamental biological processes learned in the post-genomic era to create energy sources, either in intact biological systems, such as microbes, or by extracting molecular machines from those organisms, isolating them in a production system in what might be considered a cross between nanotechnology and biotechnology, so as to generate products such as hydrogen. The R&D base for this is that of modern biology and the processes would be more in keeping with chemical manufacturing.

Bio-fuels are a product of agricultural R&D. They benefit the climate problem by recycling existing atmospheric carbon dioxide in the same way in which food production does, capturing solar energy in plants and releasing it either through direct combustion or conversion to another fuel, such as alcohol. Traditional wood burning is a major source of energy in the developing world. In the developed world, waste products such as wood, pulp, and paper waste, are used to fire or co-fire systems either for process heat and/or to generate electricity. If these two uses of fuel represent two developmental stages of bio-fuel, the development of energy crops is the third stage. Corn is converted to ethanol and used as an oxygen rich fuel additive in the US. In Brazil, in the year 2000, sugar used for ethanol and sugar cane bagasse directly fired for electricity production reduced the country's fossil fuel carbon emissions by about 7 percent.[15]

The biotechnology approach is still in its formative stages. There is a small but growing basic R&D effort in the public sector, such as the Genomes to Life Program at the US Department of Energy. Private efforts have been launched as well, such as Institute for Biological Energy Alternatives, led by Craig Venter, some of which is publicly funded.[16] These efforts are not yet well developed, and specific processes appropriate for large scale energy systems have not been identified, making speculation on the muddle that might develop as they go commercial scale, just that, speculation. It is an open question as to whether these methods are receiving the level of investment in basic research by either the public or private sector that is warranted by their eventual promise.

Energy crops, however, are far more developed. Here, the relative role of the public and private sectors is an emerging issue. Setting aside direct combustion of biomass, there are four basic processes that convert crops into fuels. Two of these generate ethanol. One converts vegetable oils into diesel fuel. The last is gasification of biomass, which results in a product that can be directly used in the existing natural gas infrastructure. The first three have the potential to generate an alternative to fossil fuels in the transportation sector.

First, ethanol or methanol can be made for use as fuel either through fermentation or by cellulosic conversion. The production of flexible fuel vehicles and the use of ethanol as a gasoline additive make these fuels compatible with the existing fueling system and portions of the existing vehicle fleet. Advances recently announced by Delphi in Brazil make alcohol fuels compatible with internal combustion engines over the full range of alcohol fuels, up to and including 100% alcohol. Fermentation of sugars to generate alcohol, except when heavily subsidized as it was in the 1980's in Brazil, is largely based on the excess production of crops such as corn and sugar cane, which normally have a much higher value in the market as food or feed crops. Recent advances in cellulosic conversion appear to be making this process more attractive. Specifically, cellulosic conversion is emerging as an option that results in greater net energy yield per acre when compared to sugar and corn. Continuing success in this regard would suggest that this process, which advocates feel is cost competitive for waste cellulose such as corn stover, could open the option of using crops like switch grass and hybrid poplar as energy crops for the

future. The cellulosic conversion industry feels that they are currently disadvantaged in the US market relative to fermentation of sugars by government subsidies, as discussed below.

Bio-diesel is created from vegetable oils, which can be converted through a low temperature, catalyzed reaction of the oil with alcohol (methanol), and can be directly used in existing diesel engines. The use of waste oils obviates somewhat the necessity of considering the fuel lifecycle analysis when weighing this as a fuel option. However, economics willing, if specific energy crops were developed to serve as the feedstock and there existed a well-established process for making the oils, this fuel could be easily melded into the existing fuel infrastructure. Some countries, such as Malaysia, are examining this as a mechanism for creating an alternative use for oils such as palm oil when domestic producers are faced with depressed markets due to annual fluctuations in supply and demand.

Gasification is a high temperature process which can be applied to a variety of feedstocks to generate natural gas for either combustion or electricity generation. There have been at least two decades of development on gasification and it is on its way to becoming a fully-developed technology, with the usual room for continuous improvement of the associated processes. Its current use is driven by local feedstock availability and economics.

A rising value for carbon, one consistent with stabilizing the concentration of CO_2, will eventually improve the economics of bio-fuels relative to gasoline and fossil derived diesel fuels. Their compatibility with existing energy infrastructure will facilitate the transition. The orderly expansion of these options could probably be best served by predictable carbon prices allowing sensible long-term capital investment decisions, further spurring the development of crop species giving greater net energy yields per acre of energy crops. Still, a question remains about the future of transportation fuels that a bio-fuels option creates. What will the competition between bio-fuels and hydrogen look like? The compatibility of bio-fuels with existing energy infrastructure offers some advantage. Cheap fossil fuels feedstock and effective carbon storage, combined with cheap off-peak electricity for electrolysis, may give hydrogen a sufficient edge to justify the necessary infrastructure. The early stages of this competition will likely play

out in local and regional markets, but we know of no analyses that give great insight into how the competition will evolve.

One of the key actions a government can take to bring a technology to commercial viability in the early stages of its evolution is to subsidize the adoption of the technology. This can be done in a variety of ways, ranging from direct subsidy of production to guaranteed government purchases of the product. But subsidies are a tricky business. The strategy of identifying a technology that will eventually become the dominant technology in the industry is notoriously difficult, and governments have not distinguished themselves in their ability to identify the future market successes. And, while subsidies are intended to be only a short-term push to get the enterprise going, theory and practice often diverge, and subsidized sectors can limp along under the subsidy's protection for long periods, until it is eventually recognized that they will never take over the market. In fact, for solutions to the climate problem, the scale of required deployment is so large that long-term subsidies are completely out of the question. Biologically based alcohol production provides a cautionary tale in this regard. It is experiencing a "muddle in the middle" from two subsidies, one that is widely discussed and one that is more subtle.

Most current bio-fuel production, whether of bio-diesel or alcohols, employs either waste or excess crops as a feedstock. In electing to subsidize the emergence of these technologies, the government can choose a variety of approaches. One approach would subsidize the process, starting with the feedstock. This approach would serve the dual purpose of buffering key national agricultural sectors, such as palm oil or corn, from market vagaries and produce a desired fuel. Alternatively, the government could subsidize the fuel and allow the competing supply chains to duel in the market. For example, in the US, subsidizing corn-based ethanol would give it a current market advantage over waste-based cellulosic conversion. This relative advantage for corn may make good policy sense in the near-term. In the long run, however, as the demand for bio-fuels grows, this choice may slow the development of energy crops where it appears that cellulose rich feedstock have cost and energy advantages.

The second subsidies of interest are the OECD subsidies of farm crops that are the center of trade discussions between the OECD and the developing countries. Setting aside the specific trade issues at stake

in these negotiations, one should note that such subsidies have the collateral effect of raising the value of the land on which the crops are grown. In the long term, bio-fuels and other crops cultivated specifically for energy use will, if successful, compete for land with alternative uses such as food production. While there may be national security issues associated with maintaining a sound agricultural sector in developed countries, bio-energy offers a national security benefit as well by providing a renewable domestic source of energy stocks. There have been no analyses of this particular competition between national goals, but it illustrates the complex interactions that policies like subsidies can create.

In summary, there are several important issues that arise as we consider the prospects for an energy revolution. The first relates to the creation and demonstration of the necessary technologies. The second arises as the nascent climate technologies begin to establish the commercial viability necessary for their long-term success and widespread deployment

Both the public and private sectors, in all of the countries in which energy R&D is an enterprise, will eventually need revenues to support that R&D. Management mechanisms will also be needed. This is more important for the public sector than for the private sector, where managing R&D to cut off unproductive avenues of research, to prevent duplication, and to insure focus are well developed. In the public sector, these tools will also be required.

Sources and distribution of R&D revenues will doubtless look different depending on where they occur. Differences will arise between energy service sectors, such as electricity and transportation, as well as between different regions and nations of the world. It is reasonable to expect that individual nations or groups of nations may focus their R&D efforts on energy sources and systems consistent with their natural resource mix, and that they will invest consistent with their general approach to R&D investment. The American and Australian investment in coal technology and the Northern European interest in natural gas, for example, are consistent with current resources. Similarly, the public sector's role in Japan may be much more pronounced than in the United States, and the French energy program will likely continue to have a strong nuclear orientation.

While R&D investment in specific energy consuming and generating technologies may have a national character, many of these technologies have a distinctive international flavor as well. Motor vehicles are a good example. They are traded internationally and, despite some national variation, fueling systems are very similar globally. International standards will represent an important avenue for progress.

Finally, as the technologies that will constitute the core of the revolution emerge, encouraging and not discouraging their development as commercially viable options for energy services is critical. The law of unintended consequences suggests that there will be errors and barriers. Commercial feasibility requires that the technology be successfully operated with a reasonable return on investment. There are many factors that affect successful technology development and deployment. All of those factors such as operation at reasonably predictable cost with adequate personnel to manage the facility on a day-to-day basis, minimal likelihood of operational or regulatory surprises, and widespread public acceptance of the technology, must be protected so that the technology is not consumed by the "muddle in the middle". Failure to avoid the muddle has two simple consequences. Either the cost of achieving a particular stabilization level will rise, or for a fixed societal cost, the achievable level of environmental quality will be higher than it would have been had the technology reached its potential.

The "End Game"–Cheaters, Leaks, and the Other Greenhouse Gases.

The technological revolution, like every other revolution will be imperfect. As Rayner and Malone have noted in their "Ten Suggestions for Policymakers" there are limits to rational planning.[17] From the perspective of technology, the revolution may falter due to any one of three causes. They are inherent limitations in the ability to develop technology, deployment of imperfect technology, and fundamental limits to deployment. However, achieving the particular goal of stabilizing greenhouse gas concentrations faces other hurdles that may challenge the rate and breadth of the revolution.

Before focusing on the places where the revolution may fall short, it is important to keep in mind what it means to stabilize the concentra-

tions of greenhouse gases. To do that, it is necessary to disaggregate the collection of greenhouse gases in a way that is consistent with their fate in the atmosphere. To this point in this paper we have focused on carbon dioxide, since it is the greenhouse gas with the most profound implications for technology. The concentration of carbon dioxide in the Earth's atmosphere is a consequence of the flows of carbon among a variety of different stocks of carbon. The movement among these stocks is controlled by a variety of geophysical process, each of which has a different characteristic time scale associated with it.

The times scales associated with the key processes affecting carbon dioxide concentrations can be ordered from fast to slow. There are two important fast processes. The first is the annual cycle of the growth of plants associated with the change of the seasons. This cycle is driven by spring and summer uptake of carbon dioxide due to photosynthesis and the release of carbon back to the atmosphere in the fall and winter when decay processes break down plant material at a rate in excess of residual photosynthesis. This process is large enough to be seen in the annual global variation of carbon dioxide concentration, such as that observed at Mauna Loa. The second fast process is the equilibrium that is established between the atmosphere and the upper, mixed layer of the ocean.

The next time scale is tied to these first two processes. In the case of the terrestrial component, there is a gradual net addition of carbon to standing biomass, perennial organisms like trees, and the soil. In the ocean, the waters in the mixed layer, the top few hundred meters of the ocean, are gradually mixed by ocean circulation into the deep ocean, which is out of contact with the atmosphere. These two processes operate on time scales of decades to centuries. Finally, there is a geologic scale, operating over periods with characteristic times of millennia to millions of years, where carbon is incorporated in geologic formations such as fossil fuels.

When society mines the geologic repositories of carbon to generate energy or make cement, an excess of carbon dioxide is created in the atmosphere. The ability of plants and the mixed layer of the ocean to absorb the excess is limited; and, on an annual basis, this results in about half of the excess carbon dioxide in the atmosphere being removed. The remaining carbon dioxide leads to an incremental increase in the atmospheric carbon dioxide concentration.

With this picture there are basically two carbon emission budgets. The first is a budget for the amount of carbon dioxide that can be emitted in excess of the uptake by the deep ocean and the terrestrial system. This quantity essentially charges the atmosphere with carbon dioxide up to the level at which the CO_2 concentration is to be stabilized. At stabilization, the annual release of geologic carbon cannot exceed the rate at which the deep ocean and the terrestrial carbon pools are absorbing the carbon dioxide.

Atmospheric chemistry is the principal determinate of the concentration of other greenhouse gases. First, there are gases like methane that have a natural sink in the atmosphere. For these gases, stabilization of their concentration implies that the emission rate not exceed the rate of their destruction in the atmosphere. While methane leads a very active life in the atmosphere, unlike CO_2, its concentration can be stabilized with constant emissions. Other gases, like the perfluorocarbons, have no natural sinks in the atmosphere. For these gases, the concentration just keeps rising as a result of the emissions and the only way, on the timescales of interest, that their concentration can be stabilized is by eliminating emissions altogether. All of these gases, it should be noted, have a much larger per molecule impact on the greenhouse effect than does carbon dioxide. Finally, the greenhouse story would not be complete without reference to aerosols and dark particles. These are short-lived constituents of the atmosphere, whose combined direct and indirect effects are potentially very large and are presently very uncertain—even as to the sign of their impact on radiative forcing. Their lifetimes in the atmosphere are short, less than a year, yet the stream of emissions, such as in the form of sulfur aerosols, can have a large effect. In the case of sulfur aerosols, that effect could be to cool the surface of the Earth. Technologies that reduce sulfur emissions could thus lead to net warming, simply by reducing the amount of cooling they had previously afforded. But, unlike other well-mixed greenhouse gases, which operate through relatively uniform changes in the Earth's energy balance, the effects of aerosols are highly regionalized.

With this background, it is easier to see the challenges faced by our technological revolution. First, not all emissions are equally susceptible to mitigation. Simply banning the production of the long-lived greenhouse gases will stabilize their concentration in the atmosphere.

This has been the primary strategy for ozone-depleting substances controlled by the Montreal Protocol and its subsequent amendments. However, until such a ban is achieved, the production and subsequent release of these compounds will create a floor under the ability to stabilize the entire market basket of greenhouse gases. If the goal is to stabilize at a particular level of enhanced greenhouse effect, rather than just treating the gases individually, then our inability to control the long-lived gases puts added pressure on efforts to mitigate other greenhouse gases.

The picture is complicated still further by the fact that some gases, such as methane, have a variety of natural emission sources as well as those, such as mining and gas pipeline leaks, that are the direct consequence of human activity. These natural sources of methane may in fact be perturbed by changing climate. For example, the thawing of the tundra due to global warming may lead to increased methane emissions from Polar Regions. Rising methane emissions would increase concentrations in the Earth's atmosphere, adding to the impact on the global greenhouse effect in a positive feedback effect. This would again cut into the allowable emissions of carbon dioxide from energy generation and other sources.

Similarly, human activity has created some collateral sources of CO_2, such a coal seam fires, which have proven difficult to control. While these fires do occur naturally, they also increase in number as a result of mining, and will serve as yet another hard to control source of greenhouse gases. The continued emission of carbon dioxide from difficult to control sources affects both of the carbon dioxide emissions budgets described above. Specifically, they use part of the budget of total carbon dioxide that charges the atmospheric concentration up to the target stabilization level, and they also consume part of the global emissions budget once the stabilization level has been reached. If the magnitude of the difficult to control emissions proves to be large, the controllable emissions will have to be brought to lower levels even faster, or stabilization goals will have to be raised.

Second, technologies are not perfect, and the effectiveness and durability of carbon storage provides an appropriate example. Some scenarios show that an economically viable form of deep geological storage might lead to the disposal of hundreds of billions of tons of carbon in repositories by the end of the twenty-first century. If that occurs, the

technology has several places where carbon dioxide may still enter the atmosphere. First, carbon capture may not be complete. There may be carbon dioxide leakage from the processing of the gas or its transportation. Further, undetected imperfections in the intended repository and its confining cap rock could lead to leakage of the carbon dioxide from its intended final home. While there is considerable confidence that these releases would be small, they would have to be made up by even further reductions in controllable emissions.

Third and finally, the adoption of technologies may not be complete. While there is room for a declining amount of carbon emissions in any stabilization scenario, managing this global 'resource' will be challenging. The original allocation will raise a host of issues, including potentially incompatible equity and efficiency concerns, dispensation for the least developed nations, allowances or grand-fathering for particular sectors, etc., every one of which could affect different technologies' rate and scale of penetration. Compliance with any allocation arrangement will be another matter. The inevitable cheating by actors ranging from individuals to nations (the "free rider" problem discussed earlier), will be facilitated by a large stock of discarded, and therefore inexpensive, fossil fuel consuming devices. Widespread use of these devices could quickly consume any year's allowable emissions.

Those nations that assume the responsibility for the bulk of greenhouse gas mitigation need to be mindful that all three of these factors may require that their efforts will have to achieve near-zero emissions much faster than ideal circumstances might allow.

The need for development, demonstration of commercial viability, and large-scale deployment of technologies which are both non-emitting and least-cost is great. The magnitude of the change that the technology revolution will require is extraordinary. During the twenty-first century, technologies that currently are either non-existent or bit players in the global energy system must be deployed on a massive scale. This transformation must be rapid enough to keep climate change within 'safe' bounds and at the same time not so rapid as to induce unacceptable economic burdens. We frequently liken this challenge to turning the Wright Flyer into a 747, without landing. The effort will be a blend of inspiration and perspiration.

Notes:

1. See for example the review of this literature in J. Alcamo et al., "An Evaluation of the IPCC IS92 Emission Scenarios," in *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios*, eds. J.T. Houghton et al. (Cambridge: Cambridge University Press, 1995); N. Nakicenovic and R. Swart, eds., *Special Report on Emissions Scenarios* (Cambridge: Cambridge University Press, 2000).

2. J. Leggett et al., "Emissions Scenarios for the IPCC: An Update." in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, eds. J.T. Houghton, B.A. Callander, and S.K. Varney (Cambridge: Cambridge University Press, 1992).

3. Nakicenovic and Swart, eds., *Special Report on Emissions Scenarios*.

4. United Nations, *The United Nations Framework Convention on Climate Change* (New York: United Nations, 1992). The Convention has as its goal the stabilization of the concentration of greenhouse gases at a concentration that would avoid dangerous anthropogenic interference with the climate system.

5. The size of the gap varies with both the reference scenario and the concentration. Cumulative emissions over the twenty-first century must be reduced from between 175 billion tons of carbon relative to the IS92a case when the stabilization concentration is 750 parts per million to 1160 billion tons of carbon for the 350 parts per million case.

6. See IPCC Working Group III, *Workshop on Carbon Dioxide Capture and Storage*, Proceedings of a Workshop held in Regina, Canada, 18-21 November 2002, available at [ftp://ftp.ecn.nl/pub/www/library/conf/ipcc02/ccs02-pb.pdf].

7. Of course, even a mere million tons of carbon released in a confined area could be locally disastrous, even as it would go unnoticed at a global scale.

8. J. Edmonds et al., "Stabilization of CO_2 in a B2 World: Insights on The Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies," forthcoming in *Energy Economics*, Special Issue, (2003), eds., J. Weyant and R. Tol.

9. J.A. Edmonds et al., "The Potential Role of Biotechnology in Addressing the Long-term Problem of Climate Change in the Context of Global Energy and Ecosystems," in *Greenhouse Gas Control Technologies*, eds., J. Gale and Y. Kaya (Amsterdam: Pergamon, 2003), pp. 1427-1432. [PNNL-SA-37370].

10. There is a body of literature that argues the contrary. See for example, United States Department of Energy, *Least Cost Energy Strategy Report* (Washington, DC: USDOE, Office of Policy Planning and Program Evaluation, 1995). Here the argument is that market imperfections lead to inefficient allocation of resources by markets, and that intervention is required to obtain a truly efficient allocation of economic resources. However, it is not clear what the consequence would be if all markets in all sectors of the economy were made efficient. Consider, for example, shifting from a private to social discount rate for all investments. The supply of loadable funds is generally taken to be price-inelastic, and therefore using a social rather than a private discount rate throughout the economy merely redistributes investments throughout the economy and raises the market interest rate, and its effect on emissions is unclear.

11. See for example, L.R. Cohen and R.G. Noll, *The Technology Pork Barrel* (Washington, DC: The Brookings Institution, 1991).

12. We have employed the MiniCAM model described in J. Edmonds et al., "Stabilization of CO2 in a B2 World," and the A1G scenario described in Nakicenovic and Swart, eds., *Special Report on Emissions Scenarios*.

13. President's Committee on Science and Technology, *Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation*, Panel on International Cooperation in Energy Research, Development, Demonstration and Deployment (Washington, DC: Executive Office of the President, Office of Science and Technology Policy, June 1999), available at [http://www.ostp.gov/html/P2E.pdf].

14. See J. Gale et al., "Demonstrating the Potential for Geologic Storage of CO_2: The Sleipner and GESTCO Projects," *Environmental Geosciences* 8, no.3 (2001), pp.160-165.

15. W. Chandler et al., *Climate Change Mitigation in Developing Countries: Brazil, China, India, Mexico, Turkey, and South Africa* (Arlington, VA: Pew Center on Global Climate Change, 2002).

16. J. Gillis, "New Outlet for Venter's Energy: Genome Maverick To Take On Global Warming," *Washington Post*, 30 April 2002, p.E1.

17. S. Rayner and E. Malone, "Ten suggestions for policymakers," in *Human Choice and Climate Change, vol.4*, eds., S. Rayner and E. Malone (Columbus, Ohio: Battelle Press, 1998).