challenge paper

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A Technology-led Climate Policy in a Changing Landscape

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Introduction

In 2009 (Galiana and Green 2009; Galiana and Green 2009) proposed a technology-led climate policy. Specifically, we proposed that on average $100 billion be spent globally on basic research and development, testing and demonstration of low carbon energy technologies plus required infrastructure support. The expenditure would be supported by a low carbon tax (we suggested \$5.00/tCO_2) the revenues from which would be placed in dedicated trust funds in each participating country. Over time the carbon price would rise gradually (we suggested a doubling every 10 years) thereby sending a forward price signal to commercialize and deploy scalable, cost-effective energy technologies as they became available.

There are several reasons for proposing a technology-led climate policy. Five stand out, and each was elaborated on in some depth in Galiana and Green (2010). First we demonstrated that the size of the energy technology challenge to "stabilizing climate" is huge, and that it has been seriously understated by those who use the IPCC emission scenarios as baselines for estimating the size and cost of that challenge. Second, we examined the low carbon energy sources and found a current lack of technological readiness and scalability. Third, we explained why we cannot depend on carbon pricing to generate the needed long term investments in *basic* research and development the fruits of which may not prove successful; and if successful may take decades rather than years to prove so; and even then may generate benefits that are not appropriable. Fourth, we showed that a "brute force" approach to reducing GHG emissions in the absence of technological readiness could generate economic costs an order of magnitude or more, greater than the GDP cost estimates presented by the IPCC. Finally, we calculated that an effective technology-led policy would pass a benefit-cost test by wide margins.

Here we undertake an update of our proposal. Is it as compelling as it was three years ago? Would it continue to pass a benefit cost test with high marks? Is there anything important that has changed or has occurred that should be considered in a reevaluation of the proposal? Our answers to the three questions are: *yes* to compelling; *still high* to benefit-cost test; and *yes indeed* to whether the landscape has changed and there is new information to consider. It is the last of these that is the chief focus of the update.

What has changed?

1. *Receptivity to the Idea*

When we began our analysis of a technology-led policy just prior to COP15 in Copenhagen, target-based climate policies were the only game in town. COP 15 was hailed as the last chance to halt climate change by negotiating a second Kyoto commitment period. Three COPs have since passed. The first was

Copenhagen which resulted in a non-legally binding document that recognizes that actions should be taken to keep any temperature increases to 2 **°C.** The second**,** COP 16 in Cancun gave us the Green Climate Fund and a Technology Mechanism. While this defection from emission targets, as the main tool for climate policy was promising, the third COP 17 in Durban has unfortunately extended the life of the Kyoto Protocol for at least five years and the period for negotiating a new global emission reduction agreement to 2015. At best the so-called "Durban Platform" serves to distract from the pressing need to develop fundamentally new technologies. At worst we could end up with an agreement that focuses on emission reduction *ends* and overlooks the technological *means* to achieve them.

Nonetheless, it is our impression that there is now widespread acknowledgment that energy technologies are at the core of any of any serious attempt to stem the growth and begin to substantially reduce *global* emissions. We are less likely to hear that energy efficiency, conservation, and changed life-styles will largely do the trick. Perhaps this is a reflection of the growing appreciation that the lion's share of emission now and in the future will come from the developing world, in particular the newly "emerging" economies such as China, India, Korea, Indonesia and Brazil. In fact, we would go so far as to suggest that it is in the "emerging" economies that there is receptivity to a technology based stance to climate policy. This is particularly evident in the case of China.

In the West the technology response has been more tentative. In some respects it has also been perverse. As a result of the financial crash of 2008 and the deep recession and continuing slump some governments, particularly the US saw spending on (including investment in) "green technologies" as a means to a "green recovery". The American Recovery and Reinvestment Act of 2009 dedicated $112 billion (three-fold the budget of these programs) to climate related initiatives, largely related to energy efficiency and renewables. The result is technology promotion largely in the form of subsidies to production and deployment. Such a response is perverse because it generates waste and leads to spurious levels of progress without really solving the basic impediments to scalability and cost effectiveness of low carbon technologies. Subsidies, and other inducements such as feed-in-tariffs (FITs) and renewable portfolio standards (RPSs), have been shown to be extremely cost ineffective and have not impacted emissions as hoped. In the US, under RPSs, utilities are being forced into adopting gerrymandered systems in order to find some way to smooth out and provide a modicum of storage for the intermittent, non-dispatchable energies, primarily solar and wind, that they are forced to take on. The case for FITs in Europe looks no better. The UK based Renewable Energy Foundation finds the cost of abatement under FITs to be between **£**174 and **£**800 per tonne of CO_2 (Constable, 2011). In Spain, FITs have led to a record deficit of US$8.3 billion for a total 5-year deficit of about US$20 billion[1].

Moreover, subsidies have an important Achilles heel. They are prone to stop-and-go financing in the short term and from rapidly rising budgetary costs in the long run as the number of green energy suppliers and customers rise. For example, Victor and Yanosek (2011) point out that investors "flock to clean energy projects that are quick and easy to build rather than invest in more innovative technologies that could stand a better chance of competing with conventional energy sources over the long haul".

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[1] http://www.economist.com/node/21524449

In the meantime, funds for basic R&D, testing and demonstration have been limited and increasingly subject to budget cuts. Yet without the technology breakthroughs that innovation funding may bring, there is little hope of increasing the scalability and cost effectiveness of most low carbon technologies. A series of recent reports (CATF, 2009; AEIC, 2010; AEBB, 2010; ITIF, 2011; AH, 2011; Anadon, Bunn et al. 2011) and commentaries (Gates 2011; Hoffert 2011) have recognized the need for much greater support for energy technology innovation. Significantly, none of these advocate subsidies to clean energy manufacturing and deployment. And some reports such as AEBB and AH pointedly deplore the penchant for granting downstream subsidies while skimping on support for energy innovation. There has yet to be a righting of the balance.

In testimony before the U.S. Congress Joint Economic Committee, Michael Greenstone, Professor of Economics at MIT, discussed the importance of clean energy R&D (July 27th, 2010). He said:

> *"The bottom line is that for a substantial period of time, developing countries are likely to be so focused on increasing their incomes and using the cheapest energy sources available to do so. Without a change on the cost of low-carbon fuels, this will mean increased demand or fossil fuels."*

Greenstone's recommendations include increased federal funding that is focused not only on basic R&D but also on demonstration. Furthermore he goes on to say that "demonstration should not be expanded to include the deployment of new technologies." This view, which coincides perfectly with our own, has yet to widely adopted, as is evident by the growth in FITs and RPSs.

The appearance of numerous studies on the importance of combining environmental policy with R&D subsidies is encouraging. Acemoglu et al (2012) find that the optimal policy mix includes both a carbon tax and R&D subsidies. In late 2009, a group of 34 US Nobel Laureates wrote a letter[2] to urge congress to include an R&D fund of $150 billion over 10 years in climate legislation, the primary argument being the need for stable funding to induce the necessary progress. The European Commission proposed that global public support for energy R&D should at least double by 2012 and quadruple from 2020 (European Commission, 2009). In the US, recent creation of ARPA-E (Advanced Research Projects Agency - energy) shows some promise but its 2011 budget was only $300 million, which is approximately 1% of the NIH budget.

The American Energy Innovation Council, made up of representatives of the US's largest corporations, acknowledges the underinvestment of the private sector in energy R&D and calls for, among other, the support of 'innovation hubs' and increased funding for ARPA-E.

Harvard University's Belfer Center for Science and International Affairs released a report entitled "Transforming U.S. Energy Innovation' based on a three year project primarily involving industry surveys and case studies. The report recommends doubling government funding for energy research, development and demonstration to about $US10 billion per year. The Belfer survey suggests that government funded RD&D in the U.S. beyond $10 billion/yr may have decreasing marginal returns. As

[2] http://www.fas.org/press/_docs/Nobelist%20Letter%20-%2007162009.pdf

the US emits 18% of global emissions scaling up the Belfer estimate superficially implies spending *globally* \$55 billion/yr on energy R&D. Taken at face value, the \$55 billion/yr is just a little over half the \$100 billion/yr we indicated in our 2009 Copenhagen Consensus report (2010). But Belfer's \$10 billion/yr R&D estimate for the US is supplemented by a huge carbon tax, which reaches \$300/tCO2 to meet the Obama administration's 2050 target of an 80% reduction in emissions.

The Belfer survey's need for a high and rapidly rising carbon price to induce the commercialization and development of low carbon energy technologies suggests a lack of confidence that R&D alone can sufficiently reduce the cost of low carbon technologies. In our view, this result is a direct consequence of a stringent emissions target whose timeframe (83% reduction from 2005 by 2050) does not necessarily coincide with the development of scalable technologies. In our 2009 report we implied that if the R&D commitment was strong enough, not only could sufficient scalable technologies be developed but that they could be made cost effective with a low, slowly rising carbon tax. To use a metaphor from our report (2010: p) where we put the technology chicken ahead of the carbon price egg, Belfer more or less does the opposite by allowing an emission target to dictate the appropriate carbon price.

We think it revealing that Belfer does not say what would happen to global emissions if the US placed a high and rising price on carbon, but the rest of the world does not. As we note in section 3 below, and is indicated in Figures 1 and 2, since the adoption of the non-globally harmonized Kyoto Protocol, the West has transferred a substantial portion of its emission responsibilities to developing countries/emerging economies, especially in the Far East. Significantly, a recent study in *Science* (Williams et al, 2012) analyzes the technologies required to meet California's emission reduction target of 80% below 1990 by 2050. It finds not only a large gap between those technologies currently "commercialized" and scalable and those required, but its findings depend on the crucial and unrealistic assumption that neighbouring states would harmonize policy such that the carbon intensity of their energy production would be similar to that of California's.

In sum, although there is much more talk about technology in the context of climate policy, progress in adopting a technology-led policy as envisioned in Galiana and Green (2009, 2010) has been limited and slow. Worse, for political and other reasons the increasing interest in low carbon energy technologies has been used opportunistically, and in the process has probably generated considerable waste and few tangible benefits. We did not envision this occurrence in 2009.

2. *Technology Developments*

In 2009, we seemed to be on the cusp of a nuclear renaissance. While Fukushima has not put an end to nuclear development, it has slowed it, certainly when measured in global terms. As a result, a slower pace of deployment of a technology crucial to the gradual displacement of fossil fuel based electricity generation over the next half century could make it more difficult to achieve the rapid decline in carbon intensity of output needed to substantially reduce the level of *global* GHG emissions by mid-century, or shortly thereafter

An even more significant development is the emergence of shale gas as an important source of energy. Hydraulic fracturing or 'fracking' has the potential to produce large new supplies of natural gas, thus allowing for substitution away from coal, increasing energy security, and creating additional competition for and thus slowing the entry of intermittent renewables. The success of “fracking” seems likely to accelerate the transition away from coal while decelerating the move towards renewables However, the combination of impacts, while perhaps mitigating short term emission growth, may have less impact on temperature change than expected. Wigley (Wigley 2011) shows that if natural gas leakage cannot be kept at a very low level, and if the switch to natural gas hastens the elimination of sulphur dioxide emissions, the transition from coal to gas by itself may not alter the trajectory of global average temperature change. An additional concern, not taken up here, is that “fracking” may pose water and other environmental-resource issues (Zoback, Kitasei et al. 2010; Wood, Gilbert et al. 2011).

There is another aspect of “fracking” which is changing the landscape. Not only has the combination of horizontal drilling and “fracking” teamed up to greatly increase available reserves of natural gas, the same thing is now beginning to occur in the oil industry. Accessible reserves of oil in the US have jumped substantially as a result of “fracking”. Moreover, US reliance on overseas oil is declining. If reports are to be believed, it is no longer far-fetched that the US, or at least North America, will once more be self-sufficient in petroleum (oil and natural gas). If so, the implications could be far-reaching, including geopolitical ones.

There are potentially important ramifications if “fracking” makes possible US (or North American) *energy security.* In an uncertain and dangerous world, placing a value on energy security increases the social value of petroleum (oil and gas) above the value individuals place on them. The increased social value makes it all the more difficult for *low* carbon energies to out-compete fossil fuels. It would also render policies that attempt to limit the development of the oil and gas industries, such as carbon emission permits and high carbon prices, all the more anathema to voters as well as the petroleum industry.

To put it another way, an increase in energy security made possible by abundant new domestic fossil fuel reserves implicitly raises the cost of carbon dioxide mitigation when assessed in benefit-cost terms. A key new mitigation cost element is the lost user value of oil petroleum that is *artificially* priced out of the market or subjected to production constraints. In a world that depends so heavily on energy, and in which security has taken on new and important dimensions, it would be a hard sell to trade off energy security/reliability and environmental health.

While “fracking” has made possible the addition of abundant previously inaccessible gas and oil reserves, efforts to capture emissions from stationary sources that use fossil fuels and store them in the ground (CCS) has progressed much more slowly. There are to be sure a large number of pilot projects around the world (MIT website) and a small number of industrial operations actually using CCS. But it has yet to be shown that the 3.5-4.0 MtCO_2 emissions from a moderate sized (400 GW, net energy) coal-fired plant can be captured and stored safely and economically, even with a price placed on carbon of \$40/t CO2 (equivalent to \$110/t coal—or almost a 200% tax on coal used in electricity generation). From the accounts that we have seen, there continue to be unpredictable technological complications which have slowed the development of CCS, and almost surely have delayed the date at which any substantial fraction of power plant or mining operation emissions can be sequestered.

One thing that hasn't changed is the race to install wind turbines and solar arrays. This race is going on in the absence of utility-scale storage, necessary to handling more than a small amount of these intermittent and variable energy sources. The result is that while wind and solar energy capacity increase rapidly, the contribution of these sources to energy consumption remains very small. Solar and wind energies perhaps best illustrate the need for drastic technological breakthroughs if most low carbon sources are to make more than a niche contribution to global energy consumption. An important research article on battery research (Dunn, Kamath et al. 2011) and a New York *Times* report (October 2011) on a wind turbine farm in West Virginia that combined 1.3 million C and D batteries at a cost of $28 million to provide just 15 minutes of back up aptly demonstrate the need for basic scientific R&D in energy technologies.

Despite some changes in the energy technology landscape, we have barely scratched the surface of the huge energy technology challenge to climate stabilization. Perhaps as a result there is a lingering concern among some that a concerted R&D effort to fill the gap will "crowd out" other worthwhile R&D investments. In our 2009 report (Galiana and Green, 2010:321) we addressed these concerns noting (i0 the decline in energy R&D in the past quarter century; (ii0 the long-term nature of a technology-led policy giving plenty of time to develop requisite resources; and the increasing elasticity of supply of potential R&D resources as a result of a growing and more educated global population. Indeed, the evidence indicates, globally, continued growth in science and engineering personnel and peer-reviewed articles in scientific journals. In the US alone, over 5 million persons are employed in science and engineering occupations; fragmentary data indicate that the US world share continues to decline. (National Science Foundation, S&E Indicators, 2010)

The real problem is not "crowding out": it is misspending scarce financial resources on subsidies to manufacturing and deployment. The failure here is one of implementation. As we emphasized (Galiana and Green 2010:316-317) an incentive compatible technology-led policy is self-funding (we proposed a low carbon tax/fee) with revenues place in a dedicated trust fund administered by public and private sector officials, as independent from political influence as possible, with allocations made by a panel of experts, perhaps modeled along the lines of the Gates Fund. In our view "crowding out is a "straw man"; incentive compatible implementation is a very serious, and largely overlooked, concern.

3. *Emission Responsibility*

In assigning national emission responsibilities, the Kyoto Protocol followed the International Energy Agency (IEA) and the US Energy Information Agency (EIA) in using estimates of emissions produced at home. To claims that a production-based standard might induce energy (and emission)-intensive activity to move to locations without emission controls, analysts, including the IPCC have contended that the resultant "carbon leakage" would be small. Be that as it may, there is growing evidence of emission transfer from the EU and the US to developing and emerging economies especially in the Far East (Davis and Caldeira, 2010; Peters et al, 2011). Moreover, individual country studies indicate the potential for large differences in emission responsibility between emissions **produced** on the one hand and emissions embedded in goods and services **consumed** on the other For example a UK study in 2005 indicated that while measured on a production basis the UK had reduced emissions by 11% from 1990, its emissions had increased 14% on a consumption basis (Helm, 2007). In contrast, China's emissions would be an estimated 20% lower if they were measured on a consumption rather than production basis (Yan and Yang, 2010). The path-breaking research of Davis and Caldeira (2010), and Peters et al, (2011) suggest that the *global* emissions picture is a good deal more complicated than the production-based statistics would suggest. Important processes related to the interconnection between international trade and the economic transformation occurring in developing and emerging economies is driving a wedge between emission responsibilities based on production and those based on consumption. Thus as evidenced by the examples given above, a country's *responsibility* for emissions looks quite different when measured in terms of emissions embedded in the goods and services a nation consumes than in terms of those produced by a nation's activities. Figures 1 and 2 indicate that via international trade the West is transferring responsibility for a substantial amount of global emissions to the developing world, especially "emerging" economies in the Far East. The drastic increase, since 1990, in emissions produced in annex B countries and consumed in non-annex B countries exposes a fundamental flaw in production-based emission-target policies (Figure 1).

It is, of course, still a matter of debate what are the relative roles of increased trade (globalization) on the one hand and climate policy-induced "leakage" on the other is increasing the discrepancy between emissions <u>produced</u> and emissions <u>consumed</u>. Either way the wedge cannot be ignored and it is growing as Figure 2 indicates. For at least some countries that wedge makes all the more difficult-to-accept, much less defend, a *global* climate policy that has been based on the assignment of *national* **production** rather than **consumption** responsibilities Moreover, the likelihood that the wedge is at least partly attributable to climate policy-induced leakage is another reason why a technology-led climate policy is preferable to high carbon prices, especially *non*-harmonized ones.

4. Adaptations, Infrastructure and Energy

The continued build-up of GHGs in the atmosphere, the growing awareness, if not incidence of, extreme weather events, and the increasingly extended timetable for deep reductions in global emissions, (due in part to a failed climate policy), has accented the role of adaptation. In the past few years, and particularly since the Copenhagen conference in December 2009, adaptation has been given greater attention by climate policy and science. And the reasons are clear: in the circumstances in which mitigation will be slow and the climate effects of mitigation far slower, humans and other species will have to **adapt** to whatever changes occur.

In most cases human adaptation can be left to individual, group, and private sector efforts. But in two essential respects there are "public good" aspects of adaptation. First, one can think of infrastructure investments that whether financed publicly or privately convey benefits that aid in adaptive efforts. These include transportation systems, irrigation, desalinization plants, food technologies, ecosystem strengthening, Noah's Arc rules to limit species extinction, energy systems (whatever the energy source---preferably concentrated), and advanced warning systems. Second, investment in rapid emergency response systems and teams can play an essential role in reducing the costs associated with natural disasters that may, or may not, have anything to do with climate change. These investments are variously capital and "know how" intensive. But they all have one thing in common: they are likely to have *ancillary* benefits. It is likely that some of the research funded through a technology-led policy will have to come in the form of adaptation technologies and not necessarily low-carbon technologies.

They also are likely to be energy using. Thus a second common denominator is energy. It is impossible to envision adaptation and infrastructure without energy. But in the long run, the kind of energy matters greatly. Ultimately, curbing GHG emissions will require a lot of energy that is not carbon emitting. That requires an energy technology revolution, which brings us back to a technology-led climate policy.

5. *New Views about a "Level Playing Field"*

Another thing that may have changed is the view of just what is a 'level playing field'. In the case of mitigation the *sine qua non* for economists is a globally harmonized price on carbon. In fact, one might claim that climate policy has proceeded on the premise that we should at least "level the playing field" between carbon-free energy and fossil energy sources, if not tilt toward the former. A theoretical justification for leveling the playing field is that carbon energy produces a large externality in the form of heat trapping gases that can alter climate and threaten undesirable consequences, albeit these are uncertain in nature or magnitude. For economists, an efficient means of leveling the playing field is through Pigovian taxes in the form of a price on carbon. The benefit-cost analysis that underlies the Pigovian tax-price weighs climate damages avoided against the cost of mitigation.

As a practical matter such a tax-price is further away from realization than ever. But there is also some reason to believe that the economist version of a 'level playing field" may not be as compelling as once seemed. Here is why! What is the cost of mitigation? In the standard analysis it is the cost associated with a higher price for the energy input and/or the *policy*-induced limitations on the use of fossil fuels, But is this all? What of the oil and the gas left in the ground? Should not the lost value of mineral wealth "shut in" by environmental policy be recognized as a "cost" in a benefit-cost assessment?

A so-called "Green Paradox" debate (Grafton, Kompas et al. 2010; Van der Ploeg, Withagen et al. 2010) that has recently attracted a good deal of economist attention. It recognizes how a threat of an alternative technology, or future limitations on petroleum use, could lead petroleum suppliers/exporters to step up production now in order to gain something from their mineral wealth. In prosaic terms it is a matter of "use it or lose it". That point may not yet have been reached. However, we have witnessed how fear of lost economic rents from their oil wealth has made oil exporters, especially Saudi Arabia, strong opponents of UN climate treaties. Although the US is unlikely to ever again become an oil exporter (it once was 60+ years ago), could new-found petroleum energy self-sufficiency produce similar reactions?

But let us leave aside the politics and return to the economic question. Should the present value of the economic rents lost be accounted for in a benefit-cost assessment of policies designed to permanently curtail use of fossil fuel wealth? Perhaps taking a totally global view of the issue might suggest not. But if the assessment is from a national viewpoint, it seems to us that on economic grounds the wealth loss should enter into the BCA calculus alongside other mitigation costs, to be weighed against the prospective environmental benefits.

We raise the "playing field" question in part to draw attention to some recent statements made by Bill Gates concerning energy technologies. At the beginning of his review of Daniel Yergin's (Yergin 2011) new book, "The Quest: Energy, Security, and the Remaking of the Modern World", Fareed Zakaria (2011) draws attention to Bill Gates' "energy miracle" wish. If Gates were allowed only one wish "to improve humanity's lot", it would be a new carbon-free technology that produced huge amounts of energy at half the price of coal. As it happens, Gates' miracle energy technology would solve the economic rent-playing field issue discussed above.

If the Gates technology is as scalable and reliable as it must be to displace fossil fuels, and if it is at half the cost of coal, it would, in open competition, destroy the economic rents associated with petroleum wealth, whether fracking-generated or not. With a Gates' miracle technology no artificial price or quantity restraint on fossil fuel use is needed. Also there is no rent loss that needs to be tallied. The issue of rents lost as a cost in a BCA becomes moot. Gates' miracle wish avoids any problem of assessing the economic or environmental desirability of the new technology, even if in the time between invention and deployment it may prompt some "Green Paradox" behavior. Gates' miracles wish idea implicitly helps make the case for a technology-led policy.

Reassessing Benefits and Costs

Climate change is too important to ignore. At the same time climate policy should reflect what *can* be done in real world circumstances, not what *ought to be* done. Ideally, if the requisite low carbon energy technologies were at hand, a focus on rapid mitigation could be both timely and inexpensive. Realistically, however, that is simply not the case—far from it. Lacking the requisite low carbon energy technologies, difficult-to-achieve emission-reduction policies are both expensive and destined to failure.

DICE model results from 2009 CC on CC (3% discount rate)			
	early return to R&D	mid return to R&D	late return to R&D
2010-2110	3.64	3.31	2.23
2010-2200	11.66	10.95	8.59

In 2009, our proposal for a technology-led climate policy made sense. It still does! This brings us finally to the quintessential Copenhagen Consensus concern: benefit-cost ratios. In 2009, (Galiana and Green, 2010: 322-329), we use three different approaches to calculate BCRs for the technology-led policy we proposed. All produced BCRs greater than 1. For 2010-2100 the BCRs relative to business-as-usual ranged from 1.36 to 57.80, with the lowest (highest) ratios when we use a 4% (1.4%) rather than a 3% discount rate.

When compared to the alternative, a "brute force" target-based mitigation policy, our BCRs were 10 or higher regardless of discount rate. In table 1 we summarize the DICE-model results from our 2009 analysis for a 3% discount rate. Note that the benefit/cost ratios are always higher for the long term (2010-2200). This is due to the fact that the greatest benefits of a technology-led policy are derived once the innovations are deployed on a large scale. While a technology-led policy does not generate immediate benefits in terms of emission reductions, over the long-term the induced transitions to a ‘low-carbon’ economy more than offsets the initial climate damages. It is this characteristic of a technology-led policy that allows the BCAs to remain high despite a slight delay in its implementation.

For the Copenhagen Consensus 2012 (CC-2012) BCA, we need to answer two questions:

1. Has “landscape” change substantially altered the BCRs calculated for the CC- 2009 assessment?
2. Does it matter for the BCRs we calculated in 2009 that the initial CC-2012 budget is much smaller than in 2009? For CC-2012 our charge is to address in a qualitative manner whether the BCRs out to 2100 and 2200 are much affected if the total budget for the first 4 years is $75 billion ($18.75/yr)

We address each of these questions in turn.

(a) Landscape changes

We do not think that the changes in landscape we have described will have much effect on the range of benefit-cost ratios, we calculated in 2009. We acknowledge that delays in adopting a technology-led policy to date may lower the BCR’s somewhat when compared to damages avoided in the DICE model---although not with respect to “brute force” mitigation. Fortunately, we may be able to buy some time if non-CO_2 GHGs (soot, methane, ozone) are reduced substantially in the next few decades. Shindell et al (2012) demonstrate that technologically achievable reductions in these short-lived emissions, with non-climate (air quality, health) as well as climate-related benefits that substantially outweigh their mitigation costs could slow the rise in global average temperature by 0.5C out to 2050. We therefore remain confident that a long-term commitment to a technology-led policy will produce fruits –and will generate benefits-- that far outweigh the costs. We feel certain that where CO_2 mitigation is concerned the technology-led policy continues to dominate---and probably by a wide margin. It would be an even more compelling policy if it were combined with adaptation-easing infrastructure investment.

(b) Budget constraint change

We do not think the altered budget constraint in the first four years makes much difference to the BCRs we calculated in 2009. A technology-led policy is a long run policy. What matters is not how much is spent initially but whether (i) continued funding can be counted upon, and (ii) that rising levels of R&D, testing and demonstration (R&DTD) receive the support needed to bring about an energy technology revolution. In this regard, we wish to underline the importance that we placed in our 2009 paper (Galiana and Green, 2010) on a low, dedicated carbon fee/tax that provides a regular source of revenue to finance R&DTD. Although in Galiana and Green (2009, 2010) we used a constant level of R&DTD of $100 billion annually over a 90-year (2010-2100) period (easily financed by a $5.00/tCO2 fee), we were cognizant that as a practical matter spending would start lower and rise over time.

We are confident that an initial amount of $75 billion spent over the first four years would do no harm and in fact could improve the BCAs for two reasons. First, the lower initial investment reduces our costs significantly in the benefit-cost analysis. Second, it is likely that, in the near term investments beyond $75 billion have decreasing returns thus minimally affecting our benefits. Both the Belfer report and the

Nobel laureates' letter to the US Congress have suggested annual US expenditure on R&D of $10 billion and $15 billion, respectively. What is vital for a technology-led policy to be effective is a stable source of RDD&D funds that rises very substantially in succeeding years.

Fig. 1

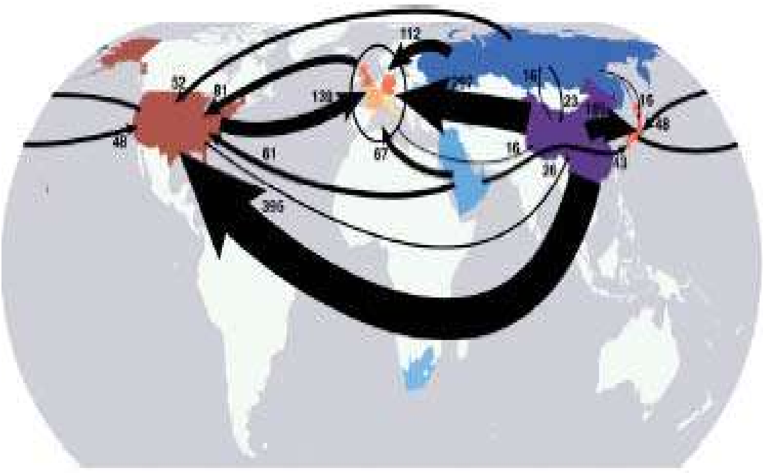
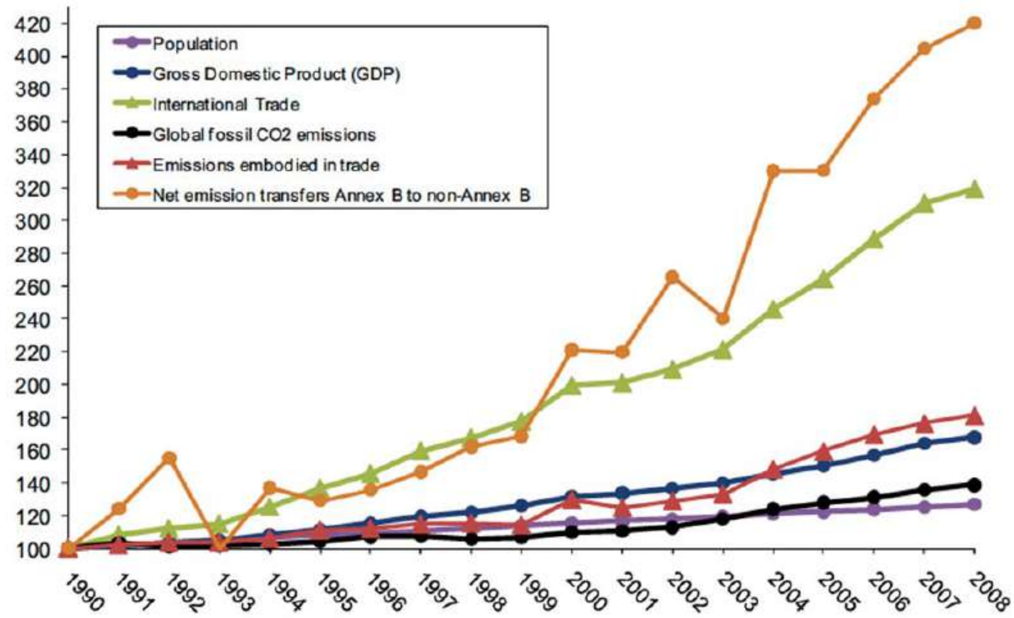


Fig. 1. Largest interregional fluxes of emissions embodied in trade (Mt CO_2 y^{-1}) from dominant net exporting countries (blue) to the dominant net importing countries (red). Fluxes to and from Western Europe are aggregated to include the United Kingdom, France, Germany, Switzerland, Italy, Spain, Luxembourg, The Netherlands, and Sweden.

Source: Davis and Caldeira, 2010

Fig. 2



Source: Peters, Minx et al., 2011

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