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A Technology-Led Climate Change Policy for Canada

Isabel Galiana, Jeremy Leonard and Christopher Green

If Canadian governments truly want to contribute to global climate change mitigation, they should adopt policies to bring about the necessary technology breakthroughs, rather than setting GHG emissions reduction targets they are unlikely to meet.

Plutôt que de se fixer des cibles difficilement tenables en matière de réduction des gaz à effet de serre, les gouvernements canadiens devraient adopter des politiques pour engendrer les percées technologiques dont nous avons tant besoin ; ils apporteraient ainsi une véritable contribution à l’atténuation des changements climatiques.

Compétitivité,
productivité et
croissance économique

Competitiveness,
Productivity and
Economic Growth

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Summary

As Canada has formally withdrawn from the Kyoto Accord, what can we do to contribute meaningfully to reducing global greenhouse gas (GHG) emissions? Climate policy activists and experts have long argued that adopting emissions-reduction targets and implementing policies to try to meet these targets is the best approach. In this study, Isabel Galiana, Jeremy Leonard and Christopher Green take a contrarian view. They argue that the policy focus on meeting GHG emissions reduction targets over the past 15 years has been a failure, and that adopting a technology-led policy would be a more effective way for Canada to contribute to global climate change mitigation.

The authors begin by describing the primary drivers of GHG emissions to illustrate the degree of "decarbonization" of the economy required to meet the emissions-reduction target of 50 percent by 2050 set by the G-8 countries, and they find that it would entail a virtual tripling of the current global rate of decline in the carbon intensity of output. Even if aggressive carbon pricing did encourage wider use of existing low-carbon technologies, evidence casts considerable doubt on whether these technologies can deliver the necessary improvements in energy efficiency and reductions in carbon intensity — and certainly not without incurring major costs in terms of economic growth.

Galiana, Leonard and Green's conclusions about energy technology development differ considerably from those in much of the literature, which are based on scenarios that assume implausibly large declines in global energy and carbon intensities, even without government intervention. As a result, these widely used scenarios greatly understate the magnitude of the technology challenge in stabilizing climate change and the economic costs of mitigation.

Essentially, nothing short of a technological revolution will be required to sufficiently cut emissions. There has been a remarkable lack of progress in technology development and emissions reduction in the past 20 years, and the main reason, according to the authors, is that policymakers have put the emissions-reduction "chicken" before the technology-development "egg."

While many economists assume that the use of carbon pricing will induce the development of new energy technologies by the private sector, the authors disagree. They argue that what is needed is basic scientific research, followed by testing and demonstration which, due to their public good characteristics, will require governments to play a role.

The authors recommend that Canada take a lead in developing next-generation technologies by establishing a low-carbon energy research council — funded by a modest carbon tax — to provide secure, long-term funding for research and development. As a large producer and user of energy, Canada could benefit directly from the development of low-carbon-emitting technologies. Given its minor 2-percent share of global emissions, this would also be the most globally effective contribution it could make.

Résumé

Le Canada s'étant officiellement retiré du protocole de Kyoto, comment peut-il aujourd'hui contribuer efficacement à la réduction des émissions mondiales de gaz à effet de serre (GES) ? Selon les experts et intervenants en politiques climatiques, la meilleure approche consiste à définir des cibles de réduction puis à prendre des mesures en conséquence. Or dans cette étude, Isabel Galiana, Jeremy Leonard et Christopher Green soutiennent à contre-courant que cette priorité donnée depuis 15 ans aux cibles de réduction des GES est un échec et que le Canada serait mieux avisé d'adopter une stratégie axée sur le développement de nouvelles technologies qui permettront réellement d'atténuer les changements climatiques.

Après avoir décrit les grands facteurs d'émission de GES pour illustrer quel niveau de « décarbonisation » de l'économie permettrait d'atteindre en 2050 la cible de réduction de 50 p. 100 fixée par les pays du G8, les auteurs montrent qu'il faudrait pour y arriver tripler le taux actuel de diminution de l'intensité des émissions de carbone. Et même si de forts prix sur le carbone stimulaient l'usage de technologies à faible teneur en carbone, tout indique que celles-ci ne pourraient produire les améliorations requises en efficacité énergétique et atténuation de l'intensité de carbone, et sûrement pas sans compromettre gravement la croissance économique.

L'avis des auteurs sur le développement de technologies énergétiques diffère sensiblement des conclusions de bon nombre de recherches sur la question, qui reposent sur d'improbables scénarios de forte réduction de l'intensité énergétique mondiale, même sans intervention des gouvernements. Pourtant largement utilisés, ces scénarios sous-estiment grandement l'ampleur des défis technologiques à relever pour stabiliser les changements climatiques ainsi que les coûts à engager pour les atténuer.

En vérité, il faudra ni plus ni moins qu'une révolution technologique pour réduire suffisamment les émissions de GES. Or depuis 20 ans, très peu de progrès ont été accomplis en matière de développement technologique et de réduction des émissions, en grande partie parce que les décideurs ont choisi de placer la « poule » avant l'« œuf », c'est-à-dire la réduction des émissions avant l'innovation technologique.

Les auteurs divergent aussi d'avis avec les nombreux économistes qui croient qu'une tarification du carbone inciterait le secteur privé à créer de nouvelles technologies. Ils soutiennent qu'il faut plutôt privilégier la recherche scientifique fondamentale, qui est par essence un bien public et doit donc être soutenue par les gouvernements.

Aussi recommandent-ils au Canada de prendre l'initiative en vue de développer la prochaine génération de technologies à faible teneur en carbone en établissant un conseil de recherche sur ces énergies, qui serait financé par une modeste taxe sur le carbone et se consacrerait au financement à long terme de la R-D, des essais et des démonstrations. Important producteur et consommateur d'énergie, le Canada profiterait directement des nouvelles technologies mises au point dans ce secteur. Et vu sa part déjà faible de 2 p. 100 des émissions mondiales, c'est ainsi qu'il pourrait le mieux contribuer à leur réduction.

A Technology-Led Climate Change Policy for Canada

Isabel Galiana, Jeremy Leonard and Christopher Green

What can Canada do to contribute meaningfully to reducing global greenhouse gas (GHG) emissions — in particular, those associated with energy use? The answer climate policy activists and "experts" usually give is to adopt emissions-reduction targets, implement policies that try to meet the targets and perhaps set an example for other countries to follow.

There are, however, problems with such an approach, aside from the fact that Canada's share of global emissions is just 2 percent and declining. First, what Canada might do to reduce emissions would not necessarily be replicated in the rest of the world. On the contrary, sticking to strict, date-specific national GHG emissions-reduction targets could accentuate the ongoing shift of emissions and emission-intensive activity to other parts of the world, especially the rapidly growing emerging economies (Davis and Caldeira 2010; Peters et al. 2011). Second, meeting strict reduction targets assumes — erroneously, we argue — that the requisite low-carbon energy alternatives are available on a large scale or that they would be if enough pressure were applied to reduce global emissions substantially and rapidly. And, third, even if Canada were to adopt tough emissions-reduction targets, existing low-carbon energy technologies would not be adequate to meet such targets without incurring unacceptably high economic costs. Such an outcome would be a counterproductive example for the rest of the world.

In this study, we offer an alternative way forward. We begin by describing the macro drivers of GHG emissions, to illustrate the degree of "decarbonization" of the economy that would be required to meet emissions-reduction targets, and we compare that process to recent trends. We then discuss the global energy technology challenge, explain why we believe the challenge is larger than much of the existing research literature assumes, and examine the economic costs of meeting existing GHG targets. We make the case for a Canadian technology-led policy, which would be a more effective way for Canada to contribute to climate change mitigation than setting targets we believe cannot be achieved.

Our conclusions about energy technology development differ considerably from those reported in much of the research literature. The differences stem from more recent work by a number of researchers demonstrating, first, that many emissions-reduction scenarios — including those of the Intergovernmental Panel on Climate Change (IPCC 2000) — assume implausibly large global energy intensity declines that would require substantial and sustained improvements in energy efficiency; and, second, that emissions-reduction scenarios could be a poor basis for technology analysis because they understate the magnitude of the low-carbon-energy challenge entailed in stabilizing climate change. Furthermore, a simple thought experiment suggests that widely published estimates of mitigation costs might be too low by an order of magnitude under reasonable assumptions about the evolution of current low-carbon energy technologies. Our conclusions are echoed by more recent studies that cast doubt on the readiness and capabilities of current energy technologies to achieve deep emissions reductions without significant reductions in output (Fischer and Newell 2008; Davis, Caldeira, and Matthews 2010; Hoffert 2010; Myhrvold and Caldeira 2012).

Many economists contend that, if the requisite low-carbon technologies are not yet available, the application of a carbon price would induce their development. We explain, however, why this induced-technological-change hypothesis is flawed if the energy technology challenge is as large as we argue it is. Although imposing a tax or fee on carbon emissions probably would encourage the deployment of low-carbon technologies that are close to the commercialization phase, it is highly unlikely that such a policy would spur the large and risky up-front investments in basic research and development (R&D), testing and demonstration required to develop next-generation technologies. Instead, we propose a made-in-Canada blueprint for financing and developing the technological means to cut future GHG emissions, especially those of energy-related carbon dioxide (CO_2). Our proposal would use carbon pricing in a uniquely pragmatic and arguably politically acceptable manner — namely, by imposing a very low carbon tax or fee that would provide the needed long-term funding for energy technology R&D, testing and demonstration with minimal economic disruption.

It is important to emphasize that a technology-led climate change policy would be a first step, rather than a stand-alone response to the challenge of reducing GHG emissions. Over time, as reliable and scalable new technologies are developed, the carbon price could be allowed to slowly rise in order to send a forward price signal to energy providers and consumers to adopt and deploy these technologies. Other policies to reduce emissions might be necessary as well, and these undoubtedly would result in economic costs. But our key point is that putting the technology-development “egg” before the emissions-reduction “chicken” would make these costs economically manageable and politically acceptable.

This is not to say that all existing policies to encourage the use and diffusion of existing low-carbon technologies should be abandoned. Even though we do not believe that available technologies are sufficient to solve the climate change problem, every contribution helps. But if deep reductions in energy-related GHG emissions are desired, then at least some countries must invest in a long-term technology revolution to enable them. Indeed, remarkably little progress in energy technology or emissions reduction has been made in the 20 years since climate change became a major global concern, in our view largely because policy-makers have focused excessively on emissions-reduction targets and commitments. A technology-led policy would aim to encourage movement on deep GHG emissions reductions that cannot be achieved using the low-carbon energy options available today. We believe, moreover, that Canada should take the lead on this front, if for no other reason than that it is the most globally effective contribution this country could make.

A Framework for Understanding Drivers of Greenhouse Gas Emissions

To understand the sources of GHG emissions from a macro perspective, it is useful to call on the “Kaya identity,” formulated by Japanese economist Yoichi Kaya (1990), which decomposes carbon emissions into the constituent factors that drive them:

$$C \equiv P \times (GDP/P) \times (E/GDP) \times (C/E),$$

where C = carbon emissions, P = population, GDP/P = gross domestic output per capita, E/GDP = energy intensity, and C/E = carbon content of energy. Table 1 shows the Kaya decomposition of CO_2 emissions for Canada, the United States, China, India and the entire world. Several noteworthy trends stand out. First, demographic and economic forces are putting upward pressure on emissions in all four countries. Population growth is largely a function of fertility rates and changes in life expectancy, and cannot be affected easily by public policy short of government *diktat* — China’s one-child policy has succeeded in reducing average population growth below that of the United States and Canada in the 2000s — while GDP per capita is a broad measure of a country’s material well-being, and few, if any, countries would want to enact policies that significantly reduce its growth.

Table 1: Factors driving carbon emissions based on the Kaya identity, Canada, the United States, China, India and the world, 1990-2008

	Canada		United States		China		India		World	
	1990-2000	2000-08	1990-2000	2000-08	1990-2000	2000-08	1990-2000	2000-08	1990-2000	2000-08
	(average annual percentage growth rates)									
CO_2 emissions	2.0	0.5	1.5	-0.1	2.3	10.9	5.0	4.7	1.0	3.1
Population	1.1	0.8	1.2	0.9	1.0	0.5	1.8	1.6	1.4	1.2
Real GDP per capita	1.8	1.3	2.1	1.0	8.9	9.5	3.5	5.4	1.7	2.7
Energy intensity of output	-1.1	-1.4	-1.7	-2.0	-6.9	0.5	0.0	-2.2	-1.7	-1.1
CO_2 content of energy	0.1	-0.2	-0.1	-0.1	-0.6	0.3	-0.3	-0.1	-0.5	0.3

Sources: United States, Energy Information Administration; International Monetary Fund.
Note: Because the Kaya equation is an identity, the CO_2 content of energy can be calculated as the difference between the growth rate of CO_2 emissions and the sum of its other three components. CO_2 emissions include only emissions from the consumption of energy.

The second trend is that all four countries have succeeded in reducing the energy intensity of production (measured as the average kilograms of oil equivalent to produce one dollar of output). Canada has reduced its energy intensity by almost 20 percent since 1990 (an average of 1.2 percent per year); this is less than the United States has achieved, but the pace of Canada’s improvement accelerated somewhat in the 2000s. The emerging economies have been more successful on this front, but this is a function more of their stage of economic development than of their explicit energy efficiency policies. In both China and (to a lesser extent) India, structural changes in both the economy and the organization of production — in particular, manufacturing — have led to jumps in productivity as domestic firms have begun to adopt best-practice production techniques. As this process becomes more advanced, however, further incremental improvements will be increasingly difficult to achieve. This dynamic is borne out in table 1: China's energy intensity declined by an average of 6.9 percent per year in the 1990s, but actually increased slightly over the 2000s; India, which is somewhat behind China in terms of industrial development, saw an acceleration of the decline in energy intensity in the 2000s for essentially the same reasons. At the same time, in both countries rapid industrialization has led to a large increase in their consumption of carbon-emitting fossil fuels, with the result that the decline in energy intensity has been insufficient to offset the growth in their carbon emissions — indeed, in China, the carbon content of energy used has actually increased.

From these trends, it is clear that deep reductions in global emissions in the context of continuing economic and population growth will require a significant acceleration in the decline of energy intensity and/or the CO_2 content of energy. For Canada to reach its near-term target of a 17 percent reduction in emissions from 2005 levels by 2020, it would have to reduce average annual emissions by 1.2 percent per year. If this is to be achieved with minimal impact on Canadians' economic well-being, the combination of energy intensity and the carbon content of energy would have to decline at a rate of 3.3 percent per year — more than double the combined average annual rate of decline over the past two decades.

In contrast, in China, the world's largest CO_2 emitter, emissions have grown by an average of 6.6 percent annually since 1990 (although table 1 reveals that China's emissions growth accelerated dramatically in the 2000s with the onset of rapid industrialization). Thus, simply stabilizing emissions, much less meeting proposed reduction targets, would require economic growth to stop in its tracks if recent trends in energy intensity and carbon intensity were to continue. It is no wonder that China and other large emerging economies are loath to commit to binding targets.

On a broader scale, the notional goal of reducing global CO_2 emissions by 50 percent by 2050 (which would require emissions to decline by an average of 1.7 percent per year) appears to be mathematically out of reach without either significant economic disruption or dramatic decreases in carbon intensity. At the past two decades' rates of GDP per capita and population growth, this would mean a 4.8 percent annual reduction in the average CO_2 intensity of GDP — the sum of the rates of decline in energy intensity of output and CO_2 intensity of energy. This is more than triple the rate of reduction experienced over the past two decades and, as we argue below, likely to be exceedingly difficult to achieve and sustain over a long period.

This unpleasant arithmetic underscores the importance of technology in addressing the climate change challenge. Short of arbitrary population controls and unpalatable attempts to stunt global economic growth, reductions in global emissions will depend heavily not only on major advances in energy efficiency, but especially on the development of scalable, reliable and reasonably cost-effective low-carbon energy supplies and the technologies to produce them — that is, nothing short of an energy technology revolution (Galiana and Green 2009).

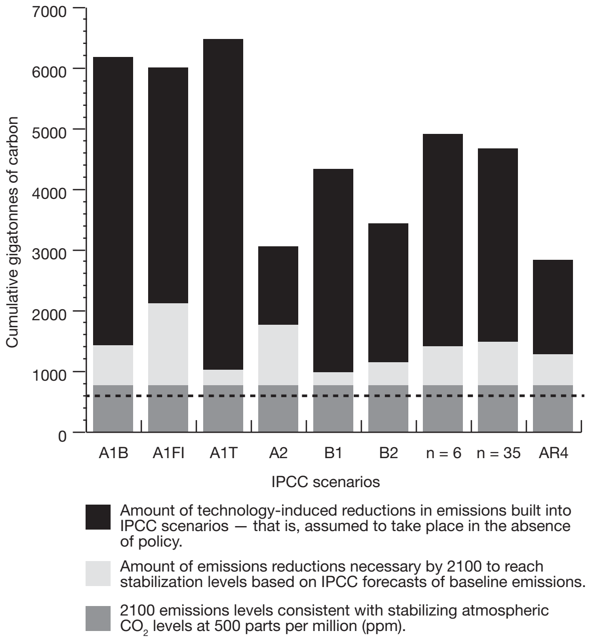
The Magnitude of the Energy Technology Challenge: A Global Perspective

The energy technology challenge of stabilizing the atmospheric concentration of GHGs is huge, getting bigger as the bar for the acceptable concentration (or average global temperature rise) is lowered and, most important, is generally understated. The challenge is huge in two respects. First, properly measured, the technological gap between what we are doing and what we must do is much larger than that implied by comparing most emissions scenarios with stabilization paths. Second, the gap between the current capabilities of low-carbon energy technologies and what is required for stabilization remains stubbornly large. Consider this: in a world of growing economies, in which more than 80 percent of energy consumption is carbon emitting, it is fairly straightforward to estimate that the current 2.5 terawatts of carbon-emissions-free power (generated almost entirely by nuclear plants and hydroelectric installations) would have to be raised to 15 to 20 terawatts by 2050 and to 25 to 40 terawatts by 2100 to stabilize atmospheric carbon concentration at approximately 550 parts per million, which is double the pre-industrial concentration (Hoffert et al. 1998).

Indeed, GHG emissions scenarios, especially those developed for the IPCC (2000, 2001, 2007a) are seriously misleading indicators of the energy technology challenge, with regard to both establishing the effective size of the challenge and estimating the economic costs of reducing emissions. The crux of the matter is that the IPCC's "business as usual" scenarios (meaning the estimated future path of GHG emissions without policy actions to reduce them) in fact assume an acceleration of the decarbonization of the global economy without specifying how that should occur. Instead, the technical summary of the 2007 report (IPCC 2007b, 41) merely states that "[b]aseline scenarios usually assume significant technological change and diffusion of new and advanced technologies," although the report's more detailed discussion on technology appears to acknowledge considerable uncertainty about how low-carbon technologies will evolve in the absence of explicit policies to encourage their development and diffusion. The IPCC's assumptions draw heavily from Nakicenovic et al. (2006), who conclude that rates of decarbonization of the global economy will double or even triple relative to trends over the past two centuries even without any policy action — an acceleration that is predicated on, among other factors, market forces raising the price of fossil fuels and inducing the adoption of low-carbon alternatives. It is important to note, however, that forecast decarbonization rates vary considerably across the scenarios surveyed by the authors, with some showing steady or even decelerating rates.

To determine how much the IPCC emissions scenarios understate the global energy technology challenge, Pielke, Wigley, and Green (2008) analyze several of these scenarios under the assumption that current energy technologies do not change (meaning that there is no further decline is the carbon intensity of the global economy) and compare them with the forecast emissions based on IPCC assumptions about decarbonization. Figure 1, which summarizes the results of that work, shows the level of global GHG emissions reductions that are assumed to take place as a result of technology improvements under the IPCC scenarios. The sum of the three stacked bars shows the total estimated GHG emissions for each scenario under the socalled frozen-technology baseline.[1] Because each scenario employs different assumptions about economic growth, population trends and other factors that affect emissions, total emissions under the frozen-technology assumption differ depending on the scenario.

Figure 1: Assumptions of the effects of technological change on future emissions reductions under various Intergovernmental Panel on Climate Change (IPCC) emissions scenarios,[1] 2000-2100



Source: Pielke, Wigley, and Green (2008).

[1] Note that the unit of measure for this figure is gigatonnes of carbon (GtC), which should not be confused with gigatonnes of carbon dioxide (GtCO$_2$). One GtC is equal to 3.7 GtCO$_2$. The dash line represents the cumulative GtC consistent with an atmospheric concentration of carbon of 450 ppm.

The top bars in figure 1 show the Pielke et al. estimates of GHG emissions reductions that the IPCC assumes would occur "spontaneously" in the absence of explicit emissions-reduction policies. These reductions come from the technological change assumptions built into each IPCC scenario and, as the figure shows, they typically are very large. In the A1B scenario, which is widely used for climate policy modeling, assumed technology improvements would reduce cumulative GHG emissions from 6,183 to 1,431 gigatonnes of carbon between 2000 and 2100. This represents more than 80 percent of the reduction required to reach the level consistent with stabilizing atmospheric concentration of emissions at 500 ppm or 775 gigatonnes of carbon. Indeed, such assumed technology improvements are responsible for more than half of the emissions reductions in all of the IPCC scenarios. The middle bars in figure 1 show the emissions reductions that under the IPCC scenarios would have to be achieved through climate-change mitigation policies to stabilize atmospheric concentrations of GHGs over and above the technology advances already assumed in each scenario. If we accept these IPCC technology assumptions at face value, it appears that the policy challenge of climate stabilization is not as daunting as it may be. Taking the A1B scenario again as an example, total emissions over the next century would have to be cut approximately in half, from about 1,431 to 775 gigatonnes. The required reduction would be even smaller in several other scenarios.

The assumed technology advancements embedded in IPCC scenarios imply, however, an unprecedented rate of carbon intensity reduction, through a combination of declines in energy intensity (E/GDP) and in the carbon content of energy (C/E). In the A1B scenario in figure 1, the implied annual decline in the global carbon intensity of output is 2.4 percent per year (consisting of a 1.4 percent decline in E/GDP and a 1 percent decline in C/E); this is three times the rate from 2000 to 2008 and nearly double the long-term historical trend. While we do not take issue with the fact that some improvements in energy efficiency and low-carbon technologies have occurred under current policies, it stretches the imagination to believe that such a dramatic acceleration would happen in the absence of aggressive policies to encourage the development of next-generation low-carbon technologies. The IPCC itself notes that "[a]ll of the technological options assumed to contribute towards further decarbonization and reduction of future GHG emissions require further…R&D to improve their technical performance, reduce costs and achieve social acceptability" (IPCC 2007b, 221).

With regard to energy efficiency, a decline in energy intensity (E/GDP) in excess of 1 percent per year (as implied in the A1B and many other scenarios) is possible over a period of one to two decades. Indeed, as table 1 shows, the average annual decline in the energy intensity of output was 1.7 percent in the 1990s but decelerated to 1.1 percent annually over the 2000-08 period. However, average annual rates of decline that exceed 1.0 to 1.2 percent would be difficult to sustain over a 50-to-100-year period. As Baksi and Green (2007) show, a global century-long energy intensity decline of 1.5 percent annually would require a three- to sixfold improvement in energy intensity in most sectors, while an annual rate of decline of 2 percent or more would require energy intensity to improve tenfold in most sectors. In short, the IPCC understates the energy technology challenge by generally overstating achievable rates of energy intensity decline.

The analyses by Baksi and Green (2007) and by Green, Baksi, and Dilmaghani (2007) suggest, moreover, that doubling or tripling the rate of decline in the carbon intensity of output would put most of the onus on the decarbonization of energy supply. This is no small feat! As table 1 shows, average rates of decline in the CO_2 content of energy (C/E) experienced since 1990 have been on the order of a few tenths of a percentage point; globally, C/E has actually increased slightly over the 2000-08 period. Such a dramatic change in the rate of decarbonization of energy supply would require not only matching the superior energy performance of fossil fuels, but also overcoming many technological barriers that currently stand in the way of scalable and reliable low- or non-carbon-emitting energy sources and technologies. Such improvements certainly cannot be simply assumed into existence, as in the IPCC scenarios.

The more fundamental issue in our view is that much of the climate policy community, including official sources such as the IPCC in its third and fourth assessment reports (IPCC 2001, 2007), have overstated the current capabilities of low-carbon sources of energy. On the contrary, whether viewed individually or in combination, current low-carbon technologies are far from capable of displacing carbon fuels for several reasons: the potential for new hydroelectric sites is limited; the fallout of the disaster at the Fukushima nuclear plant in Japan shows the difficulty of scaling up nuclear power; and demonstrating the technical feasibility and practicality of large-scale application of carbon capture and storage at anything like the levels required to sequester a substantial portion of CO_2 emissions from electricity-generating plants is proving to be a slow, painstaking process (see, for example, Hoffert et al. 2002; Caldeira, Jain, and Hoffert 2003; Green, Baksi, and Dilmaghani 2007; Lewis 2007; Barrett 2009; Galiana and Green 2010).

Then there are the renewable energy sources on which so much hope is pinned. "First-generation" biomass (ethanol from corn; diesel from soybeans) has proven costly, on a life-cycle basis uses almost as much energy to produce as is provided by the output and, depending on whether or not the energy input source is carbon based, might not even reduce emissions (see Pimentel and Patzek 2005; Farrell et al. 2006; Fargione et al. 2008; Searchinger et al. 2008). At the same time, the diversion of cropland from food production to energy might be contributing to food price increases (Pimentel et al. 2009; Wise et al. 2009). Unless there are technological breakthroughs in "second-generation" biomass, this renewable source is not likely to make much of a net contribution to low-carbon energy supply or to mitigating climate change; indeed, it appears to be generating other problems.

Solar and wind power, while plentiful enough in theory, are available in very small amounts in practice. Their diffuse nature means they require extensive areas to be covered with wind turbines and solar arrays, raising various social, ecological and land-use problems. More important, these energy sources are variable, and because they cannot be stored, they are not available on demand. They thus require reliable backup and, consequently, are more costly ways to generate electricity than estimated total average costs suggest (Joskow 2012). Without major, and quite uncertain, technological breakthroughs in energy storage, then, it would be difficult to scale up solar and wind power to levels sufficient to displace large amounts of carbon-based energy sources.

Underestimating Climate Change Mitigation Costs

The mathematics of the Kaya identity mean that underestimating the technology challenge leads inevitably to underestimating the costs of meeting a given GHG reduction target. Most estimates of the cost of stabilizing atmospheric concentrations of GHGs by mid-century have been in the range of 1 to 5 percent of cumulative gross world product (IPCC 2007b). But without revolutionary changes in energy technologies, we believe these estimates are much too low (particularly if IPCC emissions scenarios are used as baselines against which to assess the cost of mitigation), since a great deal of energy technology change is already built into the baselines.

But even if emissions scenarios are not at issue, low cost estimates are often suspect, because they typically assume that there are carbon-free backstop technologies on the shelf that can be scaled up to create large supplies of carbon-free energy, albeit at a price that is higher than the cost of the fossil fuel energy they are to displace; and/or that placing a price on carbon would spur the technological innovation needed to assure sufficient and scalable low-carbon technologies are made available (see IPCC 2007a, chap. 11). Neither assumption is justified.

The first essentially assumes away the energy technology problem by implicitly accepting claims that needed technologies are available, scalable and sufficient, leaving the impression that the only problem is their cost. But our reading of the evidence indicates that, at least in their current form, low-carbon technologies cannot support a supply of low-carbon energy on a scale capable of displacing carbon energy, although with major improvements and scientific breakthroughs they could begin to do so. As for the second assumption, placing a price on carbon is unlikely to induce sufficient private investment in the type of R&D needed to meet the technology challenge. The reason is that much of the investment would have to be in science-driven, "basic" R&D, with highly uncertain outcomes, which even if shown to be promising in the laboratory, would still require extensive testing and demonstration to prove reliability and scalability. Private investors are unlikely to undertake such risky investments on their own, and even if successful, expected commercial payoffs typically would be decades away, and might not accrue to the R&D investors in any case, because intellectual property protection is not given to scientific knowledge as such (Nemet 2009, 2010; Popp 2010). In these circumstances, the attempt to impose substantial reductions in energy-related CO_2 emissions without assurance that the required low-carbon technologies are ready could be costly. A simple "thought experiment" shows why.

Suppose we use the Kaya identity to calculate the rate at which the carbon intensity of output would have to be reduced in order to lower global emissions to 50 percent below current levels by 2050 (an average of 1.7 percent per year), while maintaining annual growth in gross world product at its 40-year historical average of 2.3 percent. Our calculations indicate that the carbon intensity of output would have to decline at an annual average rate of 4.0 percent. Achieving this rate of reduction would require huge and rapid improvements in low-carbon energy technologies. Even if improvements in energy technologies enabled the carbon intensity of output to decline at a highly optimistic 3.0 percent annual rate (more than double the average annual rate of decline since 1970), the cumulative loss of gross world product between 2010 and 2050 would be almost 20 percent (see table 2), up to an order of magnitude higher than the estimates of 1 to 5 percent cited above.

Table 2: Global cost of "brute force" emissions reduction[1]

Average annual change in carbon intensity of output (%)	Cumulative loss of global gross world product (%)
-3.5	-10.3
-3.0	-19.3
-2.5	-27.2
-2.0	-34.2
-1.4	-41.4

Source: Authors' calculations.

[1] The calculations in this table are based on (1) a global-emissions reduction target that requires a 1.7 percent average annual rate of decline in carbon emissions over a 40 year period from 2010 to 2050; and (2) an assumption that in the absence of "brute force" attempts to meet the emissions reduction target, the global economy would grow at 2.3 percent.

The example illustrates the potentially high cost of what we term "brute force" emissions reduction — the attempt to reduce emissions without having sufficient capabilities on the energy technology side. In this case, emissions reductions, if pursued vigorously with current technology capabilities, would reduce global economic growth drastically. In short, mitigation cost estimates of 1 to 5 percent are plausible *only if* the required low-carbon technologies were available, reliable and scalable. But we do not think the evidence is strong in support of this contention. Yet, the IPCC, in its third assessment report, states that the required technologies *are* available and that no "drastic" technological breakthroughs are needed. It then draws the troublesome conclusion that mitigation is not primarily a technological problem but one of political will (IPCC 2001, 9). The IPCC's fourth assessment report (IPCC 2007b) essentially repeats this mantra.

Our conclusions also differ substantially from those of other Canadian studies such as Labriet (2001), Jaccard, Nyboer, and Sadownik (2002), Jaccard and Rivers (2007), and Bataille, Dachis, and Rivers (2009), which have a much more sanguine view of the capabilities of existing technologies. In good part, this is because of assumptions in those studies about the degree to which consumers would be willing and able to switch from high- to low-carbon energy sources, as well as assumptions about the availability and scalability of current low-carbon energy that are much more optimistic than we think is warranted by the evidence. Our conclusions are, however, consistent with a growing body of literature that is critical of the rosy view of the state of low-carbon energy technology that has prevailed in much of the research literature (see, for example, Fischer and Newell 2008; Helm 2008; Tavoni and Tol 2009; Acemoglu et al. 2012; Baker and Peng 2012; Fischer and Sterner 2012).

Stimulating Technological Change: Market- versus Policy-Based Approaches

Many observers, including many economists, accept the need for new and improved low-carbon energy technologies, but assume that the market would induce the necessary innovation effort if a rising price were placed on carbon emissions (see, for example, Grubler 2002; IPCC 2007a, chap. 11; Nordhaus 2008). This argument would be plausible if the required technologies were commercially available (or close to being so) and scalable, even if at a somewhat higher cost than that of carbon fuels. But if, as we suggest above, technologies with these characteristics are not available, the picture is different.

A carbon price is unlikely to induce the required investment in basic R&D, testing and demonstration, in large part because of the “public good” factors surrounding the outcomes of such investment. In addition to issues of uncertainty, distant payoff dates and non-appropriability, there is another problem. Present governments cannot tie the hands of future governments to set carbon prices high enough to allow investors to recoup their up-front investments in R&D and production costs for technologies that prove to be commercially successful in the future (Montgomery and Smith 2007). There is, thus, a fundamental time inconsistency in proposals to leave inducements to the market (via aggressive carbon pricing): even if the market were to recognize the importance of actions to advance energy technology to achieve emissions reduction goals far in the future, investors would lack the economic incentives and financial rewards for doing so. All this points to an important role for governments in facilitating these upfront investments.

A common concern expressed by those who oppose a government role in funding energy R&D is that such investments might “crowd out” other, more valuable uses of public research funding. In our view, however, this argument is not compelling, for at least three reasons. First, until a recent uptick, energy R&D had declined over the preceding quarter-century in most industrialized countries and arguably is now grossly underfunded even as it becomes more economically and socially beneficial (Margolis and Kammen 1999; Grubler and Riahi 2010; Hoffert 2011). Second, what is contemplated here is a long-term commitment to public funding for basic R&D, testing and demonstration in amounts that are small relative to the economy, but cumulatively important. Finally, with population growth and the substantial worldwide increase in educated brainpower, there should be plenty of human capital available to conduct expanded long-term R&D of new and improved energy systems without shortchanging other fields of research.

That said, the real problem, we believe, is to design “incentive-compatible” R&D programs that increase the likelihood of producing useful results with a minimum of waste, in-fighting, jurisdictional disputes and lock-in to technologies that are inferior to later arrivals. Skepticism that such a design can be found and implemented is a more cogent reason for doubts about the efficacy of government funding for an energy technology race than are the induced-technological-change and crowding-out arguments.

In an earlier study (Galiana and Green 2010), we examined the literature on inducements to R&D and innovation, much of it drawn from the field of industrial organization, including the roles of market structure, patents and prizes. The long-term and public-good nature of the R&D, testing and demonstration that we believe are essential to transformational changes in energy technology suggests that the mechanisms to fund these activities should be designed in such a way as to: (1) assure a long-term pool of funds to finance energy R&D and related activities; (2) insulate the funds as much as possible from political influence and lobbying activities; (3) assure that at least some funds are channelled into advanced ideas, ones that might appear to hold little chance of success and even less of a near-term payoff but that have a big potential if proven successful; (4) avoid trying to "pick winners," while assuring that substantial funds go toward opportunities that appear highly promising; and (5) reduce the likelihood of lock-in to early successes that turn out to be inferior to later arrivals.

Why a Technology-Led Climate Change Policy? A Canadian Perspective

A technology-led climate change policy would address or avoid many of the problems associated with a regime that focuses on date-specific emissions-reduction targets. Target setting rarely gives adequate consideration to whether the implied emissions reductions are supportable given the state and capabilities of available low-carbon technologies. And in the rare cases where such consideration is given, the targets are criticized as not ambitious enough, as was the case for Japan in 2009 (Pielke 2009). In contrast, a technology-led policy would foster the development of technologies capable of eventually supporting deep reductions in emissions.

However, a technology-led policy should not be seen as a stand-alone response to the potential effects and damage wrought by climate change. It is not a substitute for investments in infrastructure, know-how and rapid-response capabilities that would reduce vulnerabilities and enhance adaptation to climate change and resilience to severe weather events. Nor is it a substitute for attention to other environment-related problems associated with climate change and local carbon "footprints." These issues are beyond the scope of this study, but they do require the development of appropriate policy instruments.

Does the global case for a technology-led climate change policy apply specifically to Canada? Why should Canada adopt a technology-led policy when no other country has yet adopted one, at least not formally? Would it be in Canada's interest to take the lead in adopting such a policy? What would Canada have to gain or lose? We begin by addressing the last question, because the response does help clear the stage for considering an alternative approach.

Abandoning emissions-reduction targets

The main thing Canada would give up if it were to adopt a technology-led climate change policy would be emissions-reduction targets. These have been the core guideposts (if only in theory) of Canadian policy since 2002, when Canada ratified the Kyoto Protocol, thereby formally committing to reducing emissions 6 percent below 1990 levels by 2012. But in 2002 emissions were already 21 percent above 1990 levels, and Canada lacked any coherent plan, much less feasible means, of achieving such a daunting target.

In 2007, with emissions 25 percent above 1990 levels, the Harper government effectively gave up on Canada's Kyoto commitment, which could not be met even though the carbon intensity of Canadian output had declined at a rate of 1.3 percent per year since 1990. (From this perspective, Canada's formal withdrawal from the Kyoto protocol in December 2011 was inevitable.) Soon thereafter, in its *Turning the Corner* plan (Environment Canada 2007), the Harper government set a new emissions-reduction target of 20 percent (later reduced to 17 percent) below the 2005 level by 2020, and also set a more notional long-term target of at least 50 percent below 2005 levels by 2050. To reach the 2020 target, the government mandated reductions in emissions intensity for five industrial sectors (electricity generation, pulp and paper, cement, oil and gas extraction and iron and steel). Firms unable to meet the mandated emission intensity reductions can purchase credits from other firms that are able to exceed them or, alternatively, contribute to a technology fund at a rate of $15 per tonne of CO_2 emitted. However, because the new policy targeted reductions in emissions *intensity,* rather than in the absolute level of emissions, it was never clear from the outset how GHG emissions would fall by 17 percent by 2020 (particularly in the context of sustained economic growth in the wake of the 2008-09 recession). Indeed, recent analysis by the environment commissioner indicates that the absolute emissions reductions promised will not materialize (Office of the Auditor General of Canada 2012), and the National Round Table on the Environment and the Economy (NRTEE) concludes that Canada will only achieve 50 percent of the target (NRTEE 2012). We would argue that, without new and improved low-carbon energy technologies, the longer-term target, too, will go by the boards in time.

Suppose, instead of using industry regulations to achieve emissions-reduction targets, Canada decided to put all its policy eggs in the carbon tax basket. The idea would be to set a carbon price that was high enough or rising quickly enough to obtain, on paper at least, substantial emissions reductions. The chips would be left to fall where they may with regard to the precise effect of the carbon price on the level of emissions. The Liberal Party of Canada's "Green Shift" proposal in the 2008 federal election campaign might be described as just such an initiative, though it did not articulate specific emissions-reduction targets. The proposal received plaudits from many in the economics profession, but it proved economically and politically toxic. Moreover, had Canada implemented the proposal unilaterally, emissions-intensive activity likely would have shifted to other countries, at least partially offsetting emissions reductions achieved in Canada. The main problem with the Green Shift and similar carbon-pricing proposals is that they put the emissions-reduction chicken before the energy-technology egg.

It is important to point out that abandoning emissions targets in favour of a technology-led approach to climate change mitigation does not necessarily mean that Canada should abandon current policies designed to curb emissions. We emphatically do not support abandoning measures related to fuel efficiency, hybrid vehicles, green building codes and countless others that are currently in force, provided they are effective at achieving their intended goals. (In fact, one could argue that the mechanism by which firms can contribute to a technology fund in lieu of meeting the emissions-intensity mandate under the *Turning the Corner* plan is consistent with a technology-led policy.) We simply believe that these measures, by themselves, will not be able to achieve the emissions reduction targets established, so it makes little sense to commit to such targets in the first place.

In recent years, Canada has openly adopted the position that its climate change policy should keep in step with that of the United States. In the first 18 months of the Obama administration, this appeared to portend a relatively active policy, but the window for US climate policy activism soon closed. First came the ambiguous outcome of the UN climate talks in Copenhagen in December 2009. Then came the failure of the US Senate to pass any climate change legislation in 2010, much less to agree to the cap-and-trade/offset-heavy Waxman-Markey bill that had passed the House of Representatives in 2009. By summer 2010, it was evident that the United States might not do much, if anything, on the climate policy front in the near future. That impression was confirmed in the mid-term congressional elections in November 2010. Many of the triumphant Republicans (and at least one prominent and successful Democratic senatorial candidate) had successfully run against cap and trade (calling it "cap and tax"). Some went further, questioning the scientific basis for predictions of global warming. The result has been effectively to shelve any major national climate change policy initiative in the United States for the time being. And Canada has followed step. Indeed, as long as climate policy advocacy at home continues to deem emissions-reduction targets the only game in town, Canada probably has no alternative but to lie low.

Yet the climate change problem has not gone away and will not do so. It thus does not make sense to wait to see if the inherently flawed Kyoto-type approach to climate change mitigation once again gains political favour. Instead, progress requires a new direction for climate policy (see Prins et al. 2010). Looked at through the prism of past failures and futilities, Canada does not appear to have anything to lose by seeking a fundamentally new means of tackling climate change.

Advantages of adopting a technology-led policy

It is much more difficult to determine what Canada would gain from adopting a technology-led policy than what it would lose, which, the preceding section suggests, is essentially nothing. We must acknowledge, however, that any move away from the current emissions-reduction-target focus would be accompanied by criticism from quarters that are wed to past regimes and climate politics. But criticism of Canadian climate policy is nothing new, and will probably continue as long as Canada fails to meet targets that are arbitrarily set and impossible or costly to achieve.

What, then, would Canada have to gain from a technology-led policy on climate change? The alternative is to continue relaxing under the US umbrella or, in the extreme, to freeride — to wait until other nations develop the technologies necessary for climate change mitigation. Although, in purely economic terms, freeriding might seem a low-cost option, there are a number of benefits for Canada of adopting a technology-led policy, even if it is one of the first countries to do so.

A real effect on long-term global climate change mitigation

The primary reason for a technology-led policy is that it is the only way for Canada to contribute meaningfully to global climate change mitigation. Canada accounts for less than 2 percent of global emissions, and that share will continue to decline due to the rapid economic rise of developing countries, particularly China and India. Even if Canada were to meet its emissions targets and reduce its contribution to global emissions by 17 percent, this would still amount to less than 0.34 percent of global emissions. Put bluntly, Canada's GHG emissions are irrelevant to global climate change, but very relevant indeed is Canada's capacity to develop replicable technologies that could help it and, more important, help large emitters reduce their emissions.

But why should Canada lead? As we have seen, breakthrough technologies will require basic research with "public good" characteristics that allow others to benefit from it. There is thus a strong temptation to freeride. One argument for action, which is also invoked by those who focus on meeting emissions targets, is that there are political and diplomatic gains from being a leader. For instance, Canada's international stature was enhanced for many years by its leadership in international peacekeeping. But there are additional practical reasons for wanting to be at the forefront of the next generation of energy technologies. As a large producer of both fossil fuels and renewable hydroelectric power, Canada could benefit directly from the development of new technologies in these sectors. As a hypothetical example, development of a technology to capture and sequester carbon emissions from automobiles, thus converting conventional cars into zero-emission vehicles, would have profound positive economic implications for Canada's oil sands sector, by rendering fossil fuels a low-carbon energy source for transportation.[2]

Spillover benefits to other industries

Canada also might reap more broad-based economic benefits as a result of technological, product and/or productivity spillovers from actively engaging in a technology-led approach, with its accent on basic R&D, testing and demonstration. Although it is almost by definition impossible to calculate the potential economic benefits of spinoffs from breakthrough carbon-reducing energy and environmental technologies (since they have not yet been developed), a review of spinoffs from other "big-science" efforts in the past shows that they exist and can be substantial.

One example is defence R&D spending in the United States during the Cold War. The explicit goal was to counter the Soviet military threat, and technology development was a big part of nearly all aspects of the associated arms race. Defence R&D accounted for 50 percent of total US R&D expenditures in the 1950s before falling to about 30 percent in the 1960s and 1970s. Numerous case studies have shown that this spending contributed to the growth of entire sectors of the economy, notably computers, semiconductors, mobile telecommunications and commercial aviation (Gamota 1985; also see Jenkins et al. 2010). The most commonly known spinoff of military technology is the Internet, whose communications protocols and infrastructure were developed by the US Defense Advanced Research Projects Agency (DARPA). Although the question of whether the technology would have been developed in the absence of DARPA's efforts is an open one, the large commercial and economic benefits that ultimately resulted from them are undeniable. In an analysis of the effects of US military R&D spending on various measures of nonmilitary economic performance over the period from 1955 to 1988, Chakrabarti and Anyanwu (1993) find a strong relationship between military R&D and commercial patents, which suggests the existence of spinoff technologies. Another important finding is that defence R&D did not "crowd out" nondefence R&D, suggesting that knowledge spillovers from defence R&D augment, rather than substitute for, technology development in the commercial sector, although the direct linkage between defence R&D and the civilian economy was too small to have a statistically significant impact on overall US GDP.

Another big-science initiative whose spinoffs have been extensively studied is the US space program in the 1950s and 1960s. In 1962, at the request of the US Congress, the National Aeronautics and Space Administration (NASA) created a technology utilization program to disseminate NASA R&D to the public. By its own account, NASA is directly responsible for more than 1,500 spinoff technologies in fields that include computer technology, environment and agriculture, health and medicine, public safety, transportation and recreation. Some of the more widespread and well-known technologies include freeze-dried food, lightweight and heat-and flame-retardant firefighting equipment, water purification equipment, high-efficiency solar cells and computer-aided design software. Empirical studies in the 1970s (summarized by Hertzfeld 1985) of the economic effects of NASA's R&D spending on US gross national product show mixed results, mainly because of the difficulty of controlling for non-NASA R&D, capacity utilization, industry mix and other factors that influence economic output. Microeconomic studies of specific successful commercial spinoffs, however, provide more reliable information on the benefit of targeted R&D for other sectors of the economy, and find that benefit-cost ratios for spinoff technologies vary widely from 4:1 for cardiac pacemakers to 68:1 for nickel-zinc batteries.

These findings suggest that government investment in basic and applied research projects aimed at achieving specified long-term goals can foster the creation and growth of entirely new commercial industries, as well as create spinoff technologies that can improve products in a diverse array of existing industries. Although the most-studied examples are in the United States, there is little reason to believe that similar dynamics would not be at play in Canada.

Reframing the role of carbon taxes in climate change mitigation

A technology-led approach to climate change policy would enhance the case for putting a modest price on carbon — by adopting a carbon tax or fee — that would have minimal adverse macroeconomic effects (Galiana and Green 2009). In addition to requiring long-term and secure funding and future incentives to deploy new and improved technologies, such a policy would avoid the pitfalls associated with the traditional rationale for carbon pricing.

Virtually all policy discussions of putting a price on carbon — either directly via a carbon tax or indirectly by adopting a cap-and-trade system of emissions permits — posit that the primary goal of such a policy should be to reduce GHG emissions directly. To that end, carbon pricing has long been a leading instrument in the toolkit of economists and since the early

2000s has gained favour among climate policy activist groups. The assumption is that carbon pricing would induce not only the substitution away from carbon-based fuels by consumers and businesses, but also innovation leading to new and improved low-carbon technologies.

There is, however, justified skepticism that carbon pricing would do what its proponents suggest. Substitutes for carbon-based energy are often limited — in particular, low-carbon alternatives to fossil fuels are currently limited in both their application and scalability. Moreover, as we have noted, there are reasons to believe that carbon pricing on its own is a weak reed with which to induce the private sector to undertake risky investments in next-generation low-carbon energy technology and innovation whose payoffs, if successful, have distant dates and doubtful appropriability. Ignoring these risks could make carbon pricing culpable as an accomplice to costly “brute force” mitigation. That said, carbon pricing, if properly framed — especially in the form of a low, gradually rising carbon fee or tax, as opposed to tradable emissions permits — could play an important, even essential role. If carbon pricing is viewed as necessary to developing and then deploying new and improved energy technologies, then there is a reasonable chance that, if appropriately explained, it could be made acceptable.

In sum, there is clearly a case for carbon pricing, but on a less aggressive scale than is usually proposed.[3] Until recently, carbon pricing and government-supported technological innovation policy have often been treated as substitutes for each other, with the latter considered inferior to the former. To the extent that promotion of innovation has been deemed important, carbon pricing rather than direct support of basic R&D, has been considered the primary policy lever, thus relying on market incentives to drive new technology development. In contrast, the technology-led approach we propose recognizes an essential complementarity between carbon pricing and technology policy.

Implementing a Technology-Led Policy

In essence, the key element of a technology-led climate-change mitigation strategy for Canada is an initially very low, but slowly rising, carbon tax whose primary purpose would be to provide long-term and stable funding to develop the breakthrough technologies necessary to meet long-term global (not just Canadian) GHG emissions-reduction targets, and whose secondary purpose would be to send a forward price signal to deploy these new technologies as they reach the shelf.

To put such a strategy into operation, we propose a $5-per-tonne carbon tax on either CO_2 emissions or the carbon content of fossil fuels, depending on the stage at which the tax is applied. The tax would be earmarked for a trust fund, kept at arm’s length from government, to underwrite the costs of basic research, testing and demonstration of breakthrough technologies that hold promise for significantly accelerating the decline in the carbon content of output.

The tax would add an estimated 1 cent per litre to the price of gasoline and $8.10 per thousand cubic metres to the price of natural gas — in effect, it would be virtually invisible to consumers and businesses. To magnify the price signal over time as new technologies are developed, the tax could be, let's say, doubled every decade (a 7 percent annual increase). Although this might seem like a large amount, the tax would reach just $10 per tonne by 2022 and $20 per tonne by 2032.[4] But the continued doubling of the tax each decade would mean that, by 2050, the carbon price would reach $80 per tonne, sufficient to have an important effect on low-carbon energy choice. Indeed, long before 2050, a powerful signal would be sent to start deploying, or planning to deploy, new and improved technologies.

A carbon tax of $5 per tonne would raise on the order of $3.4 billion per year, which would serve as the budget for a low-carbon energy research council (LCERC). This would amount to 0.2 percent of Canada's GDP, which is actually more in relative terms than NASA's R&D budget during the height of the Apollo mission to land a man on the moon.[5] It is also more than three times as large as the Natural Sciences and Engineering Research Council of Canada's 2010-11 budget of $1.1 billion.

Although an LCERC would share some similarities with existing granting councils, it would need to have some critical differences in order to be effective. To provide secure funding for energy innovation, the source of finance should be insulated, as far as possible, from the vagaries of the business cycle, the whims of legislative and budgetary processes and the influence of lobbyists. In an era of budget cutting and deficit worries, energy R&D funding should come not from general revenues but from a dedicated revenue source (in this case the $5 per tonne carbon tax) that is functionally related to the use of the funds. A model is the US federal excise tax on gasoline, the revenues from which are placed in the Interstate Highway Trust Fund, which, for almost 60 years, has been used to construct and maintain the US interstate highway system. In 2007, the Quebec government instituted a modest carbon tax (equivalent to less than 1 cent per litre of gasoline) collected from the province's approximately 50 producers of refined fossil fuels. The approximately $350 million raised by the levy annually is earmarked to a provincial Green Fund whose mission is to support sustainable development programs and, in particular, to finance several governmental climate action plan initiatives. Although the activities it funds are geared more toward exploiting existing technologies than breakthrough basic research, the use of an earmarked carbon tax is along the lines of what we are proposing.[6]

A second difference concerns the scope of activities eligible for funding. In general, existing granting councils fund basic research that leads to inventions, but usually stop short of funding large-scale testing and demonstration. However, this stage of development – the gap between invention and commercialization — is known as the "valley of death" because of the difficulty of finding private sector financing for these activities. For this reason, the mandate of an LCERC should be to fund not only basic research to discover the next generation of clean energy technologies, but also next-stage testing, demonstration and scalability. Increasing funding support at the upstream end of research, where there is a much more compelling economic rationale, would bolster the case for reducing downstream subsidies for existing clean energy technologies — such as tax credits for hybrid cars and subsidies for solar power, wind and ethanol — that have proven to be costly and largely ineffective (Jaccard and Rivers 2007), as evident in the Solyndra fiasco in the United States or Ontario's costly feed-in tariffs for solar and wind energy.[7]

The proposed LCERC should be outside the government budget process, be managed by both private sector and government-appointed officials, and use a panel of experts to allocate the funds among prospective projects. One possible model for awarding grants is that used by the Gates Foundation, a private sector foundation that has funded many human health and education projects. It provides an independent source of funding for projects of high priority chosen by a panel of experts acting as judges in an R&D competition. This model minimizes the risks of a government-picking-winners approach and "locking-in" to early, perhaps technologically inferior, discoveries, and is generally free of political interference and lobbying influence. Another model is the Advanced Research Projects Agency for Energy (ARPA-E) in the United States, which is itself modelled after the successful DARPA. This agency provides modest initial financing to public-private, high-risk, high-reward projects that, while having low probability of success, would have large payoffs if successful. ARPA-E is, however, administered by the Department of Energy, which opens the possibility of political interference in the agency's work. Effective governance of an LCERC would be essential to assuage the concerns of the many knowledgeable observers who are skeptical about a big government role in innovation, based on past failures of government R&D to bridge the gap between invention and commercialization (see, for example, Freed et al. 2009; Perelman, 2011) and the virtually limitless sinkhole created by subsidies to the producers and users of green energy. For illustrative purposes, the appendix offers a non-exhaustive list of potential research paths that could be considered for support.

The political economy of a technology-led policy

A technology-led approach would provide a firmer basis in both economics and politics for an effective long-term climate change policy. This approach would solve the "chicken-and-egg" problem of meeting long-term GHG reduction targets by developing the game-changing energy technologies that, in our view, have been largely assumed into existence by policy-makers. As we saw earlier, putting the emissions-reduction "chicken" ahead of the technology "egg" will almost certainly lead to unacceptably high costs. The 50 percent reduction in global emissions by 2050 proposed by the Group of Eight major industrialized countries at their meetings in 2007 and 2008 could be very costly if energy technologies fell short of allowing a virtual tripling of the current global average annual rate of carbon intensity decline from about 1.4 percent to 4.0 percent over the next 40 years. There is simply no reason to believe, however, that current technologies would enable anything even close to such a rate of decline. But by putting technology first, not only would the high costs (and likely failure) of an emissions-reduction-first policy be avoided, but the conditions would be put in place for even more rapid rates of decline in carbon intensity over the next several decades and beyond, the only really feasible route to stabilization (see Galiana and Green 2010).

Conclusion

Over the past 15 years, the policy focus on meeting GHG reduction targets has been a failure. An examination of the macroeconomic and demographic factors driving emissions clearly shows why: even if aggressive carbon pricing were to encourage wider use of existing low-carbon technologies, evidence casts considerable doubt on their ability to deliver the improvements in energy efficiency and reductions in carbon intensity necessary to produce deep reductions in global emissions — and certainly not without major negative economic consequences. Long-term, technically feasible emissions-reduction targets at the global level might make sense, but only if the technologies required to meet them are invented, developed and deployed. Our fundamental argument is that this will not happen without a concerted international effort, and Canada has the technological development prowess to contribute to that effort.

Having an impact on climate change is often encapsulated in the phrase “think globally, act locally,” but in Canada’s case that mantra needs to be cast in a slightly different light. By acting locally to try to meet its greenhouse gas reduction targets, Canada can contribute essentially nothing to the global climate-change mitigation challenge. Furthermore, those targets cannot be met by getting all Canadian drivers to purchase hybrid vehicles and fluorescent light bulbs or to engage in the many other environmentally friendly actions implicit in acting locally. Even if Canada could meet its targets, global emissions would decrease by less than 0.5 percent, while the costs in terms of lost GDP growth would be prohibitively high.

The inability of current technologies to generate deep GHG reductions does not mean we should stop encouraging their use — to the contrary, every little bit helps. But if Canadian governments want to get serious about having a positive impact on climate change mitigation, they should adopt policies that help develop the breakthrough technologies needed to reduce global GHG emissions significantly. In our view, a Low-Carbon Energy Research Council funded by a modest carbon tax — which would initially add less than 1 percent to end-user energy prices — would make a significant contribution to encouraging the development of cost-effective and scalable low-carbon technologies by providing a source of secure, long-term public funding for basic R&D, testing and demonstration. At the same time, proper sequencing of technology development and emissions reduction is essential. Carbon pricing can encourage the adoption of low-carbon technologies, but it is important to put the technology-development “egg” before the emissions-reduction “chicken,” to avoid potentially costly brute-force climate-change mitigation policies.

By playing a leading role in basic research devoted to next-generation, low-carbon energy technologies, Canada not only would show itself to be a leader in climate change policy (as opposed to paying lip service to unattainable targets), it could also reap considerable economic benefits from the technologies that are ultimately developed and deployed. In this context, Canada’s formal withdrawal from the Kyoto Accord — and the recognition that its targets are not attainable using today’s technologies — might be a blessing in disguise for those who truly want to enable deep greenhouse gas emissions reductions.

Appendix: Possible Research Directions for a Low-Carbon Energy Research Council

Carbon capture and storage

Canada is a leader in the development of carbon capture and storage (CCS) and home to one of the few currently operational commercial scale CO_2 storage sites, at Weyburn, Saskatchewan. Both the federal and provincial governments are contributing to CCS projects at the pilot and operational levels in the oil sands, in power plants and in the gas-processing industries. A major hurdle is how to scale up capture and storage to levels that would reduce emissions from heavy oil production and electricity generation substantially. Moreover, it is still an expensive undertaking: Shell Canada recently reported an $865 million agreement with the federal and Alberta governments (of which $120 million is to be provided by Ottawa) to fund its Quest Carbon Capture and Storage demonstration project, which is intended to capture and store one million tonnes of CO_2 per year by 2015 from Shell's heavy oil upgrader.

Shell's Quest project indicates the seriousness with which the federal government is pursuing CCS. But it also indicates that CCS is still a good distance from becoming truly scalable. Consider that a medium-sized 400 megawatt coal-fired electricity-generating plant would emit 2.8 million tonnes of CO_2 per year, and this does not take into account the 20 to 30 percent energy sacrifice associated with post-combustion capture. Moreover, the Quest project's high cost in relation to the relatively small amount that will be stored indicates that costs will have to fall substantially if CCS is to be applied to more than a small fraction of the 150 to 200 million tonnes of CO_2 associated with electricity generation and fossil fuel production in Canada and the approximately 10 billion tonnes per year emitted from these sources worldwide. As the US Interagency Task Force on Carbon Capture and Storage (United States 2010, 3) has reported, "though CCS technologies exist, 'scaling up' these existing processes and integrating them with coal-based power generation poses technical, economic and regulatory challenges." The report underlines why a technology-led policy and the funding that goes with it must include testing and demonstration, not just basic R&D.

Many other countries also have CCS projects under way, although few are as yet operational. Thus, what we learn from the Shell project and projects like it could help pave the way for technologies capable of capturing a larger share of Canadian and worldwide emissions. Among Canada's advantages is that most emissions associated with electricity generation and oil and gas production are located on or near the Pembina Basin, which spreads southeastward from northwestern Alberta to southwestern Saskatchewan. The basin's sedimentary geology is favourable to CO_2 storage, a not-insignificant factor given that storage requires close monitoring for leakage.

Geothermal space conditioning

Geothermal space conditioning (GSC) is a relatively simple technology that uses heat exchangers and pipes sunk in the ground beneath or next to buildings to supply heat in the winter and air conditioning in the summer to residences, commercial establishments and office towers. The technology might be mature, but innovation funding could be used beneficially to demonstrate the scope for residential use of GSC and the extent to which it is possible to use GSC effectively in large commercial and office tower structures.

Put another way, scale-up probably awaits confirmation of the extent to which GSC makes it possible to substitute other sources of energy, especially in larger buildings. Ultimately, the main objective of funding would be to assure that scalability in the production and installation of the equipment contributes to savings in purchased energy and fuel. In the usual course of things, it takes energy to produce energy. As with solar, wind, wave and tidal sources, geothermal allows nature to do the work. Moreover, unlike other renewable energy sources (except hydro), geothermal energy is available when needed.

Large-scale storage of solar and wind energy

Climate change policy advocacy typically is accompanied by a good deal of wishful thinking about renewable energy — particularly solar and wind energy. Their still-tiny contribution to total energy consumption, despite large increases in solar array and wind farm capacities, is an indication of the current limitations of these sources in electricity generation. The problem is easy to understand, but has been very difficult to solve. Much of the time, the wind is not blowing or the sun is not out when the energy is needed; at other times, these sources can deliver more energy than is needed. Thus, insufficiency on the one hand and wasted energy on the other means these sources are currently incapable of supplying (electric) energy reliably and cost-effectively. This lack of reliability threatens blackouts and brownouts unless sufficient “spinning reserve” (energy from backup sources) is available.

The solution is obvious: large-scale storage for intermittent solar and wind energy. But the solution has been elusive once one looks beyond “pumped” hydro (the availability of which is typically site specific) and compressed air energy storage, which is crude, cumbersome and has yet to be made operational for electric utility generation purposes. What is needed is a scalable technology capable of reliably and cost-effectively storing energy in a form that can be converted quickly to electricity. Without technological breakthroughs in energy storage, solar and wind energy is likely to remain a small contributor to the total energy picture. Relying on advances in electricity networks (such as improving grid structure and “smartness”) and diversifying the location of solar arrays and wind farms as an alternative to storage, as some energy analysts suggest (see, for example, Delucchi and Jacobson 2011; Jacobson and Delucchi 2011), is not credible if *reliability* is deemed essential.

The case for Canada’s contributing to solar and wind energy storage research is twofold. First, most countries stand to gain greatly from technological breakthroughs that lead to the successful storage of energy from intermittent sources on a very large or electric utility scale. Such success should then allow for downscaling to residential and commercial storage. Second, the chances of success in this highly uncertain but important endeavour would be increased if many groups of people work on a solution at the same time. Therefore Canada should not work alone but should collaborate with other countries on both designated R&D and funding. Such collaboration could be a model for other consortia, and help generate a real technology race to find the holy grail of renewable energy storage.

Smart grids

"Smart grids" are a much-discussed modernization of the electric grid that would improve the system's ability to monitor, protect and automatically optimize the operation of its interconnected elements (EPRI 2011, 1-1). Smart grids can improve the balance between demand and supply by the monitoring, communication and control of high-voltage systems and enhance the remote monitoring of local distribution networks so as to reduce maintenance and operating costs, thus increasing reliability and improving the response to outages (see Joskow 2012, 35, 37). However, without additional technological breakthroughs, smart grids have a limited ability to increase transmission capacity and, although they would complement grid-scale storage, they are no substitute for such storage systems. Smart grids are an example where research cooperation with the United States might be highly desirable.

Small-scale nuclear power

Until the March 11, 2011, tsunami seriously damaged the nuclear power plant at Fukushima, Japan, nuclear electric energy was enjoying something of a renaissance. That event, however, has slowed nuclear energy's return to favour, if not dashed it altogether. But Fukushima is but one part of nuclear energy's problem. The other part is the cost of capital (including construction), approval, siting, meeting regulations and safety and security (see, for example, Bradford 2012; Davis 2012). Yet, without an enhanced contribution from nuclear energy, the attempt to achieve substantial cuts in global GHG emissions by mid-century will be all the more difficult. Might there be some salvation in smaller-scale nuclear power units, perhaps with a modular construction? And if so, does Canada, once an important contributor to civilian nuclear power, still have the expertise to pursue new nuclear initiatives? A "yes" or even "maybe" could be sufficient to warrant investment in R&D, testing and demonstration in this area. Indeed, in the face of rising fossil fuel prices, the territory of Nunavut is already considering the use of small-scale nuclear plants to replace current diesel generators. Much depends on whether miniature reactor designs can live up to safety standards and be constructed cost-effectively (Brusilow 2011). Given Canada's vast territory and far-flung communities, there might well be important payoffs to the testing and demonstration of small-scale nuclear generators.

Hydrogen for heavy transport

A decade or more ago, hydrogen seemed to be the fuel of the future; indeed, there was much talk of a "hydrogen economy." In Canada, companies such as Ballard in Vancouver became synonymous with hydrogen-powered vehicles and Stuart Industries in Toronto with manufactured state-of-the-art electrolyzers for separating hydrogen and oxygen from water. But the flower wilted as it became clear that hydrogen-powered vehicles required breakthroughs in fuel systems and onboard storage and a large and complex infrastructure of refuelling stations. If basic research could reduce the energy required to create hydrogen and address storage problems, perhaps hydrogen could enjoy a revival, particularly if its role in transport were directed away from light vehicles to heavy transport such as railroads and vehicles where the refuelling infrastructure hurdles would be lower.

Notes

1 For a number of reasons, Pielke, Wigley, and Green's "frozen technology" baseline might somewhat overstate the size of the technology challenge, and could be interpreted as a worst-case scenario. First, it does not account for any energy intensity decline attributable to a shift toward less energy-intensive production (although this effect is small when considered in global terms). Furthermore, modest efficiency gains likely would be prompted by competition between firms and the adoption of best practices. Nevertheless, frozen baselines are an important benchmark for understanding that the challenge is much bigger than we are usually led to believe.

2 The idea is not as far-fetched as it seems. Researchers at the Georgia Institute of Technology (2008) are working on a system to capture and store carbon created by the combustion of conventional fossil fuels in motor vehicles before it leaves the tailpipe.

3 As a point of reference, the National Roundtable on Energy and the Environment (2009) concludes that a price of $100 per tonne would be necessary to meet 2020 targets and a price of $300 per tonne would meet 2050 targets.

4 As a point of comparison, the carbon tax proposed in the Green Shift would have started at $10 per tonne and quadrupled in just four years.

5 Significantly, NASA's total budget for the Apollo program increased to a much larger share of US GDP as investments were made to develop the applications of the initial research. Such complementary investments will undoubtedly be necessary as new energy technologies are discovered and developed.

6 British Columbia has also enacted a carbon tax of $30 per tonne of CO_2 equivalent, but the resulting revenue is used to reduce other taxes, rather than to support technology. Alberta charges a penalty of $15 per tonne of CO_2 equivalent to firms that cannot meet their provincial emissions targets or do not purchase offsets; the proceeds are put in a technology fund. But because the penalty does not apply to all emitters, it raises very little revenue.

7 Solyndra was a California-based manufacturer of solar panels. Despite having received a US$535 million loan guarantee from the US federal government and a US$25 million tax break from the state of California, it abruptly ceased operations and declared bankruptcy in September 2011. The feed-in tariff program in Ontario pays providers of renewable energy above-market rates for power generation in order to stimulate the development of renewable energy, but there is little evidence that this market expansion strategy or effort has lowered the production costs.

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