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An Analysis of a Technology-led Climate Policy as a Response to Climate Change

Isabel Galiana & Christopher Green

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PREFACE

ABSTRACT

We consider a technology-led approach to mitigating CO_2 emissions and stabilizing climate over the course of the 21st century. Our proposed approach would focus effort and commitments on researching and developing effective, scalable, and competitive carbon emission-free energy technologies to displace carbon–emitting ones. Carbon pricing would play two ancillary roles. A low carbon charge ($5.00/t$CO_2$) would be used to finance long-term commitments to energy R&D. Over time, the charge (tax) would slowly rise, doubling every decade, thereby sending a forward price signal to deploy and diffuse technologies as they "reach the shelf". The rationales for a technology-led approach to climate policy rest on: (a) the huge energy technology challenge to stabilizing climate; (b) the lack of readiness of current carbon-emission free energy technologies; (c) the energy intensive nature of growth in populous developing countries, especially in Asia; (d) the economic and political limitations of a carbon pricing-led policy; and (e) the large economic cost of "brute force" mitigation policies.

The paper also addresses a concern about technology policies: they may succumb to factors that generate waste at the expense of good results. The paper proposes a number of means which would enhance the policy's "incentive compatibility". The paper goes on to consider whether in its early stages the technology policy should focus on "enabling" or "breakthrough" technologies, or both. We use three different benefit-cost approaches to evaluate our technology-led proposal. Each approach throws a different light on the relative advantages of a technology-led approach, including the issue of whether there is a chance of limiting global temperature increase to 2°C. The final section of the paper addresses a number of issues including: (i) whether there are parallels to the proposed technology-led program; (ii) why a technology-led approach has not yet been adopted; (iii) why one will eventually be adopted, but probably not before there is another round of target-led, "brute force" policy, failure ; (iv) the relationship between our proposal and other proposals to limit climate change; and (v) the implications of "tipping points".

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The Copenhagen Consensus Center has commissioned 21 papers to examine the costs and benefits of different solutions to global warming. The project's goal is to answer the question:

"If the global community wants to spend up to, say $250 billion per year over the next 10 years to diminish the adverse effects of climate changes, and to do most good for the world, which solutions would yield the greatest net benefits?"

The series of papers is divided into Assessment Papers and Perspective Papers. Each Assessment Paper outlines the costs and benefits of one way to respond to global warming. Each Perspective Paper reviews the assumptions and analyses made within an Assessment Paper.

It is hoped that, as a body of work, this research will provide a foundation for an informed debate about the best way to respond to this threat.

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INTRODUCTION

Evidence mounts that humankind is changing the earth's energy balance. The change in energy balance is attributable to the build-up in the atmosphere of greenhouse gases (GHGs) that partially trap outgoing long wave radiation - that is radiation given off by the earth as a result of absorbing solar (short wave) radiation. There is still some debate as to how much of the change in energy balance has shown up to date in the form of changes in climate-related variables such as the global average temperature and precipitation-evaporation patterns. But there is overwhelming evidence that some GHG-induced change has occurred, as distinct from changes attributable to natural phenomena (solar or volcanic) or factors affecting long term variability in the earth's climate (Solomon, et al, 2007). We also know that at least some (perhaps half) of the imbalance is temporarily hidden--stored in the oceans (Hansen et al, 2005). Almost certainly as the twenty-first century progresses the climatological evidence of human-induced change will mount - and so will the impacts on the environment and vulnerable aspects of the economy and society.

In December 2009, the nations of the world will meet to frame a climate policy to succeed the Kyoto Protocol. Unless there is an epiphany in climate policy thinking, the emphasis will be on **how *much*** to do in the next period, rather than **how *to*** do it. Predictably, the word "targets" will be heard early and often, and used at least an order of magnitude more times than the word "technology". Commitments to "ends" (emissions reductions) will dominate discussion. Little or no consideration will be given to whether the "means" of cutting emissions are sufficient to achieve the emission-reduction "ends". The idea of committing to "means" (actions) rather than "ends" will be far from the Copenhagen imagination, even though such a commitment is likely to be both more credible (Schelling, 1992, 2005) and effective than commitments to "ends" (results). There will be much talk about the need for a price on carbon, and what it can allegedly do, with little consideration of the important things a carbon price cannot do.

This paper attempts to fill a void. It attempts to make a serious case for a technology-led climate policy. The logic is that if ***global*** emissions are to be cut 50% to 80 % by 2050 and 2100 respectively, doing so will require Herculean efforts to: (i) increase energy efficiency/ reduce energy intensity, and (ii) develop the means of producing vast quantities of carbon emission-free energy in the next 50-100 years.

An example gives some idea of the magnitude of the challenge. Suppose by 2100 we wish to reduce **global** emissions by 75% from current levels. Suppose further, that over the course of the 21st century, the "trend" rate of global GDP growth in the absence of climate policy were 2.3%. (We ignore for the moment the effect on GDP of damages produced by climate change.) To achieve the emission reduction target and not lose more than ***11%*** of the cumulative output that would otherwise flow from a 2.3% per annum growth in ***global*** economic activity, would require that by 2100: (i) ***global energy intensity is reduced by two thirds from the level in 2000***, and (ii) ***carbon emission-free energy in 2100 is two and a half times greater*** than the level of ***total*** energy consumed globally in 2000. (In 2000, global energy consumption was ~420EJ/yr, 85% of which was supplied by fossil fuels. Of the carbon-free energy produced, 95% was nuclear and hydroelectric.)

Here is another example. In order to reduce ***global*** emissions by 50% from current levels by 2050 (an oft discussed target) and 80% by 2100, the ***average annual*** rate of de-carbonization of ***global*** output (i.e. the ***rate of decline*** in the carbon intensity of output, or GDP) must be raised from its "historic" (last 30 years) rate of 1.3% to over 4.0%. **Not only must the rate of de-carbonization triple, but most of the increase will have to come from a de-carbonization of energy which "historically" has declined, in global terms, at a 0.3% rate**. Most of the long term decline in the de-carbonization of output is associated with a decline in energy intensity (1.0%), attributable chiefly to improvements in energy efficiency and, to a much lesser extent, ***global*** shifts in the composition of output. **[We shall make considerable use of the rate of decline in the carbon intensity of output (RCIO) later in the paper.]**

The calculations are not a mistake! But for many we suspect they may come as a surprise. They may seem at variance with the conclusions reached by IPCC WG III that the barriers to stabilizing climate are socio-economic and political, but not technological (Metz et al, 2001; 2007). The calculations may also appear at variance with the estimate of the Stern Review that the cost of stabilizing climate is around 1% of GDP (Stern, 2007, 2008).

At the same time, the calculations should not provide solace to those who wish to ignore the climate change threat - which is real. Nor do the calculations suggest that in benefit-cost terms the ***long term*** rise in atmospheric carbon concentration and global average temperature need only be reduced moderately (e.g., Nordhaus, 2008). As controversial as are the Stern Review (2007) estimates that climate change damages range from 5-20% of global world product (GWP), a climate policy that would only reduce the rise in global average temperature from, say, 4.0°C to 3.5°C a century from now ought to convince no one that such a policy reduces substantially the possibility of large potential damages to the global environment and economy. **Nevertheless, the calculations do imply that a new route to emission reductions must be found.**

The calculations suggest, then, that if we are going to do something significant in terms of "stabilizing climate" we will have to rethink ***how*** to proceed. In particular, we need to recognize that the key variables in climate stabilization involve energy technology changes. One set of changes is in the form of very large energy efficiency improvements that could make possible a two-thirds reduction in ***global*** energy intensity in the face of a development process in populace, developing countries that is, and for the foreseeable future will be, energy intensive (Green, 2007; Pielke, et al 2008). The other is in the form of technological breakthroughs that would make possible a vast expansion in carbon emission-free energy.

It is the technology imperative that drives us to propose a climate policy in which research and development are front and center, at least in the initial stages. Given the lags in capturing the total productivity increase of new technologies (diffusion and learning new techniques), it becomes all the more important to act quickly in developing them. **But lest there be any misunderstanding, *this paper is about mitigation, but mitigation in which technology development policies that make deep emission reductions possible are front and center.***

In sum, the paper proposes a technology-led approach to mitigating GHG emissions. Climate change will impose increasing costs, but there are no quick or easy solutions such as those the US Environmental Protection Agency imposed on emitters of sulfur dioxide (SO_2)

or nitrogen oxides. The technologies to achieve SO_2 and NOx reductions were ready and scalable, something that is not currently true of CO_2. Instead for CO_2 mitigation, **the accent is placed on energy technology research, development, and testing.** For this reason we think **the role of carbon pricing should initially be limited to a low (as global as possible to avoid leakages and to ensure broad commitment) carbon tax or fee that is used to finance energy R&D. Over time the tax should be allowed to rise slowly in order to send a "forward price signal" that would induce deployment of effective, scalable, cost competitive technologies as they reach "the shelf" (i.e. become ready to deploy).**

Confronting the proximate cause of climate change via *attempts to directly control emissions* is *defective* for several reasons:

The amount of carbon emission-free energy required to "stabilize" climate is huge -- at least 15 to 20 times more than current levels, almost all of which is supplied by nuclear and hydroelectric.

Alternative energy sources are currently neither ready nor (just as important), as yet, scalable, and in most cases these still require basic research and development

Relying on carbon pricing to cut global emissions substantially is ***neither*** likely to be politically ***acceptable nor*** economically ***time consistent***. Carbon pricing alone, or as the main policy tool, is not an effective means of inducing long term commitments to undertake and pursue endemically uncertain (of success) basic R&D. But as we shall see, carbon pricing has two important ***ancillary roles*** to play.

In the modern world, **energy is a necessity**. In the 20th century, energy consumption increased sixteen-fold. Under the best of circumstances (improved energy efficiency, conservation, and the elimination of wasteful use) global energy consumption will double by 2050 and triple by 2100. Any attempt to reduce carbon emissions by artificially reducing the availability of energy will not be accepted, at least not for long. For energy use to substantially increase while carbon emissions are substantially reduced requires that there must be a suite of good non carbon emitting energy substitutes. Except for nuclear electric, current candidates are, in technological terms, still severely limited (MacKay, 2009).

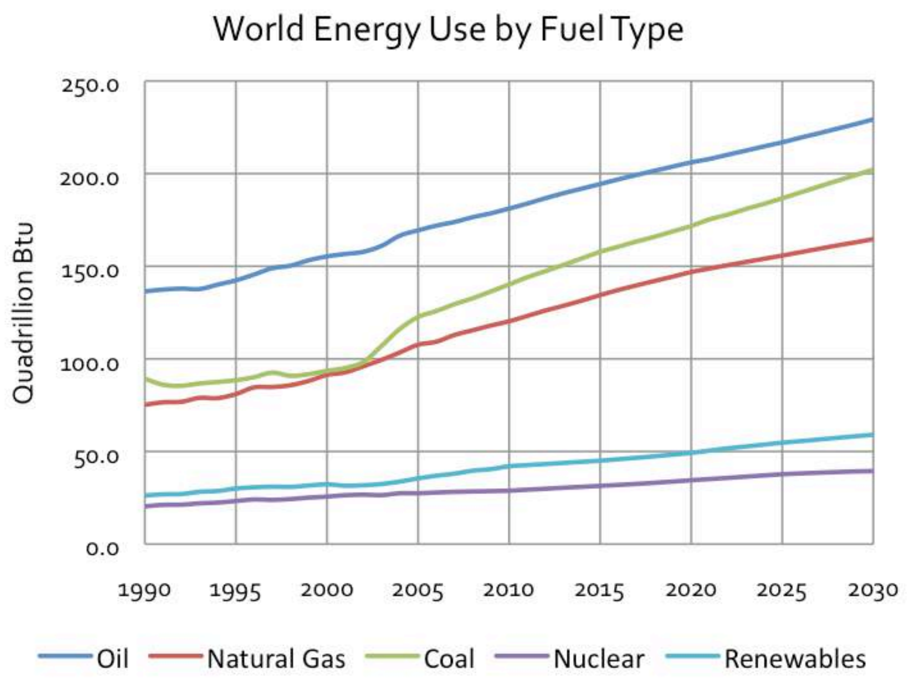
Currently, 85% of global energy requirements are met by fossil fuels. This is so for both technological and economic reasons. Fossil fuels consumption is likely to increase for the next few decades (see Figure 1) and these fuels will continue to be important deep into the current century. By 2050, global energy demand will at least ***double***. To reduce the share of fossil fuels by 50% by 2050 will be a daunting technological task. And even if it could be achieved, it would still leave carbon emissions unchanged from current levels, unless carbon capture and storage (CCS) can be quickly ramped up, itself a daunting task.

On the face of it, attempts to directly control ***global*** carbon emissions will not work, and certainly not in the absence of ready-to-deploy, scalable, and transferable carbon emission-free energy technologies. The technology requirements cannot be wished, priced, assumed or targeted away. A technology-led climate policy is a means of breaking the knot.

To be clear, **a technology-led policy is an alternative approach to mitigation. To make possible substantial, continuing emission reductions, it is necessary, we think, to focus on basic and applied research, development, and testing of alternative energy technologies, and infrastructure** to make them both viable and less expensive. A technology-led policy is **not** a recipe for subsidies to energy production, such as those given to the owners of wind farms and solar energy arrays. In general, these subsidies often are wasteful and they do not solve key technological problems.

In short, **if efforts to de-carbonize the global economy are to be effective it needs rethinking**. The blinders that have distorted climate policy to date need to be replaced by a hard-headed appreciation of the nature and magnitude of the technological task ahead.

Figure 1: World Energy Use by Fuel Type



Sources: EIA and World Energy Projections Plus (2008)

The paper proceeds as follows. In section I we present measures of the size of the technology challenge posed by climate stabilization. Current technological readiness and what might be achieved with current technologies is considered in section II. In section III we examine the implications of a failure to tackle the technology challenge ***directly***. Section IV sets out the character of the technology-led proposal and the ***ancillary***, but important, role of carbon pricing. The political economy of reliance on carbon pricing, especially as it relates to energy intensive industries is discussed in section V. Section VI takes up the important issue of institutional factors that increase the likelihood that a technology-led policy will be "incentive compatible". Some specifics of the technology-led approach are set out in section VII. In section VIII, we turn to a benefit-cost analysis, using three different methods to assess the relative benefits and costs associated with a technology-led approach to climate policy. Some concluding thoughts are presented in section IX.

THE MAGNITUDE OF THE TECHNOLOGY CHALLENGE

By any measure, the magnitude of the challenge posed by stabilizing the atmospheric concentration of GHG in the atmosphere at an acceptable (non-dangerous) level (hereafter "stabilizing climate") is huge. One measure is the cumulative emissions that need to be reduced by energy efficiency improvements and shifts to less energy using activities, and the introduction of carbon emission-free ("carbon neutral") technologies. Pielke et al (2008) estimate these for the scenarios used by the Intergovernmental Panel on Climate Change (IPCC). These cumulative emissions estimates and demands on carbon neutral technologies are much greater than would be inferred from the emissions scenarios employed by the IPCC or the Stern Review. The IPCC uses emissions scenarios that already build in 57-91% of the emission reductions attributable to technological change as baselines for measuring the size of the challenge. This is shown in Figure 2 where the blue portions of the bar represent the emissions reductions that are built into the emission scenarios. The issue here requires further explanation.

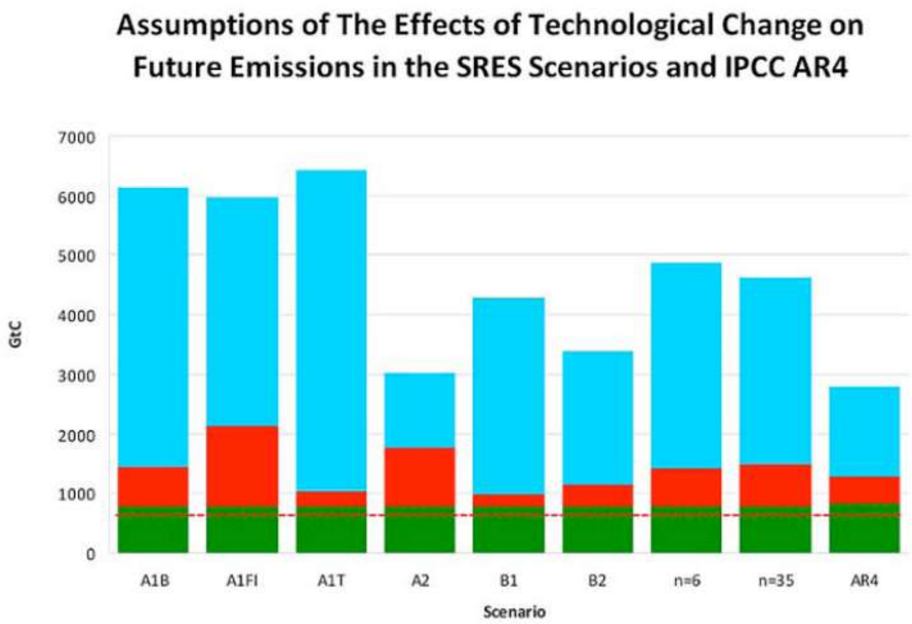
In assessing what it will take to stabilize atmospheric GHG concentrations (in cost and technology terms), models usually employ no-climate-policy emission scenarios as references or baselines. However, using emission scenarios as baselines for assessing climate stabilization creates a huge understatement of the technological change needed (and, by extension, economic cost incurred) to stabilize climate (Pielke et al. 2008). The problem is that **built into most emission scenarios are very large, primarily technologically driven, emission reductions that are *assumed* to occur *automatically***.

By building into their emissions scenarios very large technology-generated emission reductions, analysts (with important exceptions including Battelle 2001; Edmonds and Smith 2006; Fisher et al., 2007:220), Wigley et al. 2007; Pielke et al. 2008) are assuming the technology challenge is measured by the red portions of the bars in Figure 2, that is by the difference between the emissions scenario baseline and the stabilization path. The result is to substantially understate the magnitude of the energy technology challenge.

To get around the problem posed by using an emission scenario baseline for assessing the magnitude of the technology challenge, one can use a "frozen technology" baseline (Edmonds and Smith 2006; Pielke ***et al***. 2008. For a slightly different usage of the "frozen technology" concept, see D. Greene at al, 2009). A "frozen technology" baseline is an estimate of future emissions as if they were produced using today's energy technology--hence the technology is "frozen". (Frozen technology baselines were used in constructing Figure 2.)

While no one expects technology to be/remain "frozen", a hypothetical "frozen" technology baseline allows complete transparency in assumptions about future technologies, innovation and the processes that will lead to such innovation, crucial issues that are obscured by emission scenario baselines. Assessing the technology challenge from a "frozen" technology baseline also avoids the potential for "double counting" technologies, once in the emission scenario and again in movement from the emission scenario to the stabilization path.

Figure 2: Cumulative Emissions and Technology in IPCC Scenarios



The IPCC B2 scenario can serve as an example to illustrate the magnitude of the challenge to stabilizing climate even in scenarios that are relatively modest in terms of cumulative emissions. (See Figure 2 and Table 1.) In B2 the GDP growth rate 2010-2100 of 2.0% (MER)---1.77% (PPP)--- is quite modest, yet carbon dioxide emissions rise from the current level of about 8 GtC to almost 14 GtC in 2100. This occurs even though built-into the B2 scenario is (i) substantial average annual rates of energy intensity decline, and (ii) a large increase (2010-2100) in carbon-free-- or carbon-neutral- -energy consisting of a 13 fold growth in nuclear power, a six-fold increase in biomass (much more if one only considers "new" biomass --see note to table); and a 20 fold increase in other renewable (including hydro).

The energy technology change built into the B2 emission scenario will require many technological improvements and some technological breakthroughs. For example, breakthroughs would be needed in: (a) the production of biomass fuels to assure they are low carbon emitting on a life cycle basis; (b) storage for intermittent solar and wind energy which must make up a large portion of the growth in "other renewables"; and (c) generation IV and newer generations of closed cycle nuclear electric reactors (using reprocessed nuclear fuel) in order to make possible a huge increase in nuclear electricity, given limits to U-235 and waste storage capacities . **These examples make clear why it is important to consider technology built-into an emissions scenario as well as that required to move from an emissions scenario baseline to a stabilization path** (Pielke et al, 2008)

Another way to measure the stabilization challenge is to directly estimate the amount of carbon neutral energy (or power) that will be needed by 2050 or 2100 to get on a stabilization path. This is the approach undertaken by Hoffert et al (1998). For a global average GDP growth rate of 2.4% (1990-2100) estimates of the carbon-free power required by 2100 generally fall in the range of 25-40 TW, the amount depending on the global average annual rate of energy intensity decline (see Figure 3 below). A terawatt is 10^{12} watts - a terawatt over the course of a year is 8760 TW hours - or 8.76 trillion kilowatt hours. One TW equals 31.56 exajoules (EJ) of energy per year). Currently, the world's consumption of energy measured in power terms is 16.5 TW. Of this amount less than 2.5 TW are carbon neutral, almost all of it derived from nuclear and hydroelectric power.

Table 1: The IPCC B2 Scenario

	1990-2100	2010-2100	2010-2050	2050-2100
GDP growth rate %MER (%) (PPP)	**2.2 (2.0)**	**2.0 (1.77)**	**1.61 (2.22)**	**1.53 (1.42)**
Rate of decline in E/GDP (%) MER (PPP)	**0.97 (0.77)**	**0.84 (0.62)**	**1.12 (0.73)**	**0.64 (0.53)**
Rate of decline of C/GWP (%) MER (PPP)	**1.44 (1.24)**	**1.40 (1.16)**	**1.76 (1.36)**	**1.11 (1.01)**
Rate of increase of CO_2 emissions	**0.76**	**0.61**	**0.85**	**0.41**
Cumulative CO2 emissions (GtC)	**1157**	**998**	**395**	**602**
Cumulative Emissions ($GtCO_2$)	**4245**	**3661**	1451	2210
Built into the B2 scenario are (EJ/yr)				
-Nuclear {7}	**135**	**131**	**50**	**81**
-Biomass {46}	**269**	**269**	**59**	**210**
-Other renewable (incl. hydro){8}	**204**	**190**	**85**	**105**
Total	**608**	590	194	396
The numbers in parentheses ( ) mean that GWP measured in purchasing power parity (PPP) terms. The numbers in brackets { } are EJ/yr supplied by the energy source in 1990, (IPCC, 2000: Tables, B2 "Message" emission scenario). Note that almost all of the 46 EJ/yr of biomass is "old" biomass, including wood for domestic fuel, charcoal and burning of dung, mostly by poor communities without access to electricity or other commercial energy. Old biomass is replaced by ***carbon neutral*** "new" ("plantation") biomass for generating electricity or producing biofuels.				

Source: IPCC (2000)

Even with only modest growth in the demand for energy (based on the assumption of huge improvements in energy efficiency) the world will consume upwards of 30 TW in 2050. (At a 1.5% growth rate energy consumption in 2050 would be about 31 TW. A more likely 2.0% growth rate would raise energy consumption in 2050 to almost 39 TW.) To get on a stabilization path, at least half of the energy used in 2050 will have to be carbon emission-free; by 2100 almost all of it would have to be emission-free. Assuming 31 TW of power will be needed in 2050, implies a six fold rise in carbon neutral energy to 15 TW by 2050. Is that feasible? And what is needed to make it feasible? By 2100 upwards of 30 TW of carbon-free power will be required. (The Hoffert et al (1998) analysis, and accompanying Figure 3, are taken up again in section II below)

TECHNOLOGICAL READINESS

Technological readiness implies deployable (on-the-shelf) technologies that are scalable and as cost competitive as possible. Assessments of "technological readiness" require comparing the magnitude of the technology challenge (section I) with the capabilities of current carbon emission-free (or "carbon neutral") energy technologies. On this basis we are nowhere near ready to reduce global emissions substantially by mid century, much less achieve climate stabilization by the end of the century. Let us look at several energy technologies/sources and their potential contributions by 2050. (An excellent complement to the technology readiness assessment below is Barrett, 2009)

1. ***Hydroelectricity***. Sites for hydroelectric power are limited. A doubling of the present capacity is probably the best we can do. Doubling capacity would add about 340 GWe and eliminate the need for construction of about seven hundred 500 MWe coal fired plants with total emissions of 2.4 billion tonnes of ***carbon dioxide*** (or about **.65 GtC**). The addition of time-of-day pricing, thereby raising the capacity factor of hydro from around 50% to 75%, might eliminate another **.65 GtC**

2. ***Nuclear electric***. Nuclear energy has been and will likely be an important contributor to non-carbon emitting electric power generation. But in its current technological form there are resource and storage limits to its scalability (MIT, 2003). There are currently 439 nuclear reactors in the world producing an estimated 390 GWe. Many existing plants are approaching the end of their useful life. Assuming all the existing reactors are replaced when they wear out, it would require adding 15 reactors every year from 2010 to 2050 to raise nuclear generating capacity to 1TW. The ***additional*** 600 GWe of nuclear capacity would replace coal-fired electric capacity emitting **1.1 GtC** a year. (MIT, 2003)

3. ***Carbon Capture and Storage*** (CCS). Currently a lot of weight (hope) is being placed on the CCS option. There is little choice given the huge amount of coal-fired electric capacity now churning about a substantial fraction of global emissions (MIT, 2007). Moreover, the slow ramp up of nuclear capacity and huge hurdles to large scale, baseload energy from solar and wind (see below) suggest continued heavy reliance on coal to meet the rapid growth in electricity demand in many parts of the world, especially the developing world and parts of the developed world too.

4. But ramping up CCS will be slow (Edmonds et al, 2007) for several reasons: (a) CCS has not yet been applied to a coal-fired electricity generating plant; (b) the only examples of operational CCS involve relatively small scale operations, the best known being the Sleipner field project that stores about 1 Mt of CO_2 (or 270,000 tonnes of carbon) each year from Norway's North Sea natural gas operations: (c) it would take the equivalent of 3500 Sleipner fields (Pacala and Socolow, 2004) to store 1 GtC each year, and that means a large amount of geological investigation to assure the existence, safety and security of the required geologic sites; (d) pipelines would have to be built from the source of CO_2 to the designated geologic sequestration sites; (e) capture technologies have not yet been perfected, and those that are operational at a test site level would not only increase plant capital costs, but would exact an energy penalty of 20 to 40%, depending on technology. If by 2050, CCS can be ramped up to 1 GtC (~3.7 $GtCO_2$), the **net** reduction in

energy-related emissions (emissions from electricity generation net of the added energy needed to capture emissions) would be about **0.7 GtC**.

5. ***Biomass***. Although biomass has been counted on as major carbon neutral source, recent experience has greatly lowered expectations - at least from "first generation" biofuels such as corn ethanol and soybean based biodiesel. There are several reasons why biomass, at least in its current forms, is unlikely to produce in the future the large amounts of (***net***) carbon neutral energy expected just a few years ago. These reasons include: (a) the effect on food stocks and prices caused by devoting large amounts of cropable land to energy crops (Pimentel, 2009; Wise et al, 2009); (b) the enormous amounts of water that large scale biomass production will require (Bernedes, 2002; Gerbens-Leenes, et al, 2009); (c) evidence that on a life cycle basis the net energy from biofuels output is not much greater - and in some cases may be less - than the energy inputs into producing the biofuels (Farrell, et al, 2006; Pimentel and Patzek, 2005); (d) indications that converting land from pasture to energy crops may release carbon from the soils in amounts that substantially outweigh any prospective reductions in emissions that conversion from fossil to biofuels is expected to produce (Searchinger et al, 2008, Fargione, et al, 2008).

6. The realization that "first generation" biofuels may do little or nothing to reduce emissions (or energy use) has led in two directions: (i) to focus on biomass as a ***solid*** energy source for generation of electricity rather than as a ***liquid*** biofuel for use in vehicles; (ii) R&D into the possibility of "second generation" biofuels from cellulosic by-products of primary feedstocks, to switchgrass, to algae. Each has potentially important limitations. In the case of solid biomass, finding sufficient forest that can be dedicated to electricity production may be limited to a few places in the world. In the case of "second generation" biofuels, these will require technological breakthroughs and even then their scalability is in doubt. We will be hard put to produce enough **net** energy from biomass by 2050 to reduce emissions by an estimated **0.3 GtC.**

7. ***Solar and wind***. Currently, these two potentially substantial sources of energy supply only a tiny fraction (less than 1 %) of the world's energy. The reasons go far beyond their higher costs (Love, 2003; Love et al, 2003; Denholm and Margolis, 2007a, b)). Beyond reducing production costs, three big hurdles need to be overcome (in ascending order of difficulty and importance). (1) Direct current lines need to be constructed to carry solar and wind energy from the areas of highest insolation and wind speeds to the populous areas where most consumers are located - often a 1000 km or more distant. (2) More flexible, "smarter" grids will be needed to cope with the variability inherent in wind and solar power. (3) Because of their intermittency and variability, even with "smart grids", solar and wind power are unlikely to be able to supply much more than 10-15% of grid-based electricity (net of energy used in "spinning reserve" back-up) without the development of utility-scale storage. To overcome scalability barriers, scientific and technological breakthroughs will be needed (Lewis, 2007a). Assuming that in the next couple of decades sufficient investment is put into the electric grid infrastructure and into researching and developing large scale storage for solar and wind-powered electricity generation, it is possible/conceivable that by 2050 these two renewable sources could together supply 500-700 GWe, and displace up to **1.5GtC**.

8. ***Geothermal***. Geothermal power is an excellent source of power in those few areas (such as Iceland) where hot springs are abundant. Not surprisingly, it is currently a very limited source of power. With technological changes it is possible to increase the availability of geothermal for generation of electricity. Moreover, if new buildings are fitted with proper piping at time of construction, geothermal could eventually become a widespread means of space-conditioning, moderating, to a degree, the growth of demand for electricity. By 2050, it may be conceivable that geothermal could displace **.5 to 1 GtC**

9. ***Ocean Wave Energy***. There is growing interest in harvesting electric power from ocean waves. The amount of energy in the oceans' waves is large, but it is very dilute, and only a fraction is economically viable - assuming many technological problems can be overcome. One estimate of the viable resource in the US is equal to about 6% of ***current*** electricity demand. Because wave energy is concentrated at low frequencies, efficient conversion and transmission to a grid is difficult (Scruggs and Jacobs, 2009). The marine environment creates other problems including seawater corrosion, marine organism fouling, and large loads imposed by big storms on wave energy converters. Ocean wave energy might displace **0.1 GtC**.

Taken altogether, current energy technologies, if hugely scaled up, might get us halfway toward a stabilization path by 2050 - but only a fraction of the way toward achieving stabilization by 2100. One way to see why this so is to refer back to Table 1 and note there the large amount of carbon-free energy built into the B2 emission scenario. That the B2 scenario is not atypical is evident from Figure 2. Unfortunately, perceptions differ. One reason is that many analysts assume rates of energy efficiency improvement and energy intensity decline much greater than can be sustained globally over an extended period of time. As Hoffert et al (1998) demonstrate, there is a trade-off between the amount of carbon-free energy required to stabilize climate and the rate of energy intensity decline. Figure 3, based on Hoffert et al (1998), indicates the relationship. (The trade-off in Figure 3 is based on an assumed global rate of GDP growth of a little over 2.4% (1990-2100) and atmospheric stabilization of CO_2 at 550 ppm.)

As Figure 3 indicates, the amount of carbon-free energy required to achieve stabilization is very sensitive to the global rate of energy intensity decline. The amount required for a 1.0% rate of energy intensity decline is twice that required of a 1.5% rate of decline, which in turn is approximately twice the level required if the rate of energy intensity decline is 2.0%. Hoffert et al (1998) thought that the **global** economy might achieve a 1.0% rate of energy intensity decline for the 110 year period 1990-2100, a rate that reflects past trends. But many scenarios utilize no-policy rates of energy intensity decline substantially in excess of 1.0%. Here are some facts:

1. In general, the SRES scenarios build in high rates of energy intensity decline. Of the 40 scenarios (from 4 basic families, A1, A2, B1, and B2) 32 had 110 year (1990-2100) built-in energy intensity declines greater than the 1.0%/yr rate used in the BAU IS92a scenario. It is likely that, on balance, the energy intensity declines in many of the SRES scenarios are highly unrealistic. If so, they have contributed to a major understatement by the IPCC of the magnitude of the energy technology, and by extension climate stabilization, challenge.

2. Baksi and Green (2007) have devised a method, using mathematically exact formulas, for computing aggregate energy intensity decline from changes over time in the efficiency of different energy-using sectors and their relative contributions to GDP and energy use. They found that ***even after applying stabilization policies***, it would be difficult to substantially exceed a 1.0%/yr ***global, average,*** rate of energy intensity decline over 1990-2100--or about 1.1% on a 100 year (2000-2100) basis. Yet eighty percent of the ***pre-policy*** SRES scenarios build in 110 year global average annual rates of energy intensity decline that exceed 1.0%/yr (and 75% exceed 1.1%).

3. The Baksi-Green calculations of an approximately 1.0% rate of decline in energy intensity (1990-2100) assume global average energy efficiency increases in industry, commerce, and transportation of 200%, (300% for cars and light trucks), 300% in residential uses, but less than a 100% in the efficiency with which electricity is generated (Lightfoot and Green, 2001). The calculations also assume that over the course of the 21st century, there are very large reductions in the GDP and energy shares of energy intensive industries, a rise in the energy share for electricity generation, and a substantial rise in the GDP share of the commercial sector reflecting the increasing importance of services.

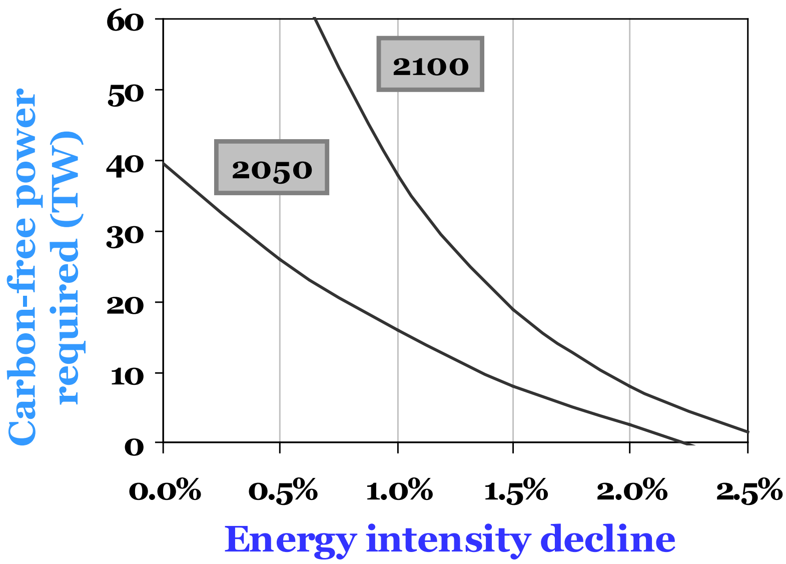
4. The formulas generated by Baksi and Green (2007) can be used to demonstrate that only about 20% (bounds of 10 and 30 percent) of the **global** energy intensity decline can be contributed by sectoral shifts from higher to lower energy intensive uses. The rest must come from energy efficiency improvement, which means widespread adoption of the best available technology plus technological change. While at the individual country level sectoral shifts can contribute considerably more than 20% of energy intensity decline, at the global level there is a lot of cancelling out as energy-intensive industries move from one part of the world to another.

5. Baksi and Green (2007) also demonstrate that achieving very high, century-long, rates of energy intensity decline (ones that would substantially reduce the amount of carbon-free energy needed for stabilization) require improvements in energy efficiency that are almost surely physically impossible. For example, Baksi and Green show (***supra,*** Table 4) that a 2.0% rate of decline (the B1 marker scenario has a 2.13% average annual rate of decline, 1990-2100), requires sectoral energy efficiency improvements ranging from 450 to 1100 %.

The IPCC (2001) technology readiness claims were contested by Hoffert ***et al***. (2002). One reason for the clash is that the methodology developed by Hoffert et al. (1998) avoids the trap of "built-in" emission reductions endemic to the IPCC emission scenario baselines. In Figure 3, the calculation of carbon-neutral energy requirements is based on the rate of growth of global GDP, ***given the explicitly accounted for average annual rate of decline in energy intensity.*** In this way, the baseline in Figure 3 (the 2100 curve) is the equivalent of a "frozen" technology baseline.

The second reason revolves around the ***scalability*** of current carbon-neutral technologies. The scalability issue, emphasized by Hoffert ***et al***. (2002), recognizes that while some technologies are not yet scalable because they are still at the R&D stage, others although apparently "on the shelf" are nevertheless not yet scalable. In some cases scalability is limited because of the lack of an "enabling technology". An example of an "enabling" technology is grid integration and storage for intermittent and variable solar and wind power. These potentially large, but dilute energy sources are not only land-intensive (Lightfoot and Green 2002), but of limited use without storage. Electric utilities generally will not be able to meet any more than about 10% of non-peak electricity demand from directly supplied, intermittent or variable sources. While pumped hydro, hydrogen, and compressed air energy storage can provide some storage potential, we are still very far from a good, reliable, and scalable means of storage for electricity generation and supply.

Figure 3: Energy Efficient-Carbon-Free Power Tradeoff



Similarly, CCS faces scalability issues on the storage side. While studies suggest that there is potentially plenty of storage capacity for CO_2 emissions captured and geologically sequestered in the foreseeable future (Herzog 2001; IPCC 2005), as a practical matter, each geological storage site needs to be checked for leakage potential. This will require a potentially time-consuming effort by a large number of geologists. Detailed examinations cannot be ignored: carbon dioxide leakage would not only limit the effectiveness of CCS, but create a public hazard because CO_2 in concentrated form is an asphixiant that disperses slowly if a leak occurs, especially if the wind is not blowing. It is true that there are a number of small scale examples of CCS, but there is nothing even remotely approaching the scale required for CCS to contribute significantly to reducing future net CO_2 emissions. Finally, "conventional", once-through, nuclear fission is not only limited by Uranium 235 supplies (MIT, 2003), but faces political and technological limitations with respect to storage of the large amounts of radioactive waste that would be generated even if nuclear simply maintained its current 17% share of global electricity generation.

Storage is not the only "enabling" technology that is required to make a number of carbon-neutral energy technologies viable. Other examples include ***retrofit*** technologies for the large and rising number of coal-fired plants, especially those in China, India and the US, or as an alternative, CO_2 capture from the air (Lackner, 2003; Pielke, 2009). While nuclear electric generation is an obvious low carbon-emitting alternative to coal, large-scale expansion will greatly increase the incentive to reprocess nuclear "waste". However, doing so will require some means of "spiking" the resulting plutonium to make it too hot to handle by terrorists, and a means of preventing nuclear proliferation. While the latter clearly involves political ingenuity, it also involves science and engineering developments, as is indicated by the apparent technological as well as political hurdles ahead for the US-promoted Global Nuclear Energy Partnership (GNEP). (Tollefson 2008) [The key reprocessing facet of GNEP has recently been cancelled.]

Once the scalability problem is understood, it is easier to see why there is still a large technology gap between usable carbon-neutral energy with current technologies and the amount required for climate stabilization. Green ***et al***. (2007), build on Hoffert ***et al***. (1998), in an attempt to measure the "advanced energy technology gap" (AETG), the gap between the carbon-neutral energy required for stabilization and the carbon-neutral energy that could be supplied from "conventional" carbon-neutral sources. "Conventional" carbon-neutral energy technologies include: hydroelectricity (subject to site limitations); once-through nuclear fission (subject to uranium 235 supplies as well as security, political and waste storage limitations); solar and wind without storage; some biomass, geothermal, tidal and wave (ocean) energies. The authors found that "conventional" carbon-neutral energy sources might, in a stretch, supply 10-13 TW by 2100. Liberally assuming 13 TW from these "conventional" sources, we still need 15-25 TW of power from advanced technologies (the AETG) to reach the 28-38 TW of carbon emission-free energy required by 2100 to stabilize at 550 ppm, assuming a 2.4 % rate of growth of GDP (1990-2100). These findings support the Hoffert *et al.* (1998, 2002) claim that major breakthroughs in new as well as existing energy technologies and sources will be required for stabilization at 550 ppm, and even more so for stabilization at 450 ppm.

IMPLICATIONS OF FAILING TO ADDRESS THE TECHNOLOGY CHALLENGE

If, as seems likely, the SRES emissions scenarios have made CO_2 stabilization appear much easier than it will be (Green and Lightfoot 2002, Pielke ***et al*** 2008), then there are important implications for climate policy. First and foremost, achieving large reductions in global CO_2 emissions requires a veritable energy technology revolution. An implication is the need for a technology-based climate policy.

A second implication involves the relationship between a carbon-price policy and a technology policy. Instead of the carbon-price policy carrying the main load of emission reduction, carbon prices should be viewed as playing two supportive roles: (a) as a means of raising revenues to finance the publicly financed component of the energy technology race without which stabilization is unachievable; and (b) as a way of sending a ***forward price signal*** that will be increasingly powerful as the carbon price slowly rises and as new technologies appear "on the shelf" (a form of what Yohe ***et al*** 2008, term "when" flexible mitigation). These considerations suggest a carbon tax that starts low and rise very gradually over time.

In thinking about climate policy, an important distinction should be made between technologies that are "on the shelf" and therefore are deployable now (if it were economically advantageous to do so), and those that either (a) require further development before deployment is possible; or (b) are still at the basic R&D stage; or (c) have not yet been thought of (Sanden and Azar, 2005). Carbon prices are likely to be effective in inducing deployment of technologies that are "on the shelf", but may well be ineffective inducements to invest, long-term, in technologies that still require basic R&D. The success of basic R&D is typically ***uncertain***. This will have a major impact on the market's evaluation of it. Even if R&D proves an initially uncertain technology to be viable, it may take decades before it is ready for deployment.

Many climate policy modelers give an important role to induced technological change (ITC). The basic idea is that a strong carbon price will induce the private sector to make investments in energy R&D and technological changes that allow firms to reduce their carbon emissions. The payoffs from these investments is the carbon emission permits that do not need to be purchased (or if allocated can be sold to other firms) and/or the carbon taxes avoided.

In our work we make an important distinction where ITC is concerned. Carbon prices are given a central role in the adoption of on-the-shelf, ready to deploy technologies. But we are much more skeptical about the role of ITC where basic R&D and the testing of untried technologies are concerned - especially where the time frames are many years or even decades rather than a few years and success is highly uncertain.

Our distinction between the role of market-based policies where technologies are "on-the shelf" and those requiring basic research and development (see Sanden and Azar, 2005) is mirrored in a recent paper by Blanford (2009, in press). Blanford puts the issue nicely:

> "Market-based abatement policies are effective mechanisms for bringing about the diffusion of existing technologies and can even spur incremental improvements through learning and induced applied R&D. Thus abatement policy is a mechanism for getting technologies 'off-the-shelf'. However, because of long time frames and limited appropriability in basic research, a second mechanism is required to put new abatement technologies 'on-the-shelf'. The implementation of a technology strategy for a long-term environmental problem such as climate change is a challenging policy task."

The distinction that Blanford (2009) is making can be framed as the difference between demand-side" and supply-side influences on energy technologies. The demand side is found to be strong where "on-the-shelf" technologies are concerned, but for longer-term breakthrough technologies a supply-side, technology-based policy approach is required. The demand side versus supply side distinction is the basis for a very useful paper by Nemet (2009).

Nemet's paper is one of the very few we have found that moves beyond theory and indirect empirical evidence to an actual case study. Nemet examines the role of "demand pull" and "technology-push" impacts on investments in the development of wind turbine technology. Nemet finds little evidence of a demand-pull influence. Most of the technology development appears to have been a response to government programs in the early and mid-1970's to pursue energy independence and reduced reliance on foreign oil, and to have preceded increased demand for wind power (Nemet, 2009). Citing earlier work by Dosi (1988) and Kemp (1997), Nemet concludes that "These results fit with earlier work suggesting incremental innovation is more likely to respond to demand-pull than to technology-push and that non-incremental innovation is more responsive to technology-push" (Nemet, 2009:707).

Finally, a study by Hoffmann (2007) found little impact in the first round (2005-2007) of the EU emission trading scheme (ETS) on large scale, long term investments by the German electricity industry. Like Blanford and Nemet, Hoffmann found that the German electricity industry "does make low carbon investments with limited risks" such as retrofits or "investments with an inherent option character (R&D)" (Hoffmann, 2007:472). Perhaps the weakly applied first phase of the EU ETS does not allow us to pass judgment on the long-term R&D and infrastructure effects of a much tighter set of emission caps than those that evolved in the 2005-2007 period. Still, Hoffmann's findings resonate with the view that carbon-pricing is unlikely to provide a strong inducement to the private sector to undertake long-term, inherently risky and uncertain investments in the development of breakthrough technologies.

An interesting question is whether price-induced technological change has led to any major technological breakthrough. An answer in the affirmative is not supplied by any of the climate-energy-economy literature we have seen. Yet, Held et al (2009, in press) state that "the inclusion of endogenous technological change led to results showing remarkably low mitigation costs for ambitious climate protection targets…." Why is this so, given the apparent lack of empirical evidence linking technology breakthroughs to either targets and/or carbon pricing?

An answer may reside in an ITC modeling comparison study carried out by Edenhofer et al (2006). Eight of the ten models explored by Edenhofer et al include "learning-by-doing" (LBD). Learning-by-doing can be a powerful influence in reducing costs as the scale of production increases. This is evident from a series of case studies (none referred to by Edenhofer et al) including: airframe production (Wright, 1936); "Liberty ships" (Searle, 1945, Lucas, 1993); semiconductors/microchips (Scherer, 1996). However, these studies apply chiefly to manufacturing operations. It is a huge (and probably unjustified) leap to applying LBD to many of the activities most critical to the appearance of new energy technologies: research, development, testing, and deployment.

It may also be significant that, in the Edenhofer et al (2006) model comparison, six of the ten models include a backstop technology. Including a backstop technology effectively solves the energy technology problem by assumption. What the "backstop" technology assumption does is to assure that raising the carbon price sufficiently will bring forth an unlimited supply of carbon emission-free energy. When the LBD and backstop assumptions are taken together, it is not surprising that ITC appears powerful even though no evidence for such an influence has been induced. It is all by assumption!

There is an additional problem. As Montgomery and Smith (2007) have demonstrated, private funding of long-term R&D encounters a "dynamic" (time) inconsistency. Generally, current governments cannot tie the hands of future governments to cover the potentially large (as well as uncertain) up-front R&D investment costs for technologies that may or may not prove successful and deployable decades hence. The Montgomery and Smith and Sanden and Azar (2005) papers therefore imply that "induced technical change" may be less important than one might gather from IPCC WG III, Ch. 11 (Barker et al. 2007). Further, to these considerations we may add a "political" time inconsistency between a 4 to 5 year election cycle and the decades-long time scale for the development of deployable and scalable carbon-neutral energy technologies. The nature of the R&D required and the time inconsistencies inherent in a long term investment problem, suggest that the price system has limitations as a tool of climate policy.

Current climate policies appear to be influenced by a perception that the technologies required for stabilization are already "on the shelf", or almost so. In 2001, in its Summary for Policy Makers (SPM) IPCC WG III argued that "most model results indicate that known technological options could achieve a broad range of atmospheric CO_2 stabilization levels, such as 550 ppmv, 450 ppmv, or below over the next 100 years, but implementation would require associated socio-economic and institutional changes" (IPCC, 2001, p.8). The IPCC defined "known technological options" as "technologies that exist in operation or pilot plant stage today…" (***supra*** p.8n). In 2007, with only slightly more caution, IPCC AR4 states in the SPM of its Synthesis Report (SYR) that "There is ***high agreement*** and ***much evidence*** that all stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are currently available or expected to be commercialized in coming decades…" (IPCC SYR 2007, p.20).

In contrast to these general assessments, there are numerous reports and studies that detail what needs to be done to **current** carbon-neutral technologies to make them ready to be deployed and/or scalable. (Some of the findings are summarized in the preceding section. Also see Barrett, 2009.) The inconsistency between careful analyses of technological readiness and the claims of IPCC WG III is traceable to a number of factors. One is the crucial issue of how scalable they are. A pilot plant operation may not be a good indicator of scalability. Another factor is some technologies that are deemed ready, such as nuclear electric and post-combustion CCS, face ***long ramp up*** times - and cost is a nagging concern as well. In still others, such as wind and solar, scalability awaits "enabling" technologies such as grid integration and storage. In short, there is a large gap between current readiness and deployability on the scale required for substantial reductions in global emissions. That "gap" has important implications for attempts to quickly push down global carbon emissions in the absence of the ready-to-deploy, scalable technologies (what we term "brute force" mitigation)

A "thought experiment" helps to illustrate. Suppose the emission reduction target is a 80% reduction in global emission from current levels by 2100. To reach the 2100 target requires a 1.8% average annual rate of decline in carbon emissions. Now suppose the expected "trend" rate of growth in global world output (GWP) from 2010-2050 is 2.2%. To avoid a reduction in the growth rate of GWP would require a 4.0% average annual rate of decline in the carbon intensity of output (RCIO). [The calculation of 4.0% for RCIO is based on C = GDP x C/GDP, a reduced form of the Kaya Identity (see Section VII) where the terms are converted to rate of change terms and RCIO is the rate of change of the C/GDP term.]

If a policy of reducing emissions by "brute force" is adopted, irrespective of technical feasibility, even an increase in the average annual RCIO to 3.6% from its "historic" rate of 1.3% (a very unlikely event in the absence of a technology-led policy) implies a reduction in the growth rate of GWP from the 2.2% "trend" rate to 1.8% for the period 2010-2100. Such a reduction would cost (an ***undiscounted***) $86 trillion in 2100 alone and an ***undiscounted*** $2280 trillion ***cumulative*** over the 90 year interval. (It is assumed GWP in 2010 is $41 trillion, measured in MER terms.) And even these huge reductions in GWP would not do the trick (meet the emission target) if we cannot push the rate of ***decline*** in C/GWP up to 3.6% (which is almost triple the "historic" rate).

The "thought experiment" casts serious doubt on the credibility of estimates of the cost of stabilizing climate. Estimates in the 1 to 3% of global GDP range - or lower (Stern, 2007; IPCC, 2007) are not credible unless there is a ***prior focus*** on reducing the technology gap. The low-cost estimates reflect a variety of self-serving assumptions. Some models employ an emission scenario baseline that builds in large, automatic improvements in energy technology. Other models include a ***carbon-free backstop technology*** (often generic) that assures that once the carbon price reaches a specified level there is an unlimited supply of carbon emission-free energy forthcoming. Still others have very high implicit rates of energy intensity decline, ones that would almost surely be physically impossible to achieve. Finally, some models make very optimistic assumptions (ones generally inconsistent with the evidence) about the availability and readiness of carbon-neutral technologies and/or the responsiveness of successful innovation of new energy technologies to carbon prices.

None of these modeling conveniences or assumptions contribute to a ***reliable*** approach to estimating the cost of mitigation. Perhaps the most deceptive are models that build-in a backstop carbon-free energy technology, because this effectively assumes away what ***is*** the problem. Unless a specific effort is made to research and develop, test, and make ready-for deployment scalable carbon emission-free technologies, the cost of mitigation is likely to be as much as an order of magnitude, or more, higher than has been reported.

The route to an effective climate policy would appear, then, to run through technological change. For all intents and purposes that means a technology policy that can assure the long term research and development of scalable carbon–neutral technologies. This in turn requires committed effort and financing plus a commitment to deploy the technologies when effective, scalable, and competitive ones reach "the shelf". How this might be accomplished is taken up in section IV.

CHARACTERISTICS OF A TECHNOLOGY-LED CLIMATE POLICY

The magnitude of the challenge, the lack of readiness of the required energy technologies, and the limitations of mitigation policies that are "brute force" in character suggest that current approaches to stabilizing climate will not work. Specifically, what is needed is a **realignment** in the ***time-related*** mix of mitigation, adaptation, and technology (R&D). Until now the emphasis has been on up-front mitigation, with adaptation and R&D adapting to needs as they arise. But such a policy mistakes the real character and magnitude of the climate problem. Climate change is a technology problem and the size of the problem is huge.

Although there is increasing pressure for big emission reductions soon (in part a response to concern about "tipping points"), our assessment suggests that, globally, large emissions reductions are not attainable without the development of new technologies and infrastructure. And realistically this will take time. Thus the pressure is likely to increase for a "quick-fix" such as that which some form of geo-engineering ***might*** supply (Crutzen, 2006; Wigley, 2006). Whatever the possible merits of geo-engineering (and we believe adoption of any such policy beyond research and possibly a local experiment is premature), it is time to think of an alternative approach to how climate policy approaches GHG mitigation.

We suggest that climate policy dispense with date specific, national emission reduction commitments. Instead, climate policy should aim at inducing technologically-capable countries (which include many countries not covered by current emission reduction mandates) to undertake energy research and development and infrastructure ***commitments***. The aim of these commitments is to develop scalable, deployable energy technologies that are capable of displacing fossil fuels at prices that are not significantly greater (and conceivably could eventually be somewhat below) that of fossil fuels - the prices of which are likely to rise in the meantime. A second set of commitments would be to deploy effective, scalable, reasonably competitive technologies as they reach the shelf and are ready to be deployed. Such a policy requires frank acceptance that the rate at which global emissions decline will depend on the uncertain (ex ante) rate of success in developing carbon neutral technologies.

An important missing ingredient in the realignment of commitments just described is that it lacks a mechanism to fund the R&D and then induce deployment of new, scalable energy technologies when they are ready - that is "reach the shelf". Even if the new technologies are relatively competitive (a version of Nordhaus' (2008) "low cost backstop"), inertia and transactions costs could substantially delay deployment. There are a number of possibilities, including technology regulations and standards. Although in some cases technology standards may be appropriate, particularly for appliances, building codes, and to some extent for vehicles too, **we believe that a modified version of carbon pricing has an important role to play.**

As climate policy has evolved, putting a price on carbon has become an increasingly widely accepted means of mitigating carbon dioxide emissions. For most economists, putting a price on carbon has become the sine qua non of an effective climate policy (e g , Metcalf, 2009; Nordhaus, 2008; Stern, 2007, 2008). Carbon pricing can be undertaken ***directly*** by placing a tax (or charge or fee) on the carbon content of energy fuels or ***indirectly*** by the issuance or auction of a limited number of carbon emission permits ("cap and trade"). The economic logic behind carbon pricing rests on the incentives a carbon price creates to reduce consumption of energy, or at least carbon emitting energy, and on its putative stimulus to the development and deployment of carbon neutral energy technologies. (An "optimal" carbon price is tied to the social cost of carbon. See Tol, 2009.)

Although the ***logic*** of carbon pricing appears impeccable, it is only a means to an end - an end which in the case of climate stabilization is achievable only with the appearance of new energy technologies that first must be researched and developed. We have already explained why we believe a price on carbon is too weak an instrument to induce the requisite R&D. A carbon price can induce deployment of "on the shelf" technologies and perhaps their prior commercialization, but the market alone is an ineffective means of stimulating, financing and sticking with research and development of technologies whose success is uncertain and which, in any event, may take many years, even decades, to reach "the shelf".

We therefore recommend a modified approach to carbon pricing. Instead of relying on carbon pricing as a first line approach to reducing emissions, we suggest that in the first instance carbon pricing be used to finance research and development of effective, scalable energy technologies and the infrastructure required to deliver them. For this purpose, a low tax on each tonne of carbon dioxide is all that is needed to raise tens of billions of dollars globally. A $5.00 per tonne CO_2 tax would raise $30 billion ***a year*** in the US, about the same in China, almost as much in the EU, and lesser, but significant amounts in Russia, India, and in other countries. Annually, as much as $150 billion could be raised in this way worldwide. A $5.00/t$CO_2$ tax or "fee" is a relatively unobtrusive method of raising funds. Its use in energy R&D could also be publicly popular in an energy-hungry world. The sums raised over time would easily finance a vigorous international energy technology race and leave monies available for up-dating national grids and other energy infrastructure.

In short carbon pricing although it would not be the centerpiece of climate policy would nevertheless play two important *ancillary* roles. First, a low carbon fee or tax would be an *ancillary* (although important) appendage to the main up-front objective: develop the technological and infrastructure *means* to reduce emissions substantially in the future. *Then while technological progress is being made, the carbon fee or charge should slowly, gradually, and by agreement, automatically rise*. This could be achieved by a commitment to increase the fee slowly so that it doubles every ten years or fifteen years. Here then is the second *ancillary* role of carbon pricing. As the carbon fee slowly rises it would take on the character of a "forward price signal", generating incentives to deploy new technologies as effective, scalable, and increasingly cost competitive ones "reach the shelf". At this point a virtuous circle may develop.

There are great advantages in the modified form of carbon pricing just described. By starting as a means of financing energy technology development and infrastructure, a carbon tax could (and should) be very low. It therefore has a chance of being adopted by all or almost all ***leading*** emitters and many smaller ones too. This would permit a widespread "harmonization" of carbon prices, something that would be impossible if carbon prices start high and/or rapidly rise from a modest level. Even if initially the rate adopted by developing countries were lower (say $3.00/tonne CO_2) than the $5.00 rate adopted by developed countries, the carbon price would be approximately "harmonized" across most of the world.

Harmonizing carbon prices is important if substantial "carbon leakage" is to be avoided. Carbon leakage occurs as energy intensive activities shift to countries that only loosely regulate or price carbon, if they do so at all. (See the discussion of "leakage" in section V.) Although good estimates of carbon leakage have been hard to come by (most estimates suggest about 20% for energy-intensive industries(Metz et al, 2007; Aldy and Pizer, 2009), the leakage problem is bound to increase as emission reduction mandates/carbon prices begin to bite in some parts of the world but not in others. Carbon leakage undermines global emission reducing efforts, and is an inevitable consequence of "brute force" mitigation. But as important as the "harmonization" and "carbon leakage" issues are, they pale by comparison with another issue that has not yet been given sufficient attention.

The heightened concern over climate change is occurring at a time when momentous changes are taking place in the developing world. One of the coincidental facts of recent history is that at the same time humankind is grasping the idea that it is changing the earth's climate, dramatic advances in economic growth and development are taking place in the most populous parts of the world. Beginning in the last decades of the 20th century, much of what was once the poorest part of the world (Asia), accounting for almost half the world's population, has begun to free itself from the bonds that had contributed to endemic poverty. The nature of growth in East and South Asia has been for a time concealed by the fact that as markets were freed up, countries with very large populations oriented themselves toward labour intensive activities and away from the production of capital, and typically energy, intensive production. This was abundantly apparent in China where economic reform began in the late 1970's. For example, China experienced an annual average rate of decline in energy intensity of about 3.5% during the first two decades of reform (1978-1998).

For most of its first two decades, reform in China was characterized by the production of labour intensive goods (clothing, furniture, household electronics, and the like), much of it carried out by town and village enterprises located outside China's cities where 80% of the population lived (Naughton, 2007; Brandt and Rawski, 2008). But as an increasing portion of the population became richer, moving into a new middle class, many began to move to cities. Given the high population to land ratios, if life in shanties and squalid slum areas was to be avoided, then residential living as well as commercial activity would have to take place chiefly in high rise buildings.

But middle class urbanization requires a shift in production toward the materials used in high rise buildings and supporting infrastructure, including urban and inter-urban transportation systems and equipment, utilities, and fresh and waste water-related facilities. The materials used in these projects, steel, cement, flat glass, aluminum are highly energy intensive. These are among the most energy intensive products in the world - 10 times or more energy intensive than most other manufactured products (Lightfoot and Green, 2001). (These industries not coincidentally are the same ones that EU countries have largely exempted from their carbon taxes and that Germany has recently asked for exemption from permit auctioning under a post-2012 Emission Trading System (ETS) design. See section V.)

To gain some measure of what is happening consider that, in 2006, China's share of world production of cement was 48%, flat glass 49%, steel 35%, and aluminum (Rosen and Houser, 2007). Not surprisingly, their production is accompanied by rising emissions, and may account for much of the tripling in the annual rate of change in ***global*** emissions from 1.1%/yr in the 1990s to 3.1%/yr in 2001-2006. Thus the development success story, particularly that coming out of Asia, is associated with a huge shift in the location and relative importance of energy-intensive industries, ones which rely heavily on power generated from combusting coal. China provides a "model".

The energy intensity of urbanization is not limited to the materials used in buildings. Not only must buildings be space-conditioned in a climate as harsh as China's, but streets need to be broad, criss-crossed with over- and underpasses. These, too, require large amounts of cement and structural steel. And so do the railways and subways that are required to transport people around the city, to say nothing of the materials required for roads and airports, viaducts for transporting water and sewage, and for the construction of huge power and water diversion projects. In short, over the next few decades, as China brings most of its 1.3 billion population into the middle class, huge amounts of energy intensive materials will be needed (and the energy to produce them) on a scale never before seen in human history. And what is now happening in China will happen to a substantial extent in other populous South East and South Asian countries from Vietnam to India.

There are very important lessons here. The rapid development of a large region with half of the world's population is a huge success story for the countries themselves. It is also a success story for the world as a whole, which helped make it possible via an open trade system. It is unfortunate that a by-product of this success is rapidly growing carbon dioxide emissions. Nevertheless, the countries that are making the historic transition from poverty to increased well-being, opportunity, and fulfillment will not give up what they are in the process of earning, whether or not they are asked to do so. (This in fact was recognized in section 2 of the UN Framework Convention on Climate Change (FCCC) and again by the Kyoto Protocol in its distinction between the 38 developed and transitioning countries that would take on emission reduction mandates and the much larger number of developing countries that would have no such obligations.)

As a result, we have only begun to see the surge in global energy use that the transformational development process now implies. And with that development process and energy surge will come growing GHG emissions that will only cease with a transformation of the world's energy systems. Not only will that transformation be a long, slow process, but the required energy technologies, for the most part, are not yet ready or ***scalable***. And when they are ready and scalable, it will likely require a huge technology transfer to the developing world before there is a substantial payoff in global CO_2 emissions reductions.

To summarize, there are four main elements of the technology-led climate policy proposal.

1. First and foremost would be long term **commitments** by technologically capable countries to undertake individually or in groups (more on this in section V) research, development and testing of carbon neutral technologies, with ultimate emphasis on their scalability.

2. The financing of those commitments could best be achieved by adopting a "fee" or tax on carbon emissions. Such a "fee" or tax would start very low - say at \$5.00/t CO_2. (Table 2 indicates what a \$5.00/tCO_2 fee/tax implies in terms of carbon fuel prices.)

3. Developing countries would be expected to levy the fee as well - even those who do not undertake energy R&D. In the case of the latter, the revenues would be used to help purchase competitive technologies when they become deployable on a wide scale.

4. A ***second set*** of commitments would be to double the "fee" or tax, say every ten years or so. Building in a slowly rising carbon price ***both*** increases financing for R&D and energy-related infrastructure and, more important, provides a price signal to induce commercialization of new technologies and their deployment when they are ready and scalable.

We should, however, step back and acknowledge that there is nothing to guarantee that the technology-led policy will succeed. Monies can be spent on research and development, but we cannot assure discovery. The search may fail in the sense that R&D will not produce an adequate carbon-intensity reducing return. If this is the case, modifying the policy by accompanying it with stronger mitigation controls, or in the worst case aborting the policy, may become necessary. But at this juncture there is no reason to believe a technology-led policy will fail, while there is plenty of evidence that alternative mitigation approaches would either be hugely costly (see sections III and VII) - and still not assure success - or have no chance of stabilizing climate at an "acceptable level. (Policies that would assure a rise in global average temperature of at least 3°C, and probably a good deal higher, would not appear to be acceptable - at least at this juncture.)

Table 2: Carbon tax equivalents

	CO_2 (tonnes)	at $5/t CO_2 ($)	2009 Price ($) per unit
Tonne of coal	**2.86**	**14.30**	**16-110**
Barrel of oil	**0.37**	**1.85**	**45-70**
Gallon of gasoline	**0.0088**	**0.044**	**2.00-2.50**
1000 cubic ft of NG	**0.055**	**0.22**	**10-11**
1000 cubic meters of NG	**2.025**	**8.10**	**~400**

What, then, would the technology-led proposal achieve?

a. It would set in motion the sort of technology program/race without which (and perhaps with which) it will not be possible to reduce global emissions substantially.

b. It provides a steady and reliable means of R&D financing, at low cost.

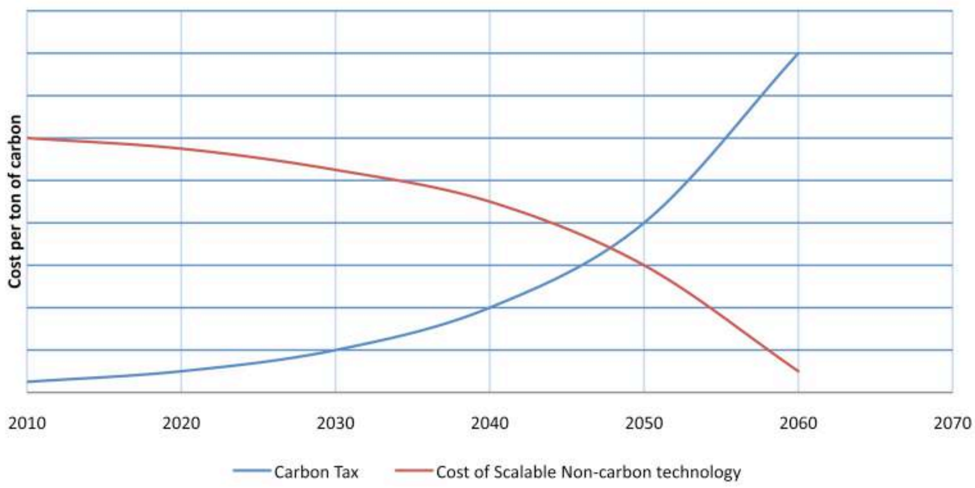
c. It holds out the best hope of bringing down the cost of new energy sources and technologies (as characterized in Figure 4). After all, much of the value of energy R&D is in reducing the cost of new energy technologies that we will need to displace current carbon-emitting ones (Edmonds et al, 2004).

d. It would embed a "forward price signal" via commitments to raise the carbon fee/tax at a slow/gradual rate, doubling every ten years or so.

e. It holds out the best hope of attracting developing countries to the fold. There are no emission reduction commitments. The fee (or tax) per tonne carbon is low and only very gradually rises. Those countries such as China, India, Brazil, Korea, which are certainly technologically capable would (with enthusiasm, we expect,) make contributions to energy technology development. Other developing countries would slowly accrue funds that would allow them to defray at least part of the cost of transferring carbon neutral technologies as they become available and ready to deploy. (Blanford et al. (2009) demonstrate the importance of developing countries making some commitment.)

Together these components add up to a means of reducing the cost of carbon emission-free energy overtime, while slowly raising the price of carbon emitting energy. In graphical terms the declining cost per unit of carbon neutral technology approaches the gradually rising price of carbon emitting energy (Figure 4). The role of a carbon fee/tax facilitates the decline in cost in the desired technology while slowly raising the price of the carbon emitting technologies which we wish displaced by carbon neutral ones.

Figure 4: Rising carbon tax and falling cost of carbon-free technology



CARBON PRICING AND TECHNOLOGY: A 'CHICKEN AND EGG' PROBLEM?

The technology-led approach to climate policy sketched out in preceding sections is prone to misunderstanding. Indeed it is evident that some misunderstanding exists. One reaction is that it is concerned with R&D but not mitigation. Another is that what little there is of carbon pricing is very "weak". Still another is that our proposal differs in extent but not kind from orthodox proposals that make carbon pricing a central feature of climate policy.

In this section we clarify some of the issues that the technology-led approach raises, and then delve deeper into the reasons why we think this approach has a good chance of succeeding where other more orthodox approaches do not. The issues treated in this section revolve around the relationship between carbon pricing on the one hand and technology on the other. We begin by comparing our approach with the more orthodox "economic" approaches.

1. A Comparison of Approaches

Our proposed approach to mitigation has technology leading carbon pricing. As explained in section IV, carbon pricing plays two roles: ***first***, the role of ***funding*** R&D and technology change; and ***second, committing to*** the slow but steady ***increase*** in the ***carbon price,*** thereby ***signaling adoption*** of on-the-shelf, ready to deploy, and scalable energy technologies. Thus, in our approach, technology and mitigation are linked via carbon pricing. ***But they are not linked via today's carbon price***, but rather via ***tomorrow's*** carbon price. In our approach, carbon pricing ***initially*** plays a largely passive and ancillary, albeit important, role. ***But as time passes***, carbon pricing plays a more active role by sending a "forward price signal" as a result of commitments to its slow but steady rise.

Thus it is ***not*** correct to interpret our approach as emphasizing R&D but not mitigation. The two are inextricably intertwined. Also it is not correct to say that we all but ignore carbon pricing. Indeed, carbon pricing plays two important roles, one financial, one signaling.

Moreover, a carbon price that starts at \$5.00/t CO_2 in 2010, and doubles every 10 years, reaches \$80/t CO_2 in 2050.

Still, our approach is the reverse of the typical carbon pricing story. In that story carbon pricing leads, or in some cases operates in parallel with, technological change. In the typical story, carbon pricing operates in two different ways. First, it creates an incentive to adopt ready-to-deploy technologies that are more expensive to use than carbon emitting ones in the absence of the carbon price. Second, carbon pricing is said to ***induce technological change*** by creating incentives to research, develop, commercialize and ultimately deploy new non-carbon emitting, or "carbon-neutral" technologies. Before explaining why we are reversing the standard story, it is interesting to compare our approach with more orthodox approaches taken by William Nordhaus (2008) and Valentina Bosetti et al (2009).

Nordhaus (2008) sets out and analyzes a suite of policies to curb greenhouse gas emissions, evaluating each in rigorous benefit cost terms. Nordhaus' "optimal" policy is a pure carbon pricing policy which maximizes net present value. Although presumably new technologies are adopted, the "optimal" policy makes no reference to energy technology and/or R&D policies. What is most interesting from our standpoint is that among the suite of policies, the one with the highest benefit-cost ratio (by far) is the one that Nordhaus terms a "low cost backstop". Indeed, Nordhaus (2008) states that:

> "Although it might not be currently feasible, the high value of the low-cost backstop technology suggests that intensive research on such energy sources is justified" (p.88).

It is interesting that the rising carbon price so fundamental to Nordhaus' analysis only reaches \$24 per tonne of CO2 (\$90\$ per tonne of carbon) in 2050 in his "optimal" policy. In the Nordhaus model, even in the policy that would limit temperature increase to 2°C, the carbon price only reaches \$80/tCO_2 in 2050.

Bosetti et al (2009a) model the role of R&D and energy technologies in climate change mitigation. Their work is important, not least because it gives a central role to "major technological breakthroughs". These breakthroughs make possible backstop technologies which Bosetti et al. define as "a compact representation of a portfolio of advanced technologies" (p.9). This is a very useful statement! However, Bosetti et al. then insist that to "achieve major technological breakthroughs, a strong price signal is still needed to spur the necessary investments" (p.6). While we agree that a price signal is a useful means of deploying on-the-shelf technologies, we disagree this would be the case for technological breakthroughs.

2. The "Chicken and Egg" Problem

There are three reasons why we have strong reservations about the necessity for a strong price signal to bring about "major technological breakthroughs". First, most "major technological breakthroughs" require basic R&D for which government funding will be needed for the usual public good/appropriability reasons. Second, there is little or no evidence that carbon pricing will induce major technological breakthroughs. The reasons for skepticism have been adduced in section III. It is perhaps telling that a major paper on scenario development by authors deeply involved with the report of IPCC WG III (2007), conclude that "from all the variables…involved in the climate change debate, technology emerges as a particularly important area worth further study". The authors go on to say that technology "represents a more 'maleable' variable for ***directed*** [our emphasis] policy interventions…" (Riahi, et al, 2007:930-31).

A third reason for skepticism is of a somewhat different nature: it is that a high and/or rapidly rising price will be unacceptable to many of the most important emitters. **Here we pursue our third claim.** To understand the Achilles heel of high and/or rapidly rising carbon prices look at Table 2. A $5.00/t CO2 carbon tax/price implies a $13.80 charge on a tonne of coal. For every $10 added to the price of carbon, add $28.60 to a tonne of coal. Current coal prices range from as low as $10.00 per tonne up to a little over a $100 per tonne. The higher part of the range is for coking coal. Most coal for electricity generating purposes sells for less than $60.00/tonne at mine mouth. Thus a carbon price of $20/t CO_2 implies an approximate doubling of carbon prices. A $100/t CO_2 carbon price would represent an increase in coal prices of between 400 and 500%.

In Bosetti et al. (2009a) the carbon price path without backstops reaches about $425/tCO2 in 2050, and even with backstops almost $200/t$CO_2$. Not only is it uncertain that "major technological breakthroughs" will emerge (Bosetti et al., 2009a, 2009b), but the resultant carbon price with breakthroughs/backstops nevertheless implies a "tax" on coal of over $550 per tonne. So not only are high and rapidly rising carbon prices required according to the Bosetti et al. (2009a) modeling exercise, but even after being more than halved by backstops the carbon price will still be very high.

Among the major emitters (some much important than the others) are the US, China, India, Russia, Australia, and Poland. What each of these countries has in common is a heavy dependence on coal. Why would any of these countries accept rapidly rising carbon prices without some assurance that these will soon be alleviated by technological breakthroughs? This important question has been obscured by the emphasis on emission reduction commitments rather than technologies.

Thus the Bosetti et al. (2009a) paper reflects a fundamental problem. The authors comprehend the technology imperative, but their insistence on a primary, up-front role for carbon pricing is not only debatable, but appears to give rise to a "chicken and egg" problem. The carbon pricing "chicken" may be ineffective without the technology "egg".

The problem goes well beyond that of coal used in electricity generation. It infects several broad industry groups that are very ***energy intensive***. Five of these sectors, ferrous metals, non-ferrous metals, pulp and paper, petrochemicals, and non metallic minerals (cement, glass) have energy intensities that are, on average, an order of magnitude higher than the average of other manufacturing industries. For many countries these industries are considered important. There is now some experience with the application of carbon pricing to these industries. The results are instructive.

3. Some Cases in Point

(a) Carbon pricing in Europe

The story begins more than a decade ago after several European nations (including Sweden, Norway, Netherlands, Germany, Finland, and Denmark) enacted carbon taxes (Metcalf, 2009). Within a short time after the introduction, it became necessary to substantially reduce (by up to 90%), or eliminate entirely, the carbon tax on energy-intensive industries such as steel, cement, aluminum, and flat glass. The concern was that the competitiveness of these industries would be harmed by high carbon taxes. Unless the tax were substantially reduced or eliminated, firms in these and other energy-intensive industries might move operations to and/or make any new investments in countries that did not have a carbon tax - or a much lower one. Not only would there be a loss of production activity and jobs at home, but there would be a "leakage" of carbon emissions abroad, muting the reduction in global emissions. The claim by IPCC WG III (2007) that "carbon leakage" would be minor, affecting no more than 20% of emissions reduction is not reflected in the response of parliaments.

(b) EU Emission Permits

The story continues with the EU Emission Trading System (ETS). In the first three years of the ETS, 2005-2007, most EU country allocated emissions permits so as to minimize the impacts of emission caps on vulnerable industries. The result was that the emission caps were hardly binding. As the second phase (2008-2012) of the ETS program began, the global recession took the pressure off the emission caps and has allowed emission permit prices to remain low. Nevertheless, concern about the impact on energy intensive industry continues. For example, Germany has moved to ameliorate the impact of rising electricity prices on such electricity intensive industries as aluminum, copper and zinc by subsidizing their electricity bills (Financial Times, May 26, 2009), And at the EU summit in December 2008, Germany successfully argued that energy-intensive industries should not be required to buy emission permits between 2013-2020.

(c) The US Waxman-Markey Bill

Similar pressures have come to bear on the US Congress' Waxman-Markey bill. The original bill had called for a 20% reduction in US emissions from their 2005 level with 100% auctioning of emission permits. However, to attain sufficient support in a Committee in which Democrats outnumber the Republicans almost two to one, many concessions had to be made to representatives from coal states and districts. When Waxman-Markey (WM) emerged from Committee it did so with: (i) a reduced emission reduction target (17%); (ii) a provision to allocate rather than auction 57% of total permits to the electric power and energy intensive industries; and (iii) a provision that would allow domestic ***uncapped*** sectors and international sources to sell up to 2 billion tons of "offsets" per annum to capped firms and industries in return for undertaking their own emission reductions. (The "offsets" are controversial. They are virtually impossible to monitor; are a recipe for fraud; add carbon price uncertainty; will provide a field day for lobbyists and "rent-seekers"; generate public distrust; erode political capital; and blemish the integrity that the Obama administration has worked hard to restore in Washington.)

By the time the WM Bill passed the US House of Representatives, by a 219-212 vote, on June 26, 85% of the permits would be allocated. Moreover, some of the limited revenues from the 15% of permits auctioned would be used to subsidize consumers who find their electricity and gas bills rising to rapidly. Little is left to underwrite basic R&D. As a result, the Breakthrough Institute (2009) has estimated that the cap in WM is not binding - is a cap in name only. Estimates made by the Congressional Budget Office and the EPA that the cost per household would be low, are another indication that actual emission reduction will come nowhere near the WM caps. Thus, in its present form, WM appears unlikely to do much to curb US emissions, while diverting funding and attention away from crucial R&D.

(d) A Carbon-Pricing Plan for Canada

Another glimpse into the potential ramifications of attempting to achieve emission reduction targets via "brute force" methods comes from Canada. The current Conservative government has proposed the adoption of emission cuts from current levels of 20% and 65% by 2020 and 2050, respectively. Although no means to achieve these targets has been adopted, Canada's National Roundtable on the Environment and the Economy (NRTEE) has worked on a plan to meet them. The NRTEE recently circulated a report with a ***carbon pricing*** proposal. The goal of the NRTEE proposal is to achieve the 20% and 65% cuts in carbon emissions using a "cap and trade" approach to carbon pricing (NRTEE, 2009).

In producing its report, the NRTEE commissioned modeling analyses of their proposal to gauge its implications. The findings are instructive---although perhaps not in the way the NRTEE report contemplated. For our purposes, there are two striking facts about the NRTEE plan. First, to achieve the 2020 target of a 20% reduction in emissions from current levels, carbon prices (in Canadian dollars) rise from $15/tCO2 in 2010 to $115/tCO2 in 2020. Secondly, the rapidly rising carbon price has a substantial impact on some energy intensive industries. How great depends on the carbon pricing policies of other countries. (See Table 3)

Bataille et al (2009) investigate the implications of the NRTEE's carbon pricing proposal for Canada's competitiveness. Their findings are indicated in Table 3. Bataille et al. consider three cases: Canada acts alone; only OECD countries follow Canada's example; all countries "cooperate - that is follow Canada's example. Since a $115/tCO2 carbon price implies a $329 tax per tonne of coal (coal prices are typically well under $100/tonne), we can assume that neither the US nor China will "cooperate", and the same is likely true of many other countries that use coal for energy purposes (e.g. Poland and Germany). Thus, if Canada adopted the NRTEE proposal, effectively Canada will be acting alone, even though Canada's goals (targets) are not dissimilar to those nominally adopted by many OECD countries.

Table 3 indicates that several energy intensive industries would experience substantial declines in physical output from "business as usual" levels. This is clearly the case for "industrial minerals", such as cement, limestone and the silicates used in glass production, and for petroleum refining. If Canada acts alone (and the watering down of Waxman-Markey suggests the US would not begin to contemplate anything like a $100/t price for carbon dioxide), paper manufacturing and chemicals will be hit hard too. Somewhat surprising is the apparent lack of impact on Canada's steel industry and the very small impact on the metal smelting sector. These may reflect Canada's relative abundance of hydro power and lack of dependence on coal for electricity generation.

Table 3: Projected Changes in Physical Output of Energy-Intensive Sectors, 2020

	Scenario		
Industry	Canada Acts Alone	OECD Cooperates (% change)	Globe Cooperates
Chemical products (tones)	-10	-3	-2
Industrial minerals (tones)	-50	-27	-14
Iron and steel (tones)	0	0	0
Metal smelting (tones)	-3	-2	-1
Mineral mining (tones)	-1	-1	0
Paper manufacturing (tones)	-9	-4	-2
Other manufacturing (2005 $ GDP)	-4	-1	-1
Petroleum refining (cubic metres)	-28	-28	-27
Petroleum crude extraction (barrels per day)	0 to -8	O to -6	0 to -5
Natural gas extraction	0 to -16	0 to -15	0 to -14
Note: For petroleum and natural gas extraction, the first estimate is with economic rents, the second is with no economic rents.			
Source: Authors' calculations from CIMS.			

Source: Bataille, et al, (2009)

Few countries, in fact, are likely to follow the steeply rising carbon pricing policy that Canadian modelers indicate is required to achieve the NRTEE plan. Not only is there a huge rise in carbon prices in the first ten years, the NRTEE plan calls for carbon prices that continue their steep rise for another decade, reaching $300/t CO2 (or about $860/tonne of coal) a little after 2030. While Canada's large hydro-electric resources limit its dependence on coal for electricity generation, and provide some insulation from the NRTEE schedule of carbon prices, few other countries are so fortunate. For the others, carbon prices in the hundreds of dollars are not thinkable until there are reliable, plentiful, and cost competitive non-carbon emitting sources of energy available and deployable, in which case high carbon prices no longer are unnecessary. Here is another reason why a carbon pricing policy should follow rather than lead a technology-led policy.

4. Of Targets and Non-Credible Commitments

Still another way to understand the logic behind the technology-led approach is as a means of freeing ourselves from the straitjacket of targets and non-credible commitments to them. Like it or not, climate policy is still ruled by the setting of emission reduction targets and pressures on countries to commit to them. Here are some examples.

a. The original Waxman-Markey Bill, drawn up by the US House of Representatives Energy and Environment Committee, called for a 20% cut in US emissions from 2005 levels by 2020, and 80% by 2050. When the bill emerged from Committee, the targets were slightly modified to 17% by 2020 and 83% by 2050.

b. The UN target of a 20-25% cut in developed country emissions below 1990 level by 2020. (Developing countries have called for the cut to be 40% by 2020 before they would sign on to emission reduction responsibilities.)

c. The G-8 target of reducing ***global*** emissions 50% by 2050 from 2007 levels. This was approved at the meeting of the G-8 in 2007, and a similar target was agreed to at the G-8 meeting in 2009.

d. (d) A 2100 target calling for a global emission cut from current levels of 80%.

We can provide some metrics by which we can evaluate the feasibility of these targets.

a. The ***original*** version of the US House of Representatives Waxman-Markey (WM) bill would have auctioned virtually all of the emission permits. To reach its targets from domestic reductions, the bill would have required a 4.5% rate of de-carbonization (rate of decline in the carbon intensity of output (CIO), C/GDP) if the US economic growth from 2010-2020 were 2.3%; if the growth rate were a more robust 3.3%, the required rate of de-carbonization (rate of reduction in CIO) would be 5.5%. Assuming a $14 trillion US economy in 2010 and a 2.3% rate of growth 2010-2020, achieving the WM emission reduction target would mean a ***cumulative*** loss of US GDP of $8.9 trillion, ***even if the rate of decline in the carbon intensity of GDP averaged a phenomenal 3.2% from 2010-2020***. (From 1980-2006, the US rate of decline in the carbon intensity of output was about 2.2%, more than 50% higher than the 1.3% average for the world as a whole.)

b. The UN 2020 targets have been the object of much recent discussion and cajoling. The UN wants these targets to provide the basis of the commitments made at the forthcoming Copenhagen 2009 Congress to finalize a successor to the Kyoto Protocol. Each developed country has been formulating plans. Japan has said it would commit to a cut of 15% below 2005 levels - or 6% below 1990. The Japanese plan has been roundly (and unfairly) criticized as much too little - although it may be feasible. The UK Climate Change Act of 2008 calls for cuts of 34% below 1990 by 2022 and 80% below 1990 by 2050. The UK plan would require 4.0%+ rates of decline in the carbon intensity of GDP 2007-2022, and a 5.5% rate 2007-2050 (Pielke, 2009) - rates which are almost certainly infeasible.

c. The G-8 target of reducing global emissions 50% by 2050 from current levels would require a 4.2% rate of de-carbonization of the global economy if the rate of growth of GWP from 2010-2050 were 2.5% per annum. By 2050, the ***world as a whole*** would have to have a carbon intensity of GDP similar to that currently enjoyed by Switzerland.

d. For the US to cut its emissions 80% by 2050, would require an average annual rate of de-carbonization of 6.0%, if US GDP grows at a rate of only 2.0%, 2010-2050. The required average annual rate of decline in the carbon intensity of GDP would have to be 6.5% if the GDP growth rate averaged 2.5%.

e. If global emissions are to be cut by 80% by 2100, then the average annual rate of de-carbonization must be 4.0%, assuming the global economy grows at a 2.2% rate from 2010-2100. If the global growth rate were 2.7%, the average annual rate of global de-carbonization in the remainder of the 21st would have to be 4.5%.

These rates are probably unattainable. In any event, it would take a technological revolution to make possible the longer-term targets. Faced with these conditions, we think the rational strategy would dispense with emission-reduction targets and reverse the time-related roles of energy R&D and carbon pricing. The main aim of current climate policy would focus on (i) raising the rate at which the carbon intensity of output declines, and (ii) bringing down the cost and raising the reliability, effectiveness, and scalability of the means of achieving large future reductions in emissions. An initially low carbon price would first finance and second, as the carbon price slowly rises, send a "forward price signal". This is the logic behind a technology-led climate policy.

AN "INCENTIVE-COMPATIBLE" TECHNOLOGY RACE

It is much easier to talk about a technology policy than it is to carry out an effective one. It is much easier to spend on R&D than assure the monies are well spent. This is especially so where the market cannot be counted on to exercise the sort of discipline that should avoid the most egregious waste. The problem is that neither the private sector nor the public sector alone possesses the appropriate incentives to create the sort of energy technology revolution that is required to stabilize climate. Both private and public investment in R&D will be needed. Although we focus on the latter, we assume there will be growing private interest (as there already is) in investments in carbon-free energy R&D, especially at the applied development and commercialization stages. Here, however, we focus on publicly funded R&D which will be especially important at the basic R&D stages. Before proceeding further, it is useful to briefly look at the R&D literature.

What do we know about inducements to R&D and innovation? Much of the relevant economic literature on R&D, patents, and innovation is found in the field of industrial organization. A dominant theme has been whether monopoly power or competition is "better" for innovation. Schumpeter (1942) postulated that market power provided both the finance (profits) and the incentive (future market power and profits) for undertaking risky and uncertain investments in R&D and other innovative activities. But Arrow (1962) demonstrated that, in principle, a firm in a competitive (price-taking) industry has more to gain from a process (cost-reducing) invention/innovation than does a monopoly firm. Of course, market power does not imply that a firm has a monopoly, and competition can be between a small number of rivals, not just among a large number of price-taking firms who ignore rival behaviour. Dasgupta and Stiglitz (1980) demonstrated that firms in a market with a small number of rivals (an "oligopoly") had the greater need, and therefore incentive, to innovate because the very survival of each might depend on at least some innovative success. The Dasgupta and Stiglitz paper is useful in thinking about the organization of a technology race.

There is a growing literature on technology change particularly as it relates to climate change. Popp, Newell, and Jaffe (2009) review a large literature on energy, environment and technological change. Clarke, et al (2006), address the sources of technological change, finding empirical support for the importance of spillovers and learning-by-doing. The IPCC (Metz et al, 2007) reviews a modeling literature in which the impact of carbon prices on (induced) energy technology change is central. Jaffe, et al (2005) address the market failures that surround technology and environmental policy. They conclude these provide a strong rationale for a “portfolio of public policies” to deal with both technology development and emissions reduction. Baker and Adu-Bonnah (2008) investigate how climate change ***uncertainty*** affects the ***optimal*** amount of investment in risky R&D programs (it increases it!).

Nordhaus (2002) uses his DICE model to assess the likely impact of induced innovation, and finds it to be relatively small. While Nordhaus has not placed much emphasis on a R&D policies in the context of climate change, it is perhaps significant that in his most recent book (Nordhaus, 2008), he finds that low cost “backstop” technology(ies), if it/they could be developed (as opposed to assumed as in many economy-environment models), dominates all other policy options. Although he appears doubtful any “low cost backstops” will appear, Nordhaus (2008: 88) says that “intensive research on energy sources is justified”. Finally, the literature on “mechanism design” and “implementation theory” (Maskin, 2008) may yield some practical applications to “incentive compatible” R&D programs.

The industrial organization literature also considers the role of patents and the implications of patent races. Patents explicitly raise issues of the effectiveness of: (i) incentives to innovate; (ii) the ability to appropriate the payoffs from successful innovation; and (iii) the ability to “invent around” patents, or “reverse engineer”. Because patents may not provide incentive enough to invest in R&D where uncertainty is high and appropriability is low, some have thought about alternative incentives. The problem is further complicated where public funding is required.

It is well known that where governments replace markets in the generation of R&D that a series of problems can arise. These include a tendency to “pick winners” - an exercise that often fails. There is also the possibility of “lock-in” to what turns out to be an inferior technology because of the government’s wish to get a quick return (before the next election) for the taxpayer/voter money it has laid out (Arthur, 1989). There is the ever-present problem of bureaucratic (turf) “infighting”, and decisions tainted by the exercise of lobbyist influence. Many of these problems could be reduced, if not eliminated, by some form of competition.

A modicum of competition can be injected into a government funded process in a number of ways. One approach is that of prizes (Wright, 1983; Montgomery and Smith, 2007). Here one might conceive of a “tournament” in which a prize(s) is given to “winners” in a contest to innovate. Still another initiative might take the form of awarding research contracts on the basis of creativity and perceived chances of success - but the choice of awardee could come perilously close to picking winners. In either case “incentive compatibility” can be increased if governments commission a set of independent (of government, and hopefully other political influence) experts to pick areas for an R&D competition and then to act as judges of the results of the competition (a version of the Gates Foundation model). This approach would minimize the problem of picking winners and “lock-in” (there could be a decision that no one won, and that another round of competition is in order), and the process should be able to avoid bureaucratic turf battles and lobbyist influence.

Another approach applies the model of an energy technology race and team work to the international arena. Here the idea is one of competing international consortia or teams acting as participants in an energy technology “race” (Green, 1994). One can conceive of several consortia, each made up of three or four countries capable of contributing science, engineering and other technology-related talent to one or more projects. Individual countries could be members of more than one consortium.

A technology "race" between competing consortia could capture public interest and imagination in its own right. It would also place a premium on creativity in developing effective, competitive, deployable carbon neutral technologies rather than requiring the sacrifices that would inevitably accompany brute-force mitigation. In this way, energy technology commitments could rally the current younger and future generations in a way that "brute force" mitigation cannot. However that may be, there would have to be intellectual property protection for new inventions, but also some agreement for cross-licensing potential users at reasonable rates.

An energy technology race that includes leading developing countries such as China, India Brazil, and S. Korea could also obviate at least part of the technology transfer problem. If these countries are parts of international consortia with developed countries they could share in successes. If they succeed on their own, they have something with which to "trade" with developed countries.

Whatever the means of introducing competition into the energy innovation process, it is crucial that the R&D be well funded, and consistent. Nothing could stunt the development of new technologies more than under-funding, or funding that is uncertain, stop and go. Although the funding of any specific venture should be held to accounts, with funding terminated after failure is inevitable, there must be adequate funds to continue a wide variety of research and development initiatives and to start new ones as older ones are terminated. The question is how to assure sufficient and consistent funding that is free (or largely free) of political interference or influence.

There are at least three possibilities. Only the last meets the tests of ***sufficiency, consistency***, and relative ***freedom from political influence***. The first is funding out of general funds, which could fail the test on all three grounds. Such funding is inherently subject to political discretion, could be diverted to other uses when tax revenues fall, and may never be sufficient in amount. The second approach is funding with a carbon tax, but if the tax revenue is not isolated from the general budget, it is prey to political interference, diversion to other uses. This approach would fail the ***consistency*** criterion.

The third approach would use a "dedicated" carbon tax, the revenues from which would be placed in a "trust fund" managed by "trustees" independent of Congress and the Administration in power. The "model" might be the US Interstate Highway Trust Fund created during the Eisenhower administration to build and maintain America's Interstate highways. It is funded by an 18 cents per gallon federal gasoline tax. Because that tax is viewed as providing clear benefits to a large part of the electorate and thus to most taxpayers, it has not generated the hostility that many other taxes have generated. A low carbon tax, dedicated to improving and strengthening the energy system, the funds for which are isolated in a "clean energy" trust fund, could be expected to be similarly welcome –or at least not too unwelcome to pass political muster.

Who or what will manage or direct a "Clean Energy "Trust Fund" is important. It is not just Congressional influence that is of concern, but political influence in general. The point of holding the carbon tax revenues in a trust fund is to increase the incentive compatibility of the R&D technology program. Thus it would make sense to draw the Board of Directors of the fund from the private sector as well as the public sector. The Directors would have to be given full oversight of how the funds are being used - hopefully drawing on engineering and scientific expertise in making choices and allocating funds. There would also have to be provision made for intellectual property protection and the allocation of patent rights. There would also have to be agreement on a reasonable rate at which other countries are cross licensed for new technologies that are developed.

A further embellishment would be to allow private entities to invest (put equity into) publicly-funded energy R&D projects. Doing so would add to the total R&D funds. As long as the Board of Directors of the Clean Energy trust fund make the choices of R&D projects, the injection of private equity should not affect the direction of innovation other than through the indirect influence of where they place their funds. One might anticipate substantial additional funding from fossil fuel producers as they attempt to diversify their portfoliosand their risks.

THE TECHNOLOGY-LED PROPOSAL

The preceding five sections have attempted to make a systematic case for a technology-led climate policy. In this section we set out proposed means of carrying through a technology-led strategy for the next 10 years (and beyond). The two strategies (i) focus on "enabling" technologies, and (ii) focus on "breakthrough" technologies are not mutually exclusive, and in some cases new technologies fit both categories. But their emphasis is different. While both strategies should be pursued at least to some extent, our analysis tries to answer the question, which should be emphasized over the next decade.

The two strategies are strongly supported by the current state and long-term capabilities of current carbon neutral energy technologies. Some technologies are close to being ready but cannot be scaled-up without the development or supply of an "enabling" technology. Examples include: (a) grid integration and upgrade; smarter grids; DC lines for long distance transmission; and most important of all utility scale storage for intermittent solar and wind energy (the last would constitute a "breakthrough" technology as well); (b) more energy efficient retrofits for fossil fuel-fired electricity generating plants to allow for CO2 capture from existing plants; (c) identification of safe and secure geologic storage sites for captured CO2; (d) methods to "spike" plutonium produced as part on a nuclear electric closed cycles process (which would greatly economize on uranium 235 and substantially reduce nuclear waste).

Examples of "breakthrough" technologies include: (a) a class of widely usable "breeder reactors; (b) nuclear fusion; (c) deep geothermal; (d) worldwide "superconducting" grid; (e) air capture of CO2; and (f) many of the steps required to make a "hydrogen economy" feasible. Most of these may be decades away from being operative. The list is not inclusive of all possibilities.

The two strategies are interdependent, particularly over longer time horizons than a decade. Many current carbon-free technologies require "enabling" technologies to become scalable. But these will not be enough. Breakthrough technologies will be needed - and research on these needs to start early. Thus in the benefit-cost analysis, we do not, and cannot, distinguish between the two.

Before proceeding to an evaluation of the technology-led proposal, there are a number of issues to consider; each provides a glimpse of how we view the technology problem from an economic standpoint.

(a) The technology cost function

(1) $C = F + vq$; where
C = total costs
F = fixed costs, most of which are up-front, sunk costs in R&D
v = long run average variable production costs

In average cost (AC) terms, we have:

(2) $C/q = F/q + v$; which implies that AC declines as the quantity of output (q) (or length of production run) increases.

If, in addition, there are learning-by-doing effects in the production of the output, we have:

(2') $C = F + vq^{\alpha}$; where $\alpha < 1$

In our view, the economics of researching, developing, and testing new, uncertain-of-success, energy technologies is wrapped up in the fixed cost factor, F. We agree with the analysis of Montgomery and Smith (2007) that there is a "dynamic" *time inconsistency* that makes highly doubtful whether the market will supply the funds for the large "up-front" sunk cost component of F, particularly when "up-front" may mean decades away rather than years. In other words, if the time from basic research and development is long, the private sector is very unlikely to make risky investments which are uncertain of success and the payoffs of which are in the distant future. Moreover, the inability of current governments to tie the hands of future governments to do anything more than cover the costs of production of a successful innovation makes the *time inconsistency* complete. The publicly funded R&D "socializes" the risks inherent in the "F" term.

(b) Competition

But that is not the end of the economic problem: the way in which the R&D funds are used should maximize the opportunities for success and minimize outright "waste". (The failure of a particular scientific initiative to bear fruit is **not** "waste".) In section VI we briefly described some means of getting the most out of the funds designated for energy R&D. We believe that the injection of competition in technological pursuit (as opposed to competition for funds) is important, and would contribute to what we term "incentive compatibility".

(c) The "Technology Return" to R&D Investment

Here we introduce a construct that we believe is very useful in undertaking the benefit-cost analysis and in comprehending our estimates. To do so, we develop what we believe is a new (and valuable) concept: the "carbon intensity-reducing return to R&D investment" (or

CIR^3D). The "carbon intensity" referred to here is the ratio of carbon emissions to output (GDP - or globally GWP). The idea underlying CIR^3D is that effective investments in energy R&D lead to reductions in the carbon intensity of output (CIO=C/GWP). They do so via reductions in: (i) the energy intensity of output (EI=E/GDP) and/or (ii) the carbon content of energy (CCE= C/E). The rate at which R&D investments are translated into carbon reducing technologies (accounting for the decline in the CIO) is crucial to estimating the benefits of a technology-led approach.

We define the following:

a. **"Baseline" or "historic" rate of CIO reduction**: this is the rate of reduction in the carbon intensity of output (C/GDP) which would occur "naturally", that is without the help of R&D investments in "enabling" and or "breakthrough" energy technologies. **[Line CD in Fig. 5]**

b. **The *constant* average annual rate of decline in CIO** that is required to achieve climate stabilization, ***given*** a trend rate of GWP growth and an emission level consistent with a "targeted" atmospheric concentration of CO_2 (or more generally GHGs). **[Line AB in Fig.5]**

c. **The "straight line" rate of decline in CIO**; this is the ***constant rate of increase*** in the decline in CIO that achieves the targeted atmospheric concentration level. [**Line EF in Figure 5**. On average, the rates indicated by EF are equal to the constant rate indicated by line AB]

d. The "trend" rate of growth in GWP (g). (This is needed in order to derive (b) and (c).)

e. The carbon intensity reducing R&D curve, the slope of which at any point is the CIR^3D (**This is the upward sloping *curve* in Fig. 5**.)

To give some feel for what we doing, it is useful first to set out the well-known Kaya Identity (3) and a further simplified form of the Identity (3'):

(3) $$C = P(\frac{GWP}{P})(\frac{E}{GWP})(\frac{C}{E});$$ where

C = carbon dioxide emissions ;
P = population;
GWP = gross world product;
E = energy consumption;

Cancelling the P and E terms we have

(3') $$C = GWP(\frac{C}{GWP});$$

Taking the time derivative of the natural logs of (3')

(4) $$\%\Delta C = \%\Delta GWP + \%\Delta(\frac{C}{GWP});$$ where %Δ is the average annual rate of change

Let us introduce some numbers. The "historic" rate of decline in carbon intensity of output (RCIO) is approximately 1.3%. If the growth rate of GWP is 3.0%, CO_2 emissions would grow at an average annual rate of 1.7%, which, in fact, is the rate of growth of CO_2 experienced from 1980 to 2006.

Now let us look forward. Suppose the long-term (2010-2100) "trend" rate of growth in GWP (g) is 2.2%. Suppose further, that in order to avoid going above a specified atmospheric concentration of CO2, emissions must be reduced from about 8 GtC in 2010 to 2.5 GtC in 2100. The rate of reduction in C implied by reducing emissions from 8 to 2.5 GtC in 90 years (2010-2100) is 1.3%.

Using (4): we can derive the ***required average annual rate of decline*** in C/GWP:

-1.3% = 2.2% + %Δ (C/GWP), implying that the last term (CIR^3D) is -3.5% .

In other words, the rate of decline in C/GWP must average -3.5%, which gives us a value for (b) above.

To derive the ***"baseline"*** rate of decline in CIO, the rate that would "naturally" hold in the absence of "enabling" or "breakthrough" technologies, we can draw on: (i) historical evidence; (ii) predictions based on what is known about the scope for EI decline (Baksi and Green, 2007), and the current capabilities of carbon-free energies (Hoffert et al, 2002, Caldeira, et al, 2003; Green et al, 2007; Lewis. 2007b); (iii) what is assumed in emission scenarios. (A problem with the scenario approach is that most of the IPCC emission scenarios are highly unrealistic about what might occur naturally. However, one of the scenarios, B2, is close enough to be used in our benefit-cost analysis.)

Using historical evidence would give a baseline decline in RCIO of 1.3% (Hoffert et al, 1998). Evidence based on analyses of EI and CCI (ii) yield a rate of 1.2% (Baksi and Green; and Green, et al, 2007), and the IPCC B2 scenario (1.4%). Pulling together the required rate of decline in CIO (line AB) in **Figure 5** and the baseline rate of decline in CIO (line CD) allows us to derive the "straight line" rate of CIO decline line, EF. The curve reflects the impact of a technology-led policy on the carbon intensity of output (CIO).

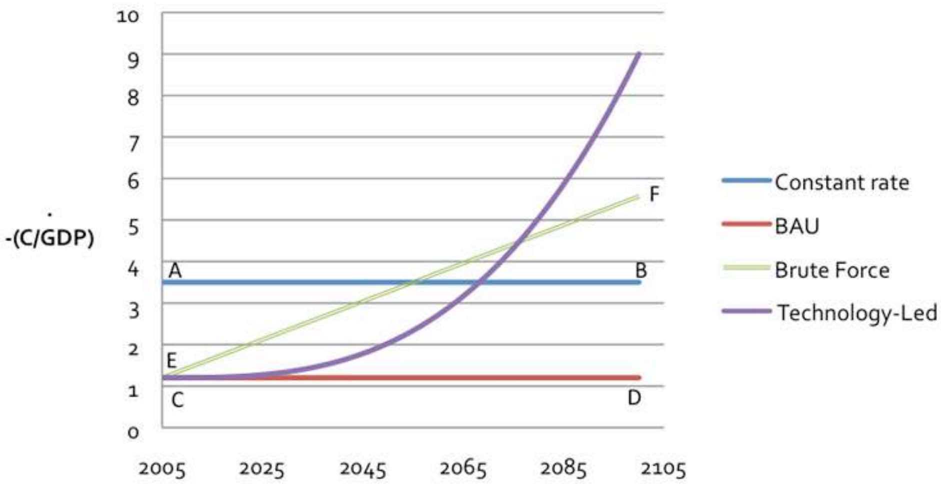
Some examples may illustrate how Figure 5 can help us understand the implications of various emission reduction proposals.

a. The G-8 target of reducing global emissions 50% by 2050 from current levels would require a 4.2% rate of de-carbonization if the global economy is to grow at an annual average rate of GWP of 2.5% per annum (2010-2050).

b. If global emissions are to be cut by 80% by 2100, then the average annual rate of de-carbonization must be 4.0%, assuming the global economy is to grow at a 2.2% rate from 2010-2100.

The examples highlight a simple fact. The widely discussed targets for emission reductions require a huge increase in the rate of decline in the carbon-intensity of output (RCIO). To come even close to achieving a long-term global average RCIO greater than 2.0, to say nothing of 3.0, 4.0 or higher rates, will require a thorough-going transformation in the way in which individual economies and the world produce and transform energy. The required rates of de-carbonization imply a transformation of energy systems so large and rapid that their achievement requires developing a fleet of scalable carbon-free energy technologies.

Figure 5: Technology Return on R&D



(d) "Crowding Out"

Before moving on, we should acknowledge an issue that has been raised by William Nordhaus (2002) and his former student David Popp (2004). Nordhaus and Popp have argued that directing R&D spending to the climate change problem is likely to misallocate scarce scientific and engineering resources. There are many competing uses for scarce scientific talent, implying an extra dollar spent on energy R&D is likely to yield benefits much smaller than spending that R&D dollar on an alternative project. In effect investment in R&D would "crowd out" other even more worthwhile R&D.

We think, however, that this argument is flawed in three ways. First, energy R&D spending, in the US and globally, has significantly declined over the last quarter century (Nemet and Kammen, 2006; Barrett, 2009). Second, climate change and the energy R&D spending that will be needed has a much longer time dimension than other scientific R&D. Thus the diversion of scientific resources away from other important uses is likely to be smaller than is implied by the Nordhaus analysis. Third, and most important, whatever concerns a large and growing global population may generate, it has meant an increase in brain power (Johnson, 2000). An increasing amount of that brain power and scientific talent is in East and South Asia.

The Nordhaus and Popp analyses appear to overlook the increasing supply elasticity of scientific and engineering talent when viewed in global terms. Moreover, the Nordhaus and Popp analyses overlook the attraction of new (or additional) talent toward a real and meaningful technology race. Such attraction may provide an outlet for the "best and the brightest" of our mathematical and physics talent, many of whom were hired (until 2007) to use their mathematical capabilities to craft financial "weapons of mass destruction" on behalf of those who helped bring on a world recession.

BENEFIT COST ANLYSIS

1. Introductory Comments

We come to what is by far the most difficult part of the project: calculating benefit-cost ratios for the proposed "solutions". There are a number of reasons why carrying out a BCA analysis is difficult and debatable, especially where technology "solutions" are concerned. One obvious problem is that because time is of the essence in climate change-related BCA analysis, it makes a difference when new, scalable energy technologies will become available, and ready for deployment. It is really impossible to predict success, much less date of success, in advance, although with a large number of technological initiatives underway, one might find that the law of large numbers comes in handy. Another problem we face is comparing specific technology "solutions" such as an emphasis on "enabling" technologies, or alternatively on "breakthrough" technologies. We therefore assume in our BCAs that both types of R&D will be undertaken, while recognizing that success in developing enabling technologies may give an earlier return to R&D investments.

A second issue is that as a matter of current decision-making, the "default" climate policy is no longer one of BAU or "no policy". Rather the "default" position at Copenhagen 2009 will be a policy, presumably one that is along the lines of the emission reduction targets and commitments adopted by most developed countries at Kyoto. This has implications for the role of "climate damages" in benefit-cost evaluations. In the standard BCA, the benefits are climate damages avoided. However, when comparing the technology-led proposal with another approach to mitigation, the main benefits are the abatement costs avoided by adopting the technology-led approach.

Given competing ways in which the benefits of a technology-led policy might be interpreted and evaluated, we have chosen three different ways of generating BCRs. These are:

a. The standard BCA approach using an emission scenario baseline. To carry out an evaluation of climate damages and those avoided by technology-led policy, we used William Nordhaus' DICE model

b. An analysis using ***cumulative emissions*** to indicate how close the technology-led approach comes to limiting the global rise in temperature to 2°C using cumulative emissions out to 2100. Here we make use of the findings of two recent papers (Meinshausen, et al, 2009; Allen, et al, 2009).

c. A third approach is estimates based on comparisons of a technology-led approach with a "brute force" mitigation approach to achieve widely discussed emission reduction targets.

Before turning to the three Benefit-Cost evaluations, we should say a word about how we approached the first of these (A), the standard BCA. As we do not have our own climate-economy model, we have used the well-known DICE model developed by William Nordhaus. There are two reasons for using the DICE model. One is that Professor Nordhaus makes the DICE model widely available (it is easily downloaded from his website). The second is that it is relatively easy (after a few weeks work) to learn to use by persons not already familiar with climate modeling.

However, the initial damage function parameter values[1] appear likely to underestimate climate damages. (See Nordhaus, 2008.) For example, the estimate of the PV of climate damages from a policy of delaying climate change action 250 years is only $22.5 trillion. At the same time the PV of climate change damages if warming could be limited to only 1.5°C is $9.95 trillion (Nordhaus, 2008, Table 5.1). What this means is that even if a technology-led policy of spending $100 billion a year for the next 90 years were able to limit warming to 1.5°C (something no one, including us, believes is achievable by any policy) the BCR would only be 3.9.

2. Benefit-Cost Calculations

In this section we undertake three different ways in which to derive benefit-cost ratios (BCAs)

A. Standard BCA

The goal here is to assess the cost-effectiveness of a technology-led policy with respect to a business-as-usual baseline scenario. To this end, we use the well known integrated assessment model (IAM) DICE-2007 designed by William Nordhaus[2] and apply a standard benefit-cost ratio (BCR):

BCR = NPV of climate damages not incurred NPV R&D expenditures[3]

Climate damages not incurred (numerator in BCR) is the difference between climate damages suffered under a baseline scenario and those not prevented under a technology-led policy. Throughout this section we assume R&D expenditures of 100 billion$/year for the period 2010-2100, an amount we believe sufficient to major reductions improvements in the carbon intensity of output. The procedure is as follows.

1) *Estimating technological return to R&D.*
Firstly, the emission path is estimated under our proposed technology-led policy by accelerating the historic rate of reduction in carbon intensity of output. A functional form for the relationship between R&D expenditures and carbon intensity of output is estimated as:

$$\bar{\mu} = 1 - \frac{\alpha\,(RD)^2}{\beta + (RD)^2}$$

Where μ is the reduction in carbon intensity of output due to R&D, α and β are parameters that may be adjusted depending on beliefs regarding R&D success; and lastly, (RD) is cumulative expenditure on R&D. This particular functional form allows for an initially slow return to R&D, followed by a period of breakthroughs and lastly decreasing returns. Although DICE is a reasonably flexible model that allows modification of its numerous parameters, only those directly related to carbon intensity have been modified in order to maintain the integrity of the BCRs and assure verifiability. The corresponding parameters in DICE used to simulate the technology led policy are: CO2-equivalent emissions-GNP ratio 2005 (SIG0); initial growth

1 Damage function parameters are not modified to obtain the BCRs in this paper.
2 http://nordhaus.econ.yale.edu/DICE2007.htm
3 R&D expenditures refers to all stages of innovation and deployment.

of sigma per decade (GSIGMA); decline rate of decarbonisation per decade (DSIG); and quadratic term in decarbonisation (DSIG2).[4]

Three alternative rates of technological return to R&D are considered, an early, mid and late return (Figure 6). Figure 7 depicts the carbon intensity return to R&D of the three technology-led scenarios while Figure 8 depicts the resulting declining carbon intensity of output. We consider a successful technology led policy to be one which achieves cumulative emissions consistent with a 50% probability of remaining below a 2°C increase in temperature (Meinshausen et.al, 2009) such as in the scenarios of early and mid R&D returns. The primary difference between the early and late policies, is that the former reaches its peak carbon intensity decline at around 2035 while the latter successfully accelerates carbon intensity decline only around 2060. In the case of the least successful R&D program, where R&D returns on carbon intensity reductions are delayed, only a 32% reduction of ***cumulative*** emissions is achieved from the B2 scenario for the 2010 to 2100 period versus a 57% reduction in the successful case. Furthermore, the successful case presented here is by no means meant to be considered a best case scenario but rather a highly plausible one.

2) Simulation of baselines and technology-led policies.

Two alternative baselines are considered in order to assess the avoided damages of a technology-led policy: the IPCC B2 scenario, discussed in detail in section I and the DICE 'no-policy for 250 years' baseline (see Figure 1: Emissions by baseline/policy). The latter is included principally as a sensitivity analysis and to highlight the importance of baseline choice. Moreover, including the DICE baseline ensures that at least one of the baselines used is well calibrated to the model. Furthermore, as the B2 baseline is only available to 2100, B2 emissions are extrapolated out to 2200 (extended scenario), with a higher rate of decline in carbon intensity of output than the 2010-2100 trend would imply so as not to favourably bias our BCRs. Although the B2 scenario is characterized by assumptions on GDP growth rates, technological change, sectorial change etc, only the CO2 intensity parameters are modified to simulate the B2 emissions path and thus obtain climate damages. Each of the three technology led scenarios, the B2 extended scenario and the DICE baseline are then simulated altering the aforementioned parameters in DICE. Finally, climate damages are read from the output.

3) ***Benefit-cost ratios (BCR)***.

BCRs of net present values are calculated from the base year 2010 for the period 2010-2110, as well as for the period 2010-2200. Discount rates of 3% and 4% are used and, as a comparison Stern's 1.4% discount rate. We extend to 2200 because, in the case of a technology-led policy the major costs are incurred up-front, while the benefits are experienced for an extended period of time. The resulting BCRs are shown in Table 4 (Early return to R&D); Table 5 (Mid return to R&D); and Table 6 (Late return to R&D).

BCRs (at 3%) for the early return and mid return to R&D range from 2.17 – 3.64 for the first ninety years and 7.03 to 11.66 for the entire 190 year period. The DICE baseline produces higher BCRs given its lower built in rate of carbon intensity decline, and perhaps, a more suitable damage function calibration within the model.

4 Please contact the authors for specific parameter choices

The BCRs may reveal something about the private sector's willingness to invest in break-through technologies. Long term investments of $100 billion/year are unlikely to appear as induced technological change. In order to induce the required amount of technological change, the price of carbon would need to be set far above the social cost for the return to basic innovation to become potentially profitable in the private sector.

Figure 6: Emissions by baseline/policy (B2 extrapolated beyond 2100 by the authors)

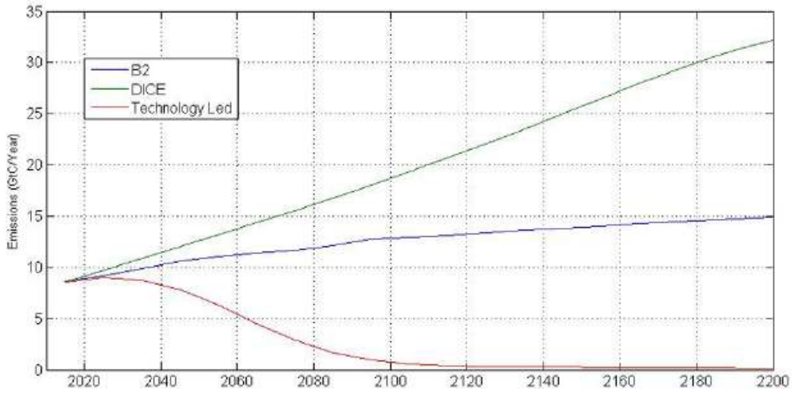


Figure 7: Carbon Intensity Return to R&D: Alternative Profiles

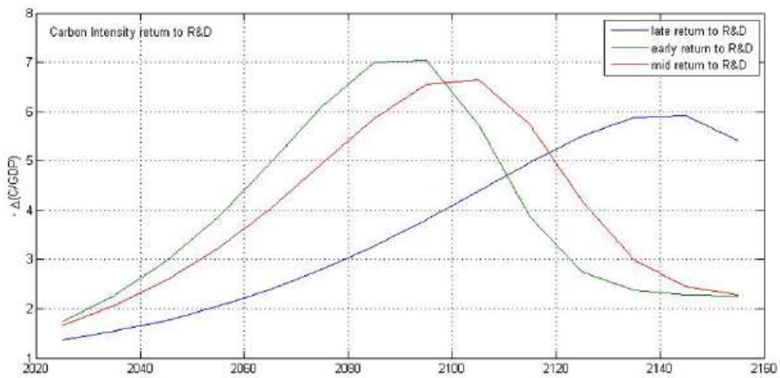
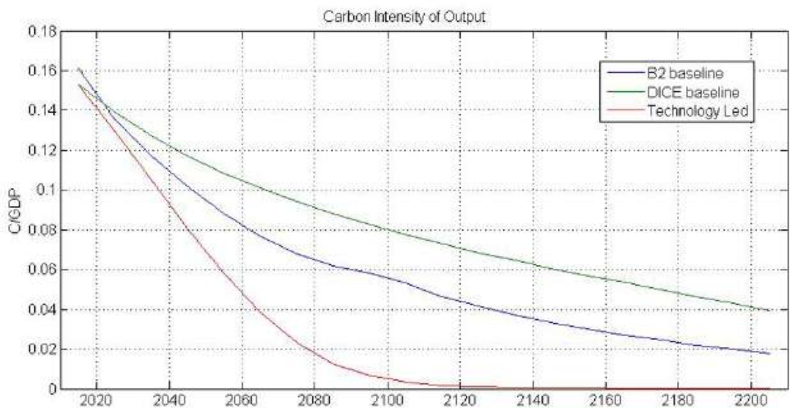


Figure 8: Carbon Intensity of Output by Scenario



B. Cumulative Emissions Analysis

Building on the notion that the global community appears determined to tackle the climate change challenge and current discussion emphasizes limiting temperature change to 2°C, we propose an alternative approach to the cost benefit analysis. We put forward the idea that the climate change debate has evolved beyond the point of whether a policy should be implemented to one which asks which policy is the most economically efficient and environmentally effective. Moreover, Allen et al. (2009) establish a fundamental notion of climate change on which our cumulative emissions analysis relies: peak increases in global temperature are dependent only on ***cumulative emissions*** and not the emission path.

We therefore propose a benefit-cost analysis based on cost-effectively limiting cumulative emissions to those consistent with limiting temperature increase to 2°C. Meinshausen et al. (2009) provide us with the basis for this alternative approach to a benefit-cost analysis. Meinshausen et al. surveyed a large number of climate models to determine the cumulative emissions 2007-2050 that would be good predictors of whether global temperature increase can be limited to no more than 2°C over the course of the 21st century. They provide cumulative global CO_2 emission budgets to 2050 and the related probabilities of a temperature increase that exceeds 2°C (also see Schmidt and Archer, 2009). Allen et al. (2009) go one step further than Meinshausen and specify cumulative emission over an indefinite time period and their associated peak warming. Particularly, in order to maintain warming to below 2°C, Allen et al. find allowable emissions to be 2050-2100 Gt CO_2 (or 572 GtC). Table 7 contrasts B2 scenario emissions, for the periods 2010-2050 and 2010-2100, with the cumulative emission allowances from Allen et al., Meinshausen et al., as well as the three technology-led proposals from the previous section.

Table 4: Early return to R&D

	Discount rate	Damages avoided from baseline (NPV)[5]		R&D costs (NPV)	BCR by baseline (R&D/damages avoided)	
		B2	DICE[6]	Tech Led	B2	DICE[7]
2010-2110	1.4%	26.57	38.57	5.1	5.21	7.56
	3%	7.75	11.27	3.1	**2.5**	**3.64**
	4%	3.77	5.49	2.43	1.55	2.26
2010-2200	1.4%	191.38	294.80	5.10	37.52	57.80
	3%	24.00	36.15	3.1	**7.74**	**11.66**
	4%	7.96	11.86	2.43	3.28	4.88

Table 5: Mid return to R&D

	Discount rate	Damages avoided from baseline (NPV)		R&D costs (NPV)	BCR by baseline (R&D/damages avoided)	
		B2	DICE	Tech Led	B2	DICE
2010-2110	1.4%	23.35	35.29	5.1	4.58	6.92
	3%	6.74	10.25	3.1	**2.17**	**3.31**
	4%	3.25	4.98	2.43	1.34	2.05
2010-2200	1.4%	178.31	281.72	5.10	34.96	55.24
	3%	21.78	33.93	3.1	**7.03**	**10.95**
	4%	7.10	11.00	2.43	2.92	4.53

Table 6: Late return to R&D

	Discount rate	Damages avoided from baseline (NPV)		R&D costs (NPV)	BCR by baseline (R&D/damages avoided)	
		B2	DICE	Tech Led	B2	DICE
2010-2110	1.4%	12.28	24.22	5.1	2.41	4.75
	3%	3.40	6.91	3.1	**1.10**	**2.23**
	4%	1.59	3.31	2.43	0.65	1.36
2010-2200	1.4%	128.83	232.25	5.10	25.26	45.55
	3%	14.49	26.64	3.1	**4.67**	**8.59**
	4%	4.39	8.29	2.43	1.81	3.42

Table 7: Cumulative Emissions Comparisons

	2010-2100	2010-2050
B2	997	395
Allen (2009) & Meinshausen (2009)	572	328
Early R&D	464	337
Mid R&D	520	350
Late R&D	727	388

The early and mid technology-led proposals remain, easily, within the cumulative emission budgets for the period 2010-2100. For the period 2010-2050 the technology-led proposals

5 NPVs are expressed in trillion $ PPP.
6 We would like to emphasize that we do not use the full power of the DICE model in that we are only using the climate damages calculated by DICE to obtain the BCRs.
7 DICE BCRs are included to complement B2 BCRs given that DICE damages are used.

fall only slightly short of the Meinshausen 2°C indicator targets, but given the rapidly declining rate of emissions in the early and mid technology-led profiles, as they apply to 2050-2100, they are largely in line with the limits established by Allen et al..

To produce a benefit-cost ratio, we compare the cost-effectiveness of a technology-led policy with a "brute force" policy in achieving a $\Delta T<2°C$ with 50% probability. Based on our analysis of achievable rates of decline in the carbon intensity of output, the 50% case may be the only one that is realizable given the considerable increases in the rate of decarbonisation required for the other, higher probability, cases. In line with the Meinshausen period, our benefit-cost analysis for the cumulative emissions case, is limited to the forty year period, 2010-2050. In Table 8, we determine the required rate of acceleration of decarbonisation, maintaining a constant growth rate of GDP that would be consistent with the probabilities of limiting cumulative emissions to or below desired levels. For a 50% probability of $\Delta T<2°C$, the emission budget for the period 2010-2050 is limited to 327 GtC. Consequently, to maintain a 2.5% growth of GDP we require an acceleration of decarbonisation of 3.5 percentage points.

The findings of Meinshausen et al. (2009) are summarized in the first two rows of Table 8. These rows indicate the carbon dioxide (CO_2) and carbon (C) emission budgets and their respective probabilities of limiting $\Delta T<2°C$. The third row indicates the required annual rise in the rate of decline in carbon intensity of output which would maintain global emissions 2010-2050 within their total budgets. Note, that in the "brute force" case, the zero value of the annual rise in the decarbonisation rate is not to be confused with a frozen technology baseline but rather a frozen rate of improvement in technology. We then use the Kaya Identity (see section VII) for a given emission budget to determine the required reduction in GDP growth consistent with BAU rate of decarbonisation growth.

We then used the net present values (NPV) of global world product for 2007-2050 (the last three rows of table 8) to calculate benefit-cost ratios for "brute force" and technology-led policies.

In the comparison of technology-led and "brute-force" mitigation policies we need make no claim on the value of the damages avoided. In both cases, damages avoided are ***assumed*** comparable as we consider identical cumulative emissions for the same period (2010-2050).

Table 8: Cumulative Emissions: A policy comparison

	'Brute Force'	Technology-Led
Prob. $\Delta T<2°C$	50	50
Cumulative CO_2	1203	1203
Cumulative GtC equiv.	327.79	327.79
Growth of	0	3.50%
2050 emissions (GtC/year)	7.449839	5.314783
Growth rate GDP (%)	1.3	2.5
NPV GDP (3%)	$1,182.77	$1,526.21
NPV GDP (4%)	$983.30	$1,246.63
NPV GDP (5%)	$830.37	$1,035.16

a. Technology-Led Policy

i. the benefits are the climate damages avoided out to 2050

ii. the costs are the discounted value of $100 billion a year of R&D for 40 years (2010-2050), $2.31 at 5% discount rate

iii. BCR = damages avoided/3.10

b. "Brute Force" Policy

i. the benefits are the climate damages avoided out to 2050.

ii. The costs of a "brute force" policy are the lower PV of GDP: $1035 - $830 = $205 trillion (at 5% discount rate)

iii. BCR = damages avoided/205

One could argue that the BCR for the brute force case is a ***worst*** case scenario (reflected in no change in the rate of decline of C/GDP from its "historic" 1.3% rate). At the same time, the results for the technology-led approach assumes that the R&D will be sufficiently successful in the next two or three decades to achieve by 2050 the Meinshausen et al. 50% Prob $\Delta T<2C$. Let us assume then that the technology-led BCR has been overstated by four-fold. Even then, the comparison of the technology-led policy with the "brute force" policy produces a BCR of 22.

C. Comparison of Technology-led and "Brute Force" Mitigation Policies

1. Introductory Comments

We also carried out a Benefit-Cost Analysis comparing a technology-led policy with a policy to achieve emission reduction targets without consideration of whether the technologies are available to meet the targets at a reasonable cost. We have termed this "brute force" mitigation, and have elaborated on its implications earlier in the paper.

We think it is important that some comparison be made between a technology-led policy and a policy that effectively calls for mitigation by "brute force". Recall that a policy is "brute force" if it requires polities to meet emission caps when the required energy technologies have not been developed. In these cases, it is necessary to either reduce the emission reduction goals or risk very large reductions in GDP (or GWP).

In section V, we noted several examples of proposed targets. Some were global some for the US. Some applied to 2020, others to 2050 or 2100. Each involved average annual reductions in the carbon intensity of output (GDP or GWP) of at least 4.0% if the targets are to be met, and met via emission reductions at home. In contrast, the "historic" rate of decline in the carbon intensity of output (RCIO) is 1.3% and that of the B2 scenario 1.4 %. Thus the gap between the ***required*** increase in RCIO and the historic or BAU RCIOs is huge. (Note that the RCIO baseline is NOT a "frozen technology" baseline, but one based on historic RCIO or B2 levels - each of which includes substantial productivity and technological change. See the description of the B2 scenario in section I, and the discussion of the RCIO in section VII.

In our BCA comparison between "brute force" and technology-led policies we need to make some assumption about the response of RCIO in the case of "brute force" policies. How much could a "brute force" policy raise the RCIO as a result of pressure to stay within or meet demanding emission caps? It is inconceivable to us that carbon pricing ***alone*** could do more than make a small dent in the between the gap between the "historic" RCIO (globally averaged at ~1.3%/yr) and the required average annual rates of decline carbon intensity (RCIO), which as the examples in sections V and VII indicate, are in excess of 4.0%/yr .

So, how much might a "brute force" policy increase the decline in RCIO above the "historic" or BAU level? A generous estimate would be 50% by 2050 and perhaps 100% (at the outside) by 2100. But if that is all a brute force policy could do, either the emission reduction targets would be missed by a very wide mark, or the GWP growth rate would be reduced to zero or negative levels, as equation (4) in section VII implies.

Thus, in our BCA comparisons of a technology-led with a "brute force" policy, we decide to set the "brute force" average annual RCIO at 100% of "historic" levels (2010- 2050) to 2.6%, and by 150% of "historic" levels (2010-2100) to 3.3%. We regard these ***as wildly and unrealistically high*** in the absence of a technology-based climate policy. But they serve our purpose by ***understating***, by a considerable margin, the mitigation costs of a "brute force" policy. (They also serve the purpose of providing a rough indicator of a "feasible brute force" policy, one in which the emission reduction targets are substantially lower and the RCIOs are more realistic.)

2. Assumptions of Technology-led vs "Brute Force" Benefit-Cost calculations

In making our calculations of the benefits and costs of a technology-led policy that is evaluated against a "brute force" mitigation baseline, the following assumptions or calculations apply. (Further details and explanations relating to these assumptions and the BCRs to follow are found in Appendix A.)

i. The **"trend"** or BAU **rate of growth of GWP** is **2.3%, 2010-2050**; and **2.0%, 2010-2100**;

ii. The targets for a "brute force" policy: ***Global*** carbon dioxide emissions from energy-related sources are to be cut 50% by 2050, from current levels of 8GtC, and by 80% by 2100. These cuts require average annual rates of decline in CO2 emissions of **1.7%** (2010-2050) and **1.8%** (2010-2050).

iii. From equation (4) in section VII, the **required** rate of decline in the carbon intensity of output (RCIO) is 4.0% for 2010-2050 (2.3% + 1.7%); and 4.0% for 2010-2100 (2.0% + 1.8%), if substantial reductions in GWP are to be avoided.

iv. However, if the maximum achievable RCIO are 2.6% (for 2010-2050) and 3.3% (for 2010-2100) under a "brute force" policy, then a rearrangement of equation (4) implies that to achieve the emission reduction targets will require limiting the GWP growth rate of GWP to 0.9% (2010-2050) and 1.5% (2010-2100).

(4) $\%\Delta GWP = \%\Delta C + \%\Delta(C/GWP)$, where RCIO is = $\%\Delta(C/GWP)$ is

$0.9 = -1.7\% + 2.6\%$ (2010-2050)

$1.5\% = -1.8\% + 3.3\%$ (2010-2100)

v. Avoidable Climate Damages Not Avoided. There will be some climate damages under either a "brute force" or a technology-led policy. Let us conservatively assume that (i) the "brute force policy achieves its emission-reduction target, albeit at the expense of (large) reductions in the GWP growth rate; and (ii) the technology-led policy, because it works at emission reduction more slowly (at least initially) results in somewhat higher temperature and higher climate damages than does a "brute force" policy that is able to achieve the emission reduction target. The difference in damages between the two we term "avoidable climate damages not avoided

vi. Avoidable climate damages that are not avoided under a technology-led policy are assumed to be 2% of GWP. This figure is consistent with 1.5°C additional (2.5°C total) warming.

vii. (See equation (6) above).

viii. R&D expenditures are $100 billion a year 2010-2100. The marginal cost of public funds used to finance the R&D is 25%. (That is, the cost of R&D spending is grossed up by 1.25.)

ix. Deployment costs of carbon emission-free (or carbon neutral) energy technologies are 1% of GWP with a technology-led policy.

x. Discount rates are: 4.0, 3.0% or 1.4%. We use both "high" and "low" discount rates to sidestep a debate that threatens to turn the "economics of climate change into a debate over the appropriate discount rate (Stern 2008; Nordhaus; 2007a, 2007b; Weitzman; 2007, 2009; Heal, 2009).

3. The BCR Formula:

$$\text{BCR} = \frac{\text{Mitigation costs avoided} - \text{Avoidable climate damages not avoided}}{\text{R\&D expenditures (1+ marginal cost of public funds)} + \text{deployment costs}}$$

4. The BCR Estimates:

Table 9: Technology-led vs. 'Brute Force' BCRs

Discount Rate	2010-2050	2010-2100
4.0%	15.7	10.0
3.0%	16.7	<u>12.4</u>
1.4%	18.0	16.5

We have not estimated a range of BCRs for the technology-led vs. "brute force" comparison. The reason is that the assumptions made in the analysis were: favorable to the performance of the "brute force" policy (the high RCIOs and the assumption that the policy could actually achieve its emission-reduction target), and/or unfavorable to the technology-led policy (it would result in substantial climate damages as a % of GWP relative to "brute force policy" and it incurs substantial deployment costs). Thus, the BCRs presented in Table 9 should be considered as the lower end of the range. Alternative assumptions would have produced higher BCRs.

Of some note is that the assumptions appear to have produced somewhat lower BCRs for 2010-2100 than for the shorter period 2010-2050. This may tell us that using "brute force" policies to attempt to achieve a 50% reduction in **global** emissions by 2050 would be especially damaging relative to a technology-led policy.

3. Concluding Comments

We have employed three different ways of evaluating our technology-led proposal. The main estimates are those with a BAU baseline, using the DICE model to estimate damages avoided. The BCRs are, with one exception, greater than 1, and are larger for the 2010-2200 period than the 2010-2100 period. The two other means of evaluating the technology-led proposal, one based on cumulative emissions with a 2°C warming benchmark, and the other a comparison of a technology-led policy with a "brute force" mitigation policy, produce high BCRs. Overall, a successful technology-led policy appears 'robust' in benefit-cost terms.

SOME CONCLUDING THOUGHTS

In our concluding section, we pose and then answer five questions. Then we summarize the main message of the Assessment paper.

A. The Questions

1. Are there any parallels to the technology challenge posed by climate stabilization?
2. Why hasn't a technology-led policy been adopted?
3. Why will there be continued resistance to a technology-led approach?
4. Why is it likely a technology-led policy will eventually be adopted?
5. What is the relation between a technology-led climate policy and some other climate-related policies?
6. What are the implications of "tipping points" and "catastrophic" climate change?

B. Some Answers to the Questions

1. Are their parallels to the technology challenge posed by climate stabilization?

In their 1998 paper in ***Nature,*** Hoffert et al concluded that "researching, developing, and commercializing carbon-free primary power… could require efforts…pursued with the urgency of the Manhattan Project or Apollo space program" (Hoffert et, al, 1998: 884). Writing again in 2002, Hoffert et al, wrote that combating global warming by radical restructuring of the global energy system could be the technology challenge of the century" (Hoffert et al, 2002: 372). Not all observers have found the Manhattan/Apollo analogs useful. Our view is closer to that of Hoffert et al (2002), in that we can find no anolog in terms of time frame, required infrastructure change, and the physics of energy to the technology challenge posed by climate stabilization.. The magnitude is so large and encompassing that the challenge of researching developing, testing and deploying a whole new energy system on a world-wide scale has no parallel.

2. Why hasn't a technology-led policy been adopted?

The answers to this question occupied parts of sections II, and III, of the Assessment paper. There we took up (and rejected) claims that: (i) the required technologies are available; and (ii) carbon pricing will provide sufficiently strong inducements to technological change to assure that the required technologies become available without inordinate delay. In section VI, we took up another concern: the effectiveness of government funded R&D. This is a legitimate concern that needs to be addressed. Therefore in section VI we set out some ways in which energy technology R&D can be made "incentive compatible".

There has been another roadblock to a technology-led policy. The obsession with (emission reduction) targets puts the emphasis on emission reductions rather than on the technological means of achieving them. Further, date specific targets are incompatible with a technology-based approach because the success of new technologies, much less the date at which success occurs, cannot be predicted ahead of time. In our view, more than any other factor, emission reduction targets have straitjacketed climate policy---and discussion of alternatives (Prins and Rayner, 2007). Target obsession has led to an insufficient focus on R&D-initiated technology change. As a result, potentially large emission reductions that could eventually follow successful technology breakthroughs are given up in a vain attempt to achieve near-term emission reduction certainty.

3. Why will there be continued resistance to a technology-led climate policy?

One reason is human obstinacy. Belief in the efficacy of emission reduction targets has not yet been dulled by the failure of commitments to them. Evidently, the response to the failure of the Kyoto Protocol to make any real difference to the course of global, or OECD, emissions is to call for even more demanding reductions and timetables. **An irony is that whereas technology is about "success breeding success", a target-based climate policy reflects "failure breeding failure".**

A new, and perhaps more compelling, factor has entered the picture. There is growing scientific evidence that climate is changing more quickly, and the probable impacts of change may be larger, than was contemplated a decade ago. The new evidence has fueled the argument that substantial emission reductions must begin now---and cannot await a technological revolution. Some argue that the government must put "science" ahead of "politics", even in the face of parliamentary or Congressional resistance. (Of course, in democracies "science before politics" may not be possible, especially when the science is uncertain, the politics involve large costs, and those who make the decisions are unlikely to survive the next election.)

The science-based compulsion for immediate action is increasingly tied to predictions that warming beyond some threshold will lead to increased probability of reaching "***tipping points***". These may occur when beyond some atmospheric carbon concentration threshold, climate change, its impacts, and the damages it produces are predicted to accelerate. The policy implication is that mitigation of GHGs must proceed sufficiently quickly that low probability events with big (undesirable) consequences do not become high (or higher) probability events. But the argument, while convincing in principle, runs up against the fact that the required pace of emission reduction may exceed what is technologically possible, and only can be achieved by ***substantially reducing*** economic growth or even reducing overall economic activity. (See sections III and VII.) In these circumstances, many are likely to conclude that the cure is worse than the disease, at which point "politics" will trump "science" in most democracies.

Still, those who admit to political realities, and the large economic costs of "brute force" mitigation, may feel uneasy about any policy which appears to lack accountability for emission reductions. A technology-led policy does not allow us to say when emissions will be reduced - because "when" depends heavily on the development of new technologies. Many may view vagueness about the path of technology-led emission reductions as unacceptable. They may believe that a technology-led approach blurs responsibility for ultimate reductions to the point where the policy lacks the necessary degree of "accountability". The accountability issue may in fact be the basis for the enduring popularity of targets. **Yet, there is nothing less accountable than politically grandstanded, non-credible, emission-reduction commitments the responsibility for which lies well beyond the next election cycle.**

4. Why is it likely that a technology-led policy will *eventually* be adopted?

The short answer is that there is no other choice. But that answer does not really address the question. To begin, the Assessment Paper has attempted to lay bare the huge costs of a target-based, "brute force" approach to mitigating emissions. Still it is likely to take more time for this realization to sink in. As a result, it may take another (wasted) decade of target-based policy, now with the US involved, before failure is admitted, and another several years before an alternative with much greater chances of succeeding is adopted.

The delay is sad and unnecessary. There is, however, one silver lining: the growing appreciation that the technology challenge to climate stabilization is huge. That recognition is spurring several countries, including China, Japan, Korea and the US, to put considerable resources into energy technology R&D.

Sooner or later the proponents of the current target-led and carbon-pricing based climate policy options will have to concede that putting the "cart" (large cuts in emissions) before the "horse" (the technological means for making the cuts) is a doomed approach. In the process of awakening, it will dawn that there is little logic in trying to price carbon emissions out of the market instead of developing good, cost effective carbon neutral alternatives that can be ***priced in***. At the point of discovery, the world may finally turn to a technology-led climate policy.

5. The Relationship Between Technology-led and other Climate Policies

While we think that the case for a technology-led climate policy is very strong, and made all the stronger by comparison with a policy of "brute force" mitigation, a technology-led policy cannot stand alone. We view a technology-led policy as at least partially (or potentially) ***complementary*** with other policies. These include: (i) adaptation (e g., Pielke, 2007); (ii) "alternative mitigation" policies; and (iii) investments in researching, and possibly testing, proposals for ***geo-engineering***. Each has a role to play in a portfolio of climate policies.

Both climate and technology change are imbued with uncertainty. As a result, the timing and extent of climate change, and the pace of technology development, not only make some adaptation inevitable, but greater adaptation may be required if, as is widely anticipated, emissions overshoot the targeted stabilization level (Parry, et al, 2009).

Mitigation is not limited to CO2. Some examples of "alternative mitigation" are: forest carbon sequestration, and black carbon and methane mitigation. Afforestation would reduce the approximately twenty percent of carbon dioxide emissions that occur as a result of changes in land use. Methane is a powerful greenhouse gas that is in good part associated with animal husbandry, agriculture (especially rice cultivation) and landfills. Black carbon is particularly associated with inefficient use of diesel fuel. If cost-effective means of reducing these sources of carbon are available then "alternative mitigation" is clearly both desirable and a ***complement*** to a technology-led climate policy.

There may also be need for a ***palliative*** in the event of rapid climate change. The role of the "palliative" would be to limit climate change while the technological means are developed to substantially reduce emissions (Barrett, 2009). One category of "palliatives" is encompassed by the term "geo-engineering". Proposals to "geo-engineer" climate (by reducing solar insolation with stratospheric aerosols or other reflective particles) are now being contemplated and researched (see for example, Crutzen, 2006; Wigley, 2006; Matthews and Caldeira 2007), although one hopes, given uncertainty about effects and effectiveness, they will never have to be used.

What about mitigation policies that call for a price, rather than quantity, based, mechanism to cut emissions while placing emphasis on ***up-front energy technology research and development***? Such a approach, under a gradually rising carbon price, would not be altogether dissimilar to our technology-led policy, the difference being more a matter of emphasis than of kind. That said, what is clear is that ***a technology-led policy is incompatible with a policy of "brute-force" mitigation***, typified by demanding, time-specific emission reduction targets. After all, the case for a technology-led policy of mitigation is in large part the case against "brute force" mitigation. But "brute force" mitigation aside, we need an arsenal of policies, ones that are ***complementary*** (or similar in kind) to a technology-led policy.

Thus the ***certainty*** of some climate impacts will require investments in adaptation, the need for a portfolio of mitigation possibilities suggests the wisdom of "alternative mitigation", and the ***possibility*** of rapid climate change calls for researching, and possibly testing, proposed means of geo-engineering climate. **Each should be considered, therefore, part of an *arsenal* of climate policies *with a technology-led policy at its center*.**

6. "Tipping Points" and "Catastrophic" Climate Change

We return once more to the argument that the ***science*** of climate change indicates that the world cannot wait for the fruits of a technology-led policy to appear. To wait for technology, the argument goes, invites "disaster". A slower pace of emission reduction than the science "demands", so the argument goes could mean huge damages, the possible transgressing of "tipping points", and the "catastrophic" changes that doing so might entail.

The first point we would note is that so far as "tipping points" and catastrophic climate change are concerned, we are still in the domain of "low probability of high consequence" events. The second is that while the argument has some merit, especially in so far as discounting and the interpretation of cost-benefit analysis is concerned (Weitzman, 2007, 2009), it has less merit when the technology challenge to climate stabilization is considered.

A major problem is the rhetoric of climate change debate. In the run-up to Copenhagen 2009, we hear much about "catastrophic" climate change and "saving the planet". We can do little about the "emotive" language, but would note the following. The debate is **not** about climate change and its scientific basis. These are firmly established. The debate is **not** about whether to act - virtually all are agreed we must act. The debate ***is*** about **how** to act; about what action is ***appropriate***. What is appropriate is as much, or more, a matter of technology, behavior, economics, and politics as it is climate science. The technology-led proposal made in this paper is different from currently favored approaches precisely because it is neither driven by climate science nor the axioms of economic theory. Rather, given what climate science is telling us, it is driven by our understanding of technology, behaviorally and institutionally based economics, and political and development realities.

The proposal is also driven by a sense that there are few more important things to human survival than energy. We obviously need air to breathe and water, but after these, virtually all of the requirements of life (including clean air and clean water) will depend in a highly populated world on abundant energy (Smalley, 2005). And survival from real "catastrophes", such as an asteroid hitting the earth, the eruption of a "super-volcano", or a nuclear conflict, clearly will require all the ***concentrated*** energy at our disposal - and that currently means mainly fossil fuels and nuclear energy.

"Catastrophes" usually happen suddenly and unexpectedly. Response must be rapid with little or no time for "adaptation". In this respect, it is not clear under what circumstances climate change would be "catastrophic". But if we really do face "tipping points" and "catastrophic" climate change, we will still need all the energy, human and especially non-human, that we can marshall. And that brings us back to technology. Whatever we do to meet the climate change challenge we will need to maintain and improve the quantity and quality of the world's energy resources and technologies.

C. A Summing Up

We will be brief. Our technology-led proposal is easy to describe. More complicated is why it is the best approach. Much of the paper is needed to demonstrate why the major alternative, and current favorite, will not work. Here we distill the main points.

i. Human induced climate change is a problem, that left unattended will become more serious as the century progresses.

ii. To substantially reduce global GHG emissions will require a technological revolution

iii. Our paper demonstrates that:

- The magnitude of the technology challenge is huge.
- The required technologies are not ready - and many still require ***basic*** research and development.
- A policy of "brute force" mitigation to meet arbitrary and time-specific emission reduction targets will not work. One cannot cap CO_2 emissions unless there are good, non carbon-emitting energy and/or energy technology ***substitutes***.
- A policy that sets aside targets and puts the up-front emphasis on energy R&D, infrastructure, and deployment of ready technologies is intuitively sensible and workable.
- Carbon pricing has an important ***ancillary*** role to play, first as a means of long-term financing of energy R&D, technology testing, and energy infrastructure development and renewal , and second as a means of sending a "forward price signal" as an (initially) low carbon price (say \$5.00/tCO_2) slowly and steadily rises over time (doubling say, every 10 years).

iv. Using a BAU baseline, the BCRs range from 1.1 to 11.66 with an outlier at 0.65 in the case of low return to R&D and non-inclusion of damages avoided from 2100-2200. In benefit-cost terms, a technology-led policy dominates a policy of "brute force" mitigation, with BCRs ranging from 10 - 18 regardless of the assumed level of climate damages.

v. A technology-led climate policy could generate an energy technology race that would challenge the creativity of the younger generations while minimizing sacrifice in lost economic activity or a weakened energy system. In contrast, "brute force" mitigation would require large sacrifices with no assurance of a stronger and more resilient energy system.

vi. Although we have neither discussed nor placed a value on spillovers from energy technology R&D into non-energy uses, it is likely that an energy technology race could generate many external benefits which could potentially prove to be as important as the contribution to reducing GHG emissions.

APPENDIX A: CALCULATION OF BCRS WITH A BRUTE FORCE MITIGATION BASELINE

Here we set out how we calculated the benefit-cost ratios for the comparisons of technology-led and "brute force" mitigation policies in Section VIII.

(a) Benefits of a Technology-led Policy

Typically the "benefits" of a policy to abate GHG emissions are the damages that such action avoids. (See Tol, 2009 for an excellent assessment of the economic costs of climate change.) But in our comparison of the two policies, the "benefits" of a technology-led policy are largely the abatement costs avoided by ***brute force*** mitigation

.

Nevertheless, in calculating the "benefits" of a technology-led policy we need to take into consideration the possibility that the slower pace of emission reduction may lead to higher avoidable damages than under a brute force policy that achieved its targets, albeit at great economic cost. The avoidable damages that are not avoided by a technology-led policy should be netted out of the benefits arising from abatement costs avoided.

(*b*) *Costs of a Technology-Led Policy*

The costs associated with a technology-led approach include the following:

i. Research and development expenditures

ii. Demonstration projects and testing

iii. Deployment costs

iv. The value of other R&D "crowded out" by carbon emission-free energy R&D

v. The marginal cost of public funds

The first two components are largely unrelated to the growth in GWP, while the second two are likely to be a small percentage of GWP.

(c) Benefit Cost Ratio (BCR)

The "benefits" (numerator) and costs (denominator) when evaluating a technology-led policy against a "brute force" baseline can be expressed as follows:

$$\text{BCR} = \frac{\text{Mitigation costs avoided minus (-) Avoidable climate damages not avoided}}{\text{R\&D expenditures (1 + marginal cost of public funds) plus (+) deployment costs}}$$

(d) The Calculation of Mitigation Costs Avoided

To calculate mitigation costs avoided, we: (i) rearrange equation (4) and (ii) use the concept of the ***required*** average annual rate of decline in C/GWP - the one that allows the emission reduction target to be met, **given** (that is without reducing) the "trend" rate of growth in GWP.

(A-1) $\%\Delta GWP = - \%\Delta C - (-\%\Delta C/GWP)$, **where %Δ is the average annual rate of change**

To the extent that the ***actual*** rate of decline in C/GWP falls short of the ***required*** rate of decline, **the rate of growth of GWP must adjust downward**, ***assuming that brute force policy single-mindedly keeps to the emission reduction target***. The m***itigation costs avoided*** term in the B/C formula are calculated as the discounted sum by which cumulative GWP is reduced as a result of the lower (than "trend") rate of growth of GWP.

(e) Calculation of Avoidable Climate Damages not Avoided

For our estimate of avoidable damages of a technology-led climate policy when compared with a "brute-force" mitigation policy, we use a simplified approach rather than taking estimates directly from the DICE model. The estimates for avoidable damages that we use in these calculations are, if anything higher, than those in DICE, and thus will lower our estimated BCRs. See below.

Cline (1992) and Nordhaus (1992, 1994) adopted a simple but powerful representation of the aggregate damages from climate change. The function takes the following form,

(A-2) $D(t)= d_0 [W(t)/S^\circ]^\alpha$

where D(t) is damages as a percent of GDP; d_0 is damages as a percent of GDP attributable to a doubling of the atmospheric concentration of carbon dioxide equivalent (CO_2e); W(t) is warming as a result of increased atmospheric concentration of CO_2e. The magnitude of W depends on "climate sensitivity", S, the response of global average temperature to a ***doubling*** of atmospheric CO_2. The parameter value of S is highly uncertain. It is estimated to fall in range of 1.5°C to 4.5°C+. S° is the anticipated or expected average climate sensitivity, typically 2.5 or 3.0°C.

Although equation (1) provides an estimate of damages, it is not a measure of damages avoided by mitigation of GHG emissions. Since CO_2 (the major component in CO_2e) is already 40% above its pre-industrial level, some damages from the resultant equilibrium warming (climate change) are now unavoidable. This problem has been dealt with in the past by arbitrarily assuming that some percentage of the damages, say 20% (Cline, 1992), are ***unavoidable***. However, this approach to bridging the gap between damages and estimates of the climate changes that are avoidable seems to us increasingly ***ad hoc***. We therefore suggest a modified form of the damage function.

Unavoidable damages from climate change are assumed to be those associated with a build up of atmospheric CO_2 from pre-industrial levels to 400 ppm. All increases in CO_2 beyond 400 ppm are assumed to be avoidable, although this may be a stretch given that we already at 386 ppm. Further it is assumed that the rise in CO_2 from pre-industrial levels of ~ 275 ppm to 400 ppm will raise the ***equilibrium*** global average temperature by 1°C, with long term damages equal to 1.0% of global world product (GWP). For climate change damages associated with increases in atmospheric CO_2e concentration **in excess** of 400 ppm, we suggest the following function and parameter values.

$$\text{(A-3)} \quad D'(t) = d'[W']^{\alpha}$$

where D' = damages as a percent of GWP; d' = 1.0; W' = warming over and above the 1°C associated with CO_2e in excess of 400 ppm; and α = 1.5. Thus damages from additional warming of 1.5°C (over and above the initial 1°C associated with an atmospheric concentration of 400 ppm) would be 1.8% of GWP. For additional warming of 3°C and 5°C, additional damages would be 5.2% and 11.2% of GWP, respectively. These damage estimates do not include possible adjustments that might be made to take into consideration income inequalities and loss aversion. (See Stern 2007, 2008)

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