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Energy and technology lessons since Rio☆

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ABSTRACT

The 1992 Framework Convention on Climate Change created the basic international architecture for addressing climate change. That treaty was negotiated at a time when the research literature examining emissions mitigation and the role of energy technology was relatively limited. In the two subsequent decades a great deal has been learned. The problem of stabilizing the concentration of greenhouse gases in the atmosphere has proved far more difficult than envisioned in 1992 and the role of technology appears even more important when emissions mitigation strategies are co-developed in the context of multiple competing ends.

1. Introduction

In 1992 the issue of climate change was new to the political process. Negotiators were heady with success of the Montreal Protocol to control stratospheric ozone depleting substances, which opened for signature in 1987 and entered into force in 1989.[1] With the Montreal Protocol the international community addressed a global atmospheric problem. In 1992 it seemed like climate change might be just another global atmospheric problem and might be amenable to a relatively rapid solution. But, while the Rio Treaty, officially the Framework Convention on Climate Change (FCCC; United Nations, 1992), was successfully negotiated and entered into force in 1994, it differed sharply from the Montreal Protocol in that it had neither clear, specific manageable objectives, nor enforcement mechanisms. Those were left for a set of subsequent meetings referred to as the Conference of the Parties (COP) to hammer out. Those details have proven far tougher to work out than the framers of the FCCC could have imagined in 1992.

The objective of the FCCC has held up rather well over the course of the past decade despite the rapidly evolving state of scientific understanding, though the same cannot be said for progress toward meeting that objective. "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (FCCC, Article 2)

Since climate depends on concentration levels of greenhouse gases, as opposed to emissions rates, which are effectively interchangeable for conventional air pollutants, the FCCC focus on greenhouse gas concentrations seems well placed. What was not as well understood in 1992 was the implication of that focus on greenhouse gas concentrations for global energy and economic systems. As we will discuss shortly, stabilization of the concentration of CO_2 implies dramatic changes to the

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[1] There were, of course, special circumstances that made the Montreal Protocol and its successful implementation possible. First, potential economic consequences were limited to a relatively narrow product line of a single sector, chlorofluorocarbons (CFCs). More importantly Dupont had developed a substitute for CFCs. This meant that the economic cost of implementing the protocol was relatively small, making agreement relatively easy, at least compared to climate change emissions mitigation (Benedick, 1998; DeSombre, 2000).

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global energy system. Yet the global political system has proved unable to put in place measures that could be expected to produce the dramatic changes to the global energy and economic systems. There seems little prospect of a grand global agreement along the lines of an Ozone Protocol in the near future. This stands in ironic contrast to the increasingly ambitious goals articulated by the political process. The Copenhagen Accord recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius." (UNFCCC, 2009, P.1) This in turn can be translated into a variety of long-term targets, all of which imply dramatic reductions in global emissions.

Nevertheless, a great deal has been learned in the decade since the FCCC was negotiated that can ultimately be applied to the development of cost-effective strategies to control the concentration of greenhouse gases in a world, which is simultaneously pursuing multiple interconnected goals and objectives. We refer to the present world with its multiplicity of actors, objectives, and instruments as a "Mosaic World" (Flannery, 2009).

The remainder of this paper contains observations, drawn from research that was undertaken since the 1992 FCCC. The intent of this paper is not to provide a text book for developing a set of mechanisms for limiting global greenhouse gas concentrations. Neither does it contain a specific technical proposal for either domestic or international political consideration. The goal of the paper is much more modest. Rather, it is to recount some of the lessons that have emerged in the post FCCC years, drawn from work undertaken at the Joint Global Change Research Institute's Global Energy Technology Strategy Program. This body of research takes a strategic perspective on the problem of stabilizing the concentration of greenhouse gases and uses that perspective draw inferences for near-term decisions. Many of these lessons, none of which were appreciated in 1992, have passed from the realm of the controversial into the realm of common wisdom, though it is doubtful that the implications of some of the most basic of these principles are in reality commonly understood.

The GTSP has not progressed in isolation from the rest of the scientific community. It has benefited from and contributed to a broader and deeper literature on the role of energy technology in addressing climate change. In fact, many of the core lessons emerging from the GTSP are consistent with core lessons growing out of other literature as well. Researchers such as Hoffert et al. (1998, 2002), Caldeira et al. (2003), Pacala and Socolow (2004), Montgomery and Smith (2007), Green et al. (2007), Barrett (2009), Galiana and Green (2009, 2010) have all made significant contributions to understanding the role of energy technology in stabilizing CO_2 concentrations.

2. Stabilizing the concentration of greenhouse gases requires profound changes for the global energy, land and economic systems

Several features make climate change distinctly different than issues with which human societies have dealt in the past. Unlike conventional local and regional pollution problems like acid deposition, for example, all emissions, from all sources, everywhere in the world determine the concentration and therefore no single country, no matter how large, can either control the concentration of greenhouse gases or capture the benefits from emissions mitigation. This characteristic is similar to the situation for stratospheric ozone depleting substances. Two additional characteristics make climate change fundamentally different from all other previous environmental problems. The first is the intergenerational time scale. The concentration of CO_2 depends not only on all emissions from all sources everywhere, but that it also depends on emissions from all sources over all time. Thus, not only can no single nation capture all of the benefits of its mitigation actions, but also no single generation of the Earth's population can capture all of the benefits from its mitigation actions.

Carbon dioxide (CO_2), the most important greenhouse gas emitted by human activities, is only removed from the carbon cycle (atmosphere–ocean–land system) over millions of years. Thus, the combustion of fossil fuels reintroduces carbon, which was removed on million-year time scales, back into the more rapidly circulating carbon cycle. That reintroduction means that carbon builds up in the atmosphere and oceans and that on century time scales will not disappear from the system. That is not to say that nature will not take some of the carbon released into the atmosphere and move it to oceans, but some fraction of fossil fuel CO_2 emissions will reside for centuries in the atmosphere with much of the remainder accumulating in oceans. And, because CO_2 is acidic, the transport of carbon from the atmosphere to oceans may dampen the pace of climate change but at the expense of ocean acidification. (see Riebeek, 2001 for more detail and further readings.)

The second characteristic that sets climate change apart from other environmental issues with which human societies have grappled is the unprecedented scope of human activities involved in emissions. The two major sources of CO_2 emissions are fossil fuel use and land-use change. Fossil fuels account for most of the world's energy use. The expanded availability of energy is essential to economic growth and development and to meeting the combined challenges of human welfare, and energy security. The other major source of carbon emissions to the atmosphere is land-use change. Thus, controlling emissions carries implications for virtually everything that humans do.

Fig. 1 illustrates the degree of change to the global energy system that would accompany limits to greenhouse gas emissions associated with even relatively modest (compared to, for example, the Copenhagen Accord) limits on greenhouse gas concentrations.[2]

The reference scenario in Fig. 1 shows one possible evolution of the global energy system in the absence of policies and measures to limit greenhouse gas emissions. In the absence of such measures local and regional environmental issues might be expected to induce substantial increases in the utilization of renewable and nuclear energy but fossil fuel use could also be anticipated to expand. The attractive features of fossil fuels, such as high energy density, portability, and cost in conjunction with the availability of local and regional pollutant emissions control technologies, imply the potential for continued dominance of fossil fuel forms in the global energy system throughout the 21st century.

In contrast the right panel of Fig. 1 shows the results of a numerical experiment in which the same population, economic growth, and technology developments as in the left panel were combined with a limit on greenhouse gas emissions sufficient to stabilize radiative forcing at 4.7 Wm^{-2}. The figure shows an accelerating use of non-emitting technologies. Technology selection in the control scenario employed two important assumptions. First, there were no limits on technology selection and deployment. Importantly nuclear power was assumed to be available as was bioenergy and CO_2 capture and storage in addition to end-use energy efficiency technologies and renewable energy forms. All expand their deployment in the control scenario.

The finding that many technologies contribute to emissions mitigation in a world in which they are allowed is general. See for example, Clarke et al. (2007). The absence of a dominant technological solution to control emissions is sometimes referred to as the "No Silver Bullet" result. See for example, Schneider, 2009. While one can never rule out the possibility of the future emergence of a single technology capable of stabilizing the concentration of greenhouse gases in the atmosphere, none has yet come to light. This result has not diminished the popularity of the idea of a "silver bullet" technology. Almost every technology has proponents that immediately after acknowledging that there is "no silver bullet," go on to claim that their technology is the solution to the problem. Yet there is no evidence that the deployment of any single technology—not wind, not solar, not end-use efficiency, not nuclear—

[2] The Copenhagen Accord does not fix a limit on radiative forcing. However, Clarke et al. (2009b), among others have estimated that limiting radiative forcing to 2.6 Wm^{-2} is approximately consistent with limiting global mean surface temperature change to less than two degrees centigrade.

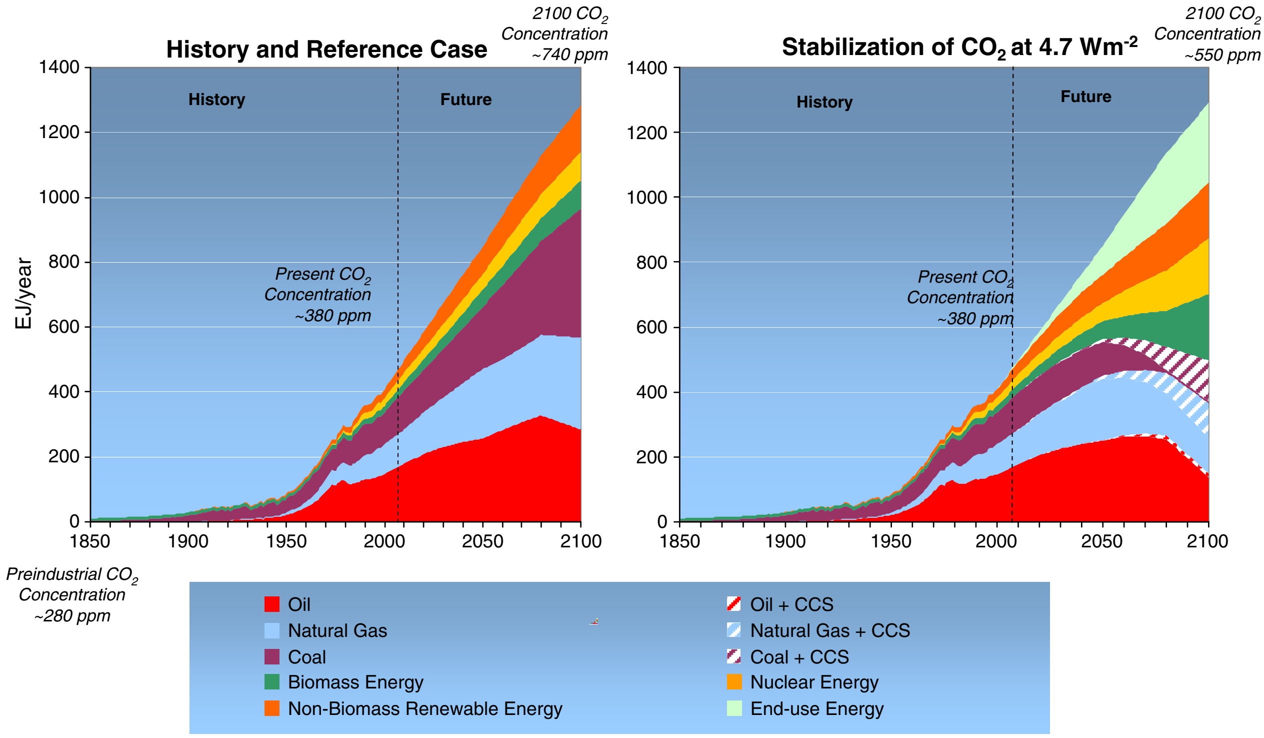

Fig. 1. The potential evolution of the global energy system under a reference scenario (left) and an alternative scenario in which radiative forcing is limited to 4.7 Wm^{-2} (650 ppm equivalent CO_2 concentration, CO_2-e).[9] An equivalent CO_2 concentration is computed by first estimating the effect on radiative forcing of all greenhouse gases and short-lived species. The level of atmospheric CO_2 ALONE that would produce that level of radiative forcing is then computed. This level of CO_2 is said to be the "equivalent CO_2 concentration." In general the equivalent CO_2 concentration (CO_2-e) is higher than the observed concentration of CO_2 since CO_2-e includes contributions to radiative forcing from other sources. Source: Edmonds et al., 2007.

is the sole or even dominant means by which emissions would be limited if all technology options were available.

3. Technology development dramatically reduces emissions even without policy intervention

Technology, and in particular energy technology, is central to addressing greenhouse gas emissions. As noted earlier, energy technology is central to not only CO_2 emissions, but also to economic development and wellbeing. The reference scenario reported in Fig. 1 produces emissions that result in a CO_2 concentration of 740 ppm by the year 2100.[3] While that concentration is more than two-and-a-half times preindustrial levels, that scenario incorporates substantial emissions reductions from assumed improvements in technology.[4] Emissions and concentrations are shown in Fig. 2.

Fig. 2 shows three contrasting scenarios. The central scenario plots the reference scenario carbon emissions (left panel) and concentrations (right panel) for the energy scenario displayed in Fig. 1 (left panel). The low emissions path plots carbon emissions associated with the right panel of Fig. 1. The CO_2 concentrations are plotted on in the right panel of Fig. 2, which for the low scenario never exceeds 550 ppm. We contrast these two scenarios with a scenario in which technology is frozen at 2005 levels. The idea is not that this is a plausible scenario, but rather to illustrate, in terms of CO_2 emissions and concentrations, how much technological change is already in a typical reference scenario. Fig. 2 shows that carbon emissions in the year 2100 are reduced by more than half going from the "Frozen Technology" scenario to the GTSP II Reference scenario.[5] Concentrations are correspondingly reduced from more than 1100 ppm to 740 ppm. The steady improvement in technologies assumed to proceed over the course of the 21st century does not stop carbon emissions and CO_2 concentrations from rising. But, it substantially tempers the rise. The rate and character of future technology improvements are therefore extremely important in shaping future carbon emissions and CO_2 concentrations.

As Pielke et al. (2008), and Galiana and Green (2009) have shown, the improvements in energy technology needed to achieve the reference scenario, to say nothing of the reference scenario, are not consistent with trends, at least prior to the recession of 2008. Since there is no guarantee that the reference scenario will be forthcoming, the challenge of emissions mitigation may be even more daunting than those discussed in the previous if reference technology developments go unrealized.

The validity of the "reference" scenario will likely never be known. First, there is only one unfolding of events and the assumptions that create the reference scenarios will almost certainly go unrealized. Population and economic growth will almost certainly turn out to be different than assumed in the reference scenario. The policy assumption that there will be no climate policy for the remainder of the century is a strong one. There are no guarantees that the technologies that are assumed available in the reference scenario will actually materialize. Others have also observed that stabilizing greenhouse

[3] Preindustrial CO_2 concentrations in the atmosphere were approximately 280 parts per million (ppm). By the year 2010 the concentration had risen to 388.5 ppm (Blasing, 2011).

[4] Specific assumptions underlying the reference scenario are detailed in Edmonds, et al. (2007). Clarke, et al. (2007) provides additional details for an updated reference scenario. A complete set of detailed assumptions that characterize the reference scenario can be found at http://wiki.umd.edu/gcam/index.php?title=Main_Page. The model, source code, and underlying data base for the most recent reference scenario can be obtained by going to http://www.globalchange.umd.edu/models/gcam/download/.

[5] See Edmonds et al. (2009) for a more complete description of the GTSP II Reference scenario. The scenario is derived using assumptions for population and economic growth that are similar to others in the literature Clarke et al. (2007). It also assumes rates of technological improvement for energy technologies that continue historical trends.

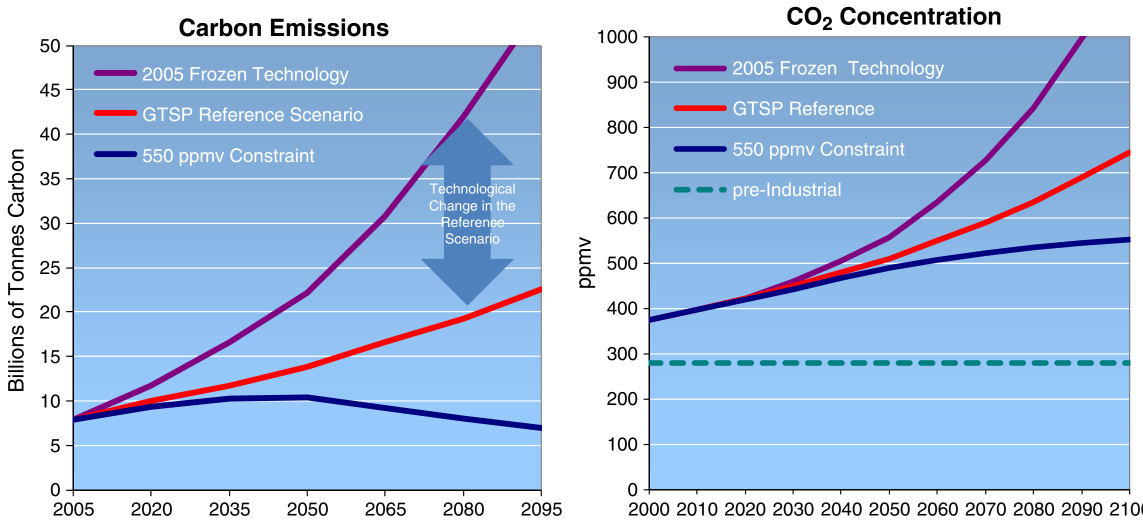

Fig. 2. CO_2 emissions and concentrations reference scenario, frozen technology, and 550 ppm CO_2 stabilization.

gas concentrations requires significant advances in energy technology, beyond that assumed in reference scenarios. See for example, Green et al. (2007) and Pielke et al. (2008).

Almost every technology available in the year 2005 is assumed to be available with enhanced performance by the year 2100. Because the global energy-economic system is highly non-linear, it is impossible to prescribe the contribution individual technologies to the reduction in emissions between the "2005 Technology" and "Reference" technology scenarios. That having been said, it is clear that both energy demands and carbon emissions benefit substantially from improvements in end-use energy intensity.[6] In addition, renewable energy technologies improve and make up an increasing share of the energy mix reducing emissions. Bioenergy, for example becomes the largest agricultural activity on the Earth by the end of the century. But, improvements in the performance of familiar technologies such as coal, gas and nuclear power generation contribute substantially to emissions reductions between the 2005 technology scenario and the reference technology scenario. One profound implication of stabilizing CO_2 concentrations is that emissions must eventually peak and decline toward zero. Since some fraction of fossil fuel emissions will remain in the atmosphere for a thousand years or more, CO_2 concentrations will continue to rise for millennia unless eventually emissions decline toward zero. The need to drive CO_2 emissions ever lower stands in sharp contrast to the challenge of conventional pollutants, whose concentrations are stabilized when their emissions are stabilized. (See for example Wigley et al., 1996).

4. Technology alone is not the "silver bullet"

In the previous section we make the case that technology is a critical determinant of future carbon emissions and CO_2 concentrations, even in the absence of policies and measures to limit emissions or concentrations. In this section we want to argue the count point—that as important as technology is to addressing climate change, technology alone is not necessarily the "silver bullet."

Technology development and deployment will mitigate carbon emissions, but it will not necessarily costlessly reduce them to zero. McJeon et al. (2011) examined 348 combinations of technology developments over 12 technology classes with a range of performance improvements posited for each over the course of the century. The range of emissions associated with the range of potential future technology development assumptions with reference population and economic growth assumptions based on those in the scenario displayed in Fig. 1 is plotted in Fig. 3.

Two results are striking. First, the range of technology assumptions leads to a relatively large range of annual emissions in the year 2100 with the best technology development paths reducing to the point of emissions stabilization by the end of the century. Second, stabilization of emissions does not lead to stabilization of concentrations. Hence, even with the best technology development assumptions in the study, concentrations continue to rise, even when technology development is rapid.

That having been said, technology developments that revolutionize the energy system are possible. As we argue in the later section on the importance of investments in basic science, the second half of the 21st century will almost certainly be characterized by a suite of technologies that have evolved in ways that we cannot presently foresee. It is quite possible and perhaps even likely that major energy technology systems will be deployed for which we do not presently have a name. These technology developments will be important and even if they do not lead to ceiling on CO_2 concentrations in this century, they could be extremely important in limiting the cost of limiting CO_2 concentrations.

In the final analysis, we see relatively little reason to conclude that absent measures to limit CO_2 emissions that CO_2 emissions will peak and decline toward zero based on market forces alone.

5. Stabilizing CO_2 concentrations means rising marginal costs

One of the unavoidable implications of stabilizing the concentration of CO_2 is that real marginal cost of carbon reductions will rise rather than fall over time, even with technological improvements. The marginal cost of carbon is the cost of reducing the last ton of CO_2 in the mitigation regime. Emissions mitigation can be achieved in many ways, each of which will have its own unique time path for the marginal cost of emissions reduction. The marginal cost could show up as a carbon tax or the price of an emissions allowance, but it could also be hidden from view as for example through the additional costs accompanying a regulatory policy. Even when an explicit carbon price exists, it can be manipulated to be lower, at the cost of higher social costs, as first shown by Baumol and Oates (1971).

[6] Energy intensity is measured as the ratio of energy use to underlying activity level. For the economy as a whole energy intensity is measured as the ratio of primary energy to gross domestic product (GDP). For individual sectors physical units are sometimes used, for example in passenger transport the ratio may be final energy consumption to passenger kilometers. This measure changes in response to two broad categories of pressures: energy technology and shifts in the mix of energy using activities.

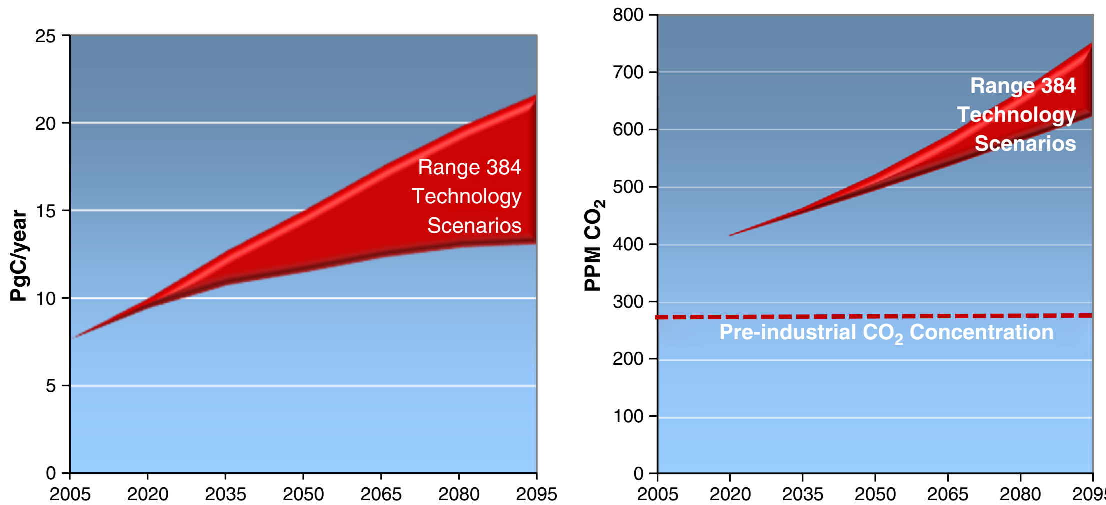

Fig. 3. Range of emissions associated with 384 technology development scenarios.

Also, see Goulder and Parry (2008). Nonetheless, the real marginal cost of carbon mitigation, which is the cost of the last (most expensive) ton of carbon removed from the global emissions stream, will rise over time as long as emissions are driven ever lower.

Carbon emissions come from an extremely broad array of sources. The challenge of driving global carbon emissions toward zero, as required to stabilize CO_2 concentrations, means that an ever broader set of human activities must be engaged in emissions mitigation. A rising carbon price creates the incentive for an ever widening set of activities to undertake emissions mitigation rather than pay for the privilege of emitting.

The rising price of carbon is therefore not about a single technology or even human activity, but rather about the necessity to continuously broaden the set of mitigating activities, beginning with those for which emissions mitigation is easiest and least expensive and progressing to ever more challenging activities. In fact, as emissions continue to decline, they are paid by an ever smaller share of the economy.

This upward progression in the marginal cost of emissions mitigation is illustrated in Fig. 4, which reports carbon prices for four alternative CO_2 stabilization concentrations assuming cost minimization. This effect is found by many research studies. See for example, EMF 22, Clarke et al. (2009b), and the U.S. scenarios reported in the Synthesis and Assessment Product 2.1a (Clarke et al., 2007) and the IPCC Fourth Assessment Report, IPCC (2007).[7] Note that the carbon price rises less rapidly as it approaches the steady-state limit on the CO_2 concentration. Once the CO_2 concentration approaches its upper limit, the rate of emissions reduction is determined by the rate at which carbon is removed from the atmosphere and absorbed by oceans, though that same atmospheric carbon removal into oceans leads to increased acidification in the oceans even as it removes CO_2 from the atmosphere.

The "true" price of carbon is the cost to society of reducing the last ton of emissions. Costs are at their lowest where it is no longer possible to reduce costs by substituting mitigation either across time, place, or human activity. That is, the total cost of stabilizing CO_2 concentrations is minimized when the cost of the last ton of reduction is equal everywhere, and when the present discounted price of the next ton is equal across time. A common global carbon price achieves this outcome across nations and human activities. A common global carbon price that rises at the rate of interest (plus the average rate of carbon removal of from the atmosphere) achieves this outcome over time.

There are many ways to lower the nominal price of carbon price, though all have the unfortunate side effect of raising the real marginal cost of CO_2 emissions mitigation that society bears. By using inefficient regulatory policies to control emissions it is possible to lower the price of carbon in those sectors where carbon was controlled through price-based measures such as carbon taxes or cap-and-trade while increasing the overall cost to society. The reason was that regulatory policies ended up having a different cost per ton than the price-based policies and such cost differentials create the opportunity to reduce total cost by reducing mitigation in high-cost activities and increasing mitigation in low-cost activities. This result is reported in for example, Aldy and Pizer (2009) and Morris et al. (2010).

In general, the less comprehensive a mitigation strategy is, the higher will be the cost of achieving that goal, though as Aldy and Pizer (2009) point out, omission of some sectors, e.g. power generation, has a larger effect than the omission of others, e.g. buildings.

6. All the carbon counts

CO_2, the most important of the anthropogenically emitted greenhouse gases, is both long-lived in the atmosphere and oceans and globally well-mixed in the atmosphere. These characteristics are defining characteristics of the global climate problem. As a consequence of these characteristics, no single nation or region or sector of the economy can determine the concentration of CO_2 in the atmosphere. All carbon emissions become part of the Earth's fast carbon cycle and therefore contribute to radiative forcing of the Earth's atmosphere. Policies that attempt to control emissions by reducing some subset of the economy's emissions, or some subset of the world's regions, are invariably more expensive than policies that pursue emissions mitigation as a common Earth enterprise.[8]

As we have argued, the world is not perfectly efficient, nor is it single-minded. And, to make matters even less convenient, the world is not linear. Human activities interact with each other. So, the likelihood that human societies will ever be able to install a regime that achieves all of society's goals at minimum cost is vanishingly small. A

[7] This result was first reported by Hotelling (1931) and then later generalized to the stabilization of greenhouse gas concentrations by Peck and Wan (1996).

[8] That is because the first principle of cost minimization is to undertake emissions mitigation up to the point where the discounted cost of reducing the last ton of carbon in the atmosphere is the same, regardless of where or when it is undertaken. In other words, there are no opportunities to reduce costs by doing a bit less of a relatively expensive emissions mitigation activity and a bit more of a relatively less emissions mitigation activity. See for example, Tol et al. (2008) for a clear articulation of this point.

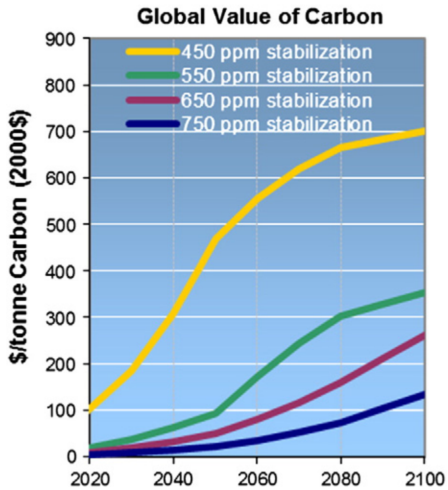

Fig. 4. Carbon price path for alternative CO2 concentration stabilization levels assuming a common global carbon tax.

more practical question might be: Are there some strategies that are significantly more expensive than others and might be avoided?

Many proposals have sought to reduce emissions in the sector with the largest emissions, power generation in isolation from other emissions sources. The problem with this strategy is that limiting the emissions of power generation in isolation from end use activities, creates a set of countervailing incentives. Limits on emissions in the power sector in isolation from the end-use sectors that it serves, raises the cost of power generation to end users of energy while leaving the cost of fossil fuels unchanged. It thus, creates an incentive to substitute direct use of fossil fuels for power. So, the ironic result is that end users shift away from power, which is decarbonizing, toward direct use of fossil fuels. Edmonds et al. (2006) showed that this can be an extremely expensive strategy for reducing CO_2 emissions. Edmonds, et al. compared the cost of limiting carbon emissions in a comprehensive program to the total cost of achieving the same cumulative emissions reductions by reducing emissions from power generation alone. The latter was a factor of five larger than the former.

Wise et al. (2009) compared two identical policies each of which limited the concentration of CO_2 in the atmosphere to levels ranging from 450 ppm to 550 ppm. One was achieved with a policy that taxed all carbon emissions equally regardless of the source of emissions—fossil fuel and industrial emissions or land-use change emissions. The other policy only penalized fossil fuel and industrial emissions. The latter was between two and three times more expensive than the former. The reason is that by ignoring land-use change emissions there is no incentive to increase forested areas. More importantly, the use of bioenergy, which is treated as a renewable energy form in the analysis, is encouraged by the carbon tax. The consequence is that the latter policy regime experiences greater deforestation and higher costs of limiting CO_2 concentrations to a fixed level.

Delayed participation in emissions limitation regimes by important emitting regions of the world similarly increases society's cost of any given concentration limit. The implications of partial regimes have been studied by numerous groups, for example Richels et al. (1996). It was in part the subject of several Stanford Energy Modeling Forum studies including EMF 22 (Clarke et al., 2009b). These studies have been summarized in assessments such as IPCC (2007).

More recently, numerical experiments reported by Edmonds et al. (2009) showed that the delay can even adversely affect the delaying regions. Edmonds et al. (2009) compared an idealized emissions mitigation regime with a regime in which some regions of the world joined the coalition only after a period of time, which varied with per capita income. Thus, the lower per capita income, the longer the region refrained from reducing emissions. Eventually all regions were assumed to enter the mitigating coalition. As one might expect the longer the delay in accession on late entrants to the coalition, the higher the total cost to society. Also, as might have been anticipated, delay in joining the emissions mitigation coalition always resulted in a shift in the share of total costs borne by first-mover regions. But, what might not have been expected is that under some circumstances, present discounted costs experienced by the late entrants themselves were actually higher than they would have been had those regions participated in a coalition that controlled emissions within a unified, cost-minimizing regime from the outset to the prescribed level.

7. Technology improvements are more important in a mosaic world

There is little evidence that the world is moving toward the adoption of a comprehensive emissions mitigation regime that will cost-effectively stabilize the concentration of CO_2 and other greenhouse gases. Policies and measures that are in place, such as those of the European Union, tend to be a patchwork of regulatory and price-based instruments, while in other locals emissions mitigation, to the extent that it occurs at all, is a byproduct of a policy aimed primarily at achieving some other goal such as energy security, local air quality improvement or economic prosperity (e.g. the China one-child policy; Greenhalgh, 2008). In fact, the standard economic notion that each policy goal should have a separate policy instrument, the "Tinbergen Rule" (Tinbergen, 1952), is routinely violated in practice (Knudson, 2008). Climate policy is developed and implemented in the context of societies seeking to simultaneously pursue other regional and local ends. This heterogeneous policy environment is sometimes referred to as a "Mosaic World" (Flannery, 2009).

Improved energy technology performance is more valuable in a mosaic world than in an idealized world where marginal costs are equal everywhere and across time. As Edmonds et al. (2012), Clarke et al. (2009a), Hoffert et al. (1998, 2002) and Galiana and Green (2009) showed, the benefit to improved technology can be very substantial (Fig. 5).

8. Basic scientific research is imperative

It is easy to get caught up in the imperative to reduce emissions in the near term. In the near term technology is largely limited to what

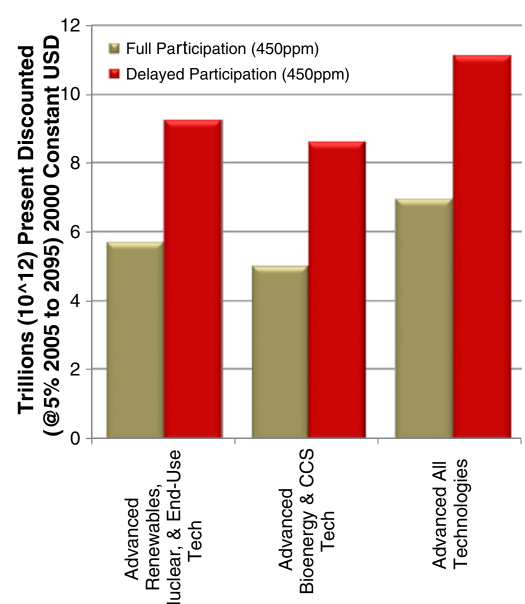

Fig. 5. Reduction in total cost of emissions mitigation from improved technology in an idealized (full participation) and mosaic (delayed participation) world for three alternative technology improvement sets.

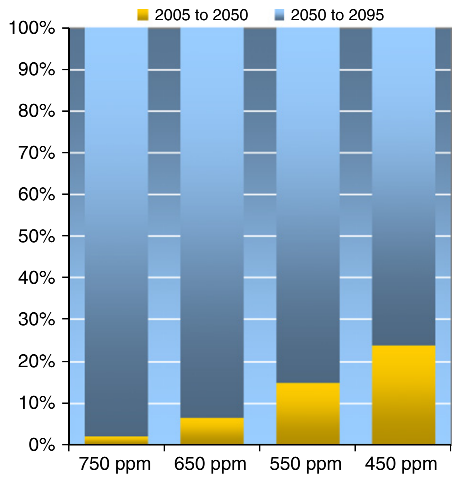

Fig. 6. Fraction of emissions mitigation undertaken in the period 2005 to 2050 as a fraction of total emissions mitigation 2005 to 2095.

is on the shelf. Thus, in the near term emissions mitigation means substituting technologies that are presently available to lower emissions for those with higher emissions and to do so as efficiently as possible.

Yet, we have argued here that climate change is a long-term, global problem in need of both a near-term, tactical approach and a long-term strategic approach. The role of technology therefore should be though about as comprising three elements: deployment of presently available technologies, a strategy for improving existing technologies, and a strategy for laying down the foundations for the creation of technologies that as yet have no name.

The deployment of existing technologies is largely a matter of providing incentives. Economists prefer a price mechanism. The improvement of existing technologies is a more complex matter. It is the place where the roles of public and private sectors meet. But, precisely where they meet is a matter that will likely continue to be debated for the indefinite future. We make no attempt to determine the appropriate boundary between the public and private sectors in the near to midterm R&D, nor the potential perils of getting that determination wrong. That problem is bigger than this paper.

In the very long term, there is no doubt that there is a public goods problem that accompanies the creation of fundamental new knowledge in that the creators of knowledge are unable to capture as private gains all of the benefits that accrue to its creation. As a consequence there is a clear role for the public sector in developing new scientific knowledge. The creation of new scientific knowledge that results in the development technologies that help societies to mitigate and adapt to climate change, represent an additional benefit that needs to be included in the determination of the optimal allocation of resources to the support of basic scientific research.

While most of the focus of climate mitigation is on near-term technology deployment it should be remembered that the bulk of emissions mitigation occurs in the long term. Fig. 6 shows the distribution of cumulative emissions mitigation over the period 2005 to 2095. The fraction of emissions mitigation that occurs in the first half of the century increases as the limit on the CO_2 concentration becomes increasingly severe. However, even when the limit on CO_2 concentrations is limited to 450 ppm less than one quarter of emissions mitigation occur before the year 2050.

The clear implication of Fig. 6 is that emissions mitigation occurs predominantly in the second half of the century. Successful new technologies have the capacity to expand from a small fraction of the market to become a major activity in half a century, Grübler et al. (1999), Grübler (1991), Häfele (1981), Marchetti (1979). This time frame is one in which the benefits of scientific discovery can pay dividends. And as Stiglitz (1999) argues, the knowledge so generated constitutes a global public good.

Unfortunately, there is substantial evidence that energy R&D and particularly basic science, and early technology research and demonstration are funded below optimal levels (Dooley, 1998; Kammen and Nemet, 2005; Margolis and Kammen, 1999; Nemet and Kammen, 2007). Increased investments in basic science as well as energy R&D holds the potential to deliver improved energy technologies that could pay a substantial role in reducing the cost of meeting greenhouse gas emissions reduction goals.

9. Final thoughts

Stabilizing the concentration of greenhouse gases, the goal set forth in the FCCC two decades ago, remains a relatively sturdy point of reference as nations grapple with the challenge of limiting anthropogenic climate change. That goal, however, has been shown to ultimately imply dramatic changes to the global energy and economic systems. Both technology and policy architectures will play important roles if greenhouse gas concentrations are ultimately to be limited. Technology developments that improve cost and performance of delivering energy services can lead to lower costs stabilizing greenhouse gas concentrations. Further, it is generally true that the better the performance of low and non-emitting energy technologies and the broader the array of such technologies that are available for deployment, the lower the cost of limiting greenhouse gas concentrations. This observation is often captured by the phrase, there is no technology "silver bullet." We also observed that across a wide range of potential technology developments greenhouse gas concentrations are not stabilized in the absence of policies that limit emissions of greenhouse gas concentrations. That is, technology itself is not a "silver bullet." It is hard to imagine a world that stabilizes greenhouse gas concentrations through technology and changes in consumer preferences alone. Technology deployment strongly interacts with the policy environment. And, to the extent that economic cost remains important to the ability of policies to be deployed and to be made increasingly stringent over time—as they must if carbon emissions are ultimately to approach zero—it is important to note that policies that control carbon emissions more comprehensively and within a context that allows marginal costs of emissions mitigation—across time, space, and sector—to be approximately equal will generally deliver emissions mitigation at lower cost. Finally, we note that in contrast to conventional pollution problems with relatively short time scales, the potential for scientific discovery to lead to technology that can play a major role in emissions mitigation is large. The large majority of emissions mitigation from "business as usual" occurs in the second half of the 21st century even when concentration limits are as ambitious as 450 ppm.

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