How Induced Innovation Lowers the Cost of a Carbon Tax

BY JOE KENNEDY | JUNE 2018

Research shows that such innovation helps reduce the cost of lowering emissions—and potentially eliminates the costs altogether if the carbon-tax revenues are used to provide tax incentives for innovation and investment.

Many nations have pledged to reduce their emissions of carbon dioxide (CO_2) over the next several decades in an attempt to keep global temperatures from rising more than 2 degrees Celsius above preindustrial levels. One policy tool that is likely to be increasingly embraced is raising the price of carbon emissions by taxing them, an effect of which would be to induce needed innovation in less carbon-intensive technology. Research shows that such innovation helps reduce the cost of lowering emissions—and potentially eliminates the costs altogether if the carbon tax revenues are used to provide tax incentives for innovation and investment (e.g., a more generous research and development tax credit). This report examines the potential impact a revenue-neutral carbon tax would have on technological development and suggests policies to maximize that impact while minimizing the economic cost.

INTRODUCTION

Despite the claims of skeptics, the scientific evidence on climate change is solid, and has been growing over the last two decades. Although a large number of uncertainties still exist, there is a strong scientific consensus about the need to significantly reduce the emission of greenhouse gases, primarily carbon dioxide (CO_2). This consensus will only get stronger over time.

As a result, virtually every nation, and a number of U.S. states, have publicly pledged to reduce their greenhouse gas emissions. A large part of this effort focuses on reducing the emission of carbon dioxide, which accounted for 81.6 percent of U.S. emissions of greenhouse gases in 2012.[1]

Carbon emissions can be reduced by focusing on either the supply side or the demand side. The supply side involves either subsidizing existing low-carbon technologies or spurring innovation in them (including through R&D funding), and the market then naturally adopting the technologies because they cost less or perform better than conventional fossil fuels. The demand side involves enacting policies that limit the consumption of carbon-intensive energy and products. There are two main kinds of demand side policies: carbon taxes and regulatory limits such as cap-and-trade programs. The former is more efficient (achieving a given level of reduction at a lower cost) and therefore preferred over a cap-and-trade regime by most economists. The cost increase from a carbon tax (or cap-and-trade) will cause technology developers to invest more in cleaner technologies and, when the marginal cost of abatement is less than the amount of the tax, lead consumers (individuals, businesses, and other organizations) and producers to adopt less carbon-intensive processes.

Putting a price on carbon will also have a secondary effect. In a competitive economy, firms constantly face pressure to invent or adopt innovations that reduce costs and increase quality. Raising the cost of carbon-intensive activity should give firms stronger incentives to develop more carbon-efficient technologies. Because they will be cheaper than existing technologies, these carbon-efficient technologies should ultimately be more widely adopted, thereby reducing the cost of achieving a given amount of emission reductions. Over the last two decades, a growing body of research has focused on the nature and size of this "induced innovation."

This report discusses induced innovation from a revenue-neutral carbon tax. After a brief review of the market failures involved in curbing global warming, it discusses the basic details of implementing a carbon tax, and then reviews the theory of induced innovation.

The report goes on to review academic attempts to model induced innovation as a response to policies that try to curb carbon emissions, such as via tax. These studies make a number of different assumptions, including the economy's responsiveness to taxes, how innovation occurs and spreads, and whether research in carbon-efficient technologies crowds out other research. Although different assumptions produce significantly different results, there appears to be a consensus that induced innovation will modestly reduce the cost of imposing a given carbon tax. According to one model, if a carbon tax imposes a dollar of cost on the economy, induced innovation will end up reducing that cost to around 70 cents.[2] Induced innovation acts mainly by reducing costs rather than increasing the environmental benefits from a carbon tax. However, if the cost of carbon abatement falls, it makes sense for society to purchase more of it by raising the tax above where it would be without additional innovation, thereby spurring more reductions. Using the revenues from a carbon tax to reduce other taxes, or to expand business incentives to perform R&D and capital investment, could actually lead to carbon taxes generating net economic benefits.

THE NEED TO REDUCE CARBON EMISSIONS

Although many uncertainties remain about the exact size of the threat, the need to address global warming is no longer a matter of legitimate dispute. Specifically, there is a broad scientific consensus on the following statements: (1) the Earth's temperature has been increasing over the last several decades; (2) the temperature rise is partially due to humans, largely through economic activity that emits carbon dioxide; (3) beyond a certain point, increased temperatures will bring an unacceptable risk of large environmental costs, including rising sea levels, increased droughts, and enhanced storm activity; and (4) nations need to begin taking actions now to reduce the emission of greenhouse gases. There is, however, less agreement about how aggressive that action should be.

Steven Pinker, generally regarded as an environmental optimist, has stated the problem:

> If the emission of greenhouse gases continues, the earth's average temperature will rise to at least 1.5°C above the preindustrial level by the end of the 21st century, and perhaps to 4°C above that level and more. That will cause more frequent and more severe heatwaves, more floods in wet regions, more droughts in dry regions, [and] heavier storms…. The effects could get still worse in the 22nd century and beyond, and in theory could trigger upheavals such as a diversion of the Gulf Stream (which would turn Europe into Siberia) or a collapse of Antarctic ice sheets. A rise of 2°C is considered the most that the world could reasonably adapt to, and a rise of 4°C, in the words of a 2012 World Bank report, "simply must not be allowed to occur."[3]

All parties of good will and open mind should be able to agree on the facts and then engage in a robust debate about the best steps to limit the negative impacts from climate change.

Blind opposition to emissions abatement is no more responsible or scientifically based than is opposition to genetically modified organisms in agriculture or to childhood vaccinations. However, that does not mean efforts to reduce carbon emissions need not pass a cost-benefit analysis, or that some policies advocated in the name of climate change are not ill-advised and would not have harmful impacts on the quality of life.

But all parties of good will and open mind should be able to agree on the facts as listed above and then engage in a robust debate about the best steps to limit the negative impacts from climate change. Clearly, steps that limit, or even eliminate, negative economic impacts, are preferred. Done right, the optimal carbon policy could yield net gains in welfare, especially if it effectively spurs technological innovation. Indeed, price and quality improvements in a number of clean technologies, including solar power, wind power, batteries, and electric cars have occurred faster than most people predicted. Moreover, there are some preliminary signs the link between economic growth and carbon emissions is weakening.[4]

THE MARKET FAILURES INVOLVED IN GLOBAL WARMING

The implementation of a revenue-neutral carbon tax gives policymakers an opportunity to address three distinct market failures associated with global carbon emissions, incentives for private research and development, and the degree of competitive pressure necessary to adopt the latest technology. Discussion of the second and third market failures is reserved for later.

The first market failure is organizations and individuals benefiting from using lower-cost, dirty fuels. Although both organizations and individuals suffer from global warming, the link between their individual emissions and the final degree of warming is infinitesimal. Because the costs associated with additional emissions are virtually zero, they will continue to emit carbon as long as the cost of carbon fuel remains less than the benefit of the economic activity they are engaged in. The net result is carbon emissions are much higher than is socially optimal. A price on carbon emissions forces organizations and individuals to consider their social costs when making decisions.

Beyond this market failure, global warming has other features that make it especially difficult to regulate. One is the lag time between incurring costs and realizing the benefits of reduced emissions is unusually long. While the cost of carbon abatement is upfront as organizations switch to more expensive low-carbon technologies, many of the environmental benefits will not be felt for decades. Businesses and governments often have a hard time making investments when the payoff is far in the future—even if they are ultimately able to capture all of the benefits. Moreover, if a normal discount rate is applied to future benefits (because benefits lose their value the longer we must wait for them), their value falls significantly, making any significant abatement difficult to justify economically.

Another problem, from a national perspective, is that with current technology, high carbon emissions have both a benefit and a cost. The close historic relationship between energy consumption and economic growth, coupled with the high carbon content of most energy today, means carbon emissions deliver material prosperity by fueling the machinery needed for factory production, transportation, home appliances, and a host of other activities. But higher emissions will also increase global temperatures, which will create economic costs. Ideally, society would stop emitting carbon once the marginal social benefit falls below the marginal social cost.

A related component of the market failure relates to geography. If only one nation bears the cost of switching to zero- or very low-carbon technologies, that nation will bear all the costs of reducing its emissions—but the lion's share of the benefits will be enjoyed by others. This is because the earth's atmosphere is, for the most part, a global commons.[5] This makes it even more difficult to justify abatement on economic grounds. In fact, if unilateral action causes high-emitting firms to relocate to other nations, a country could suffer large costs with very little reduction in global emissions. For example, a United States-only carbon tax would benefit all nations. One study estimates that the United States would receive only 7 to 23 percent of the total benefits from a domestic tax even though it would bear all of the costs.[6] Of course, if similar efforts by other countries were linked to U.S. participation, both global and U.S. benefits would be higher. In this sense, this is a collective-action problem.

The most logical solution is a binding international agreement in which all, or at least most, large countries mutually pledge to take action. However, international agreement so far has been hampered by the costs and benefits of reducing emissions differing between countries. Many developing countries believe developed countries, which are responsible for most of the historic rise in carbon concentrations, should bear most of the abatement costs.

THE BENEFITS OF A CARBON TAX

For these reasons, many policymakers and economists favor market-oriented policies over the traditional command-and-control approach to reduce warming (e.g., mandating each industry emit 20 percent less emissions). Market-oriented policies put a price on carbon emissions to reflect the social cost they impose, and then leave it to the market to discover the most efficient way to reduce emissions. Because the burden of this tax is passed upstream, firms and individuals must take this additional cost into account when making decisions. A carbon tax's impact is felt broadly and has two particular effects: boosting efficiency in the activities that emit carbon (e.g., using more fuel-efficient motors), and accelerating development of cleaner technologies that are also cheaper. Firms have a greater incentive to become more energy efficient and switch to less carbon-intensive fuel, while consumers have a similar incentive to buy fewer carbon-intensive or more fuel-efficient goods. And technology developers have a stronger incentive to invest in clean energy technologies.

Although a carbon tax leaves open the possibility that emissions will be higher than planned, it also holds out the hope they will be lower, especially if they induce more innovation.

Carbon taxes are more efficient than both command-and-control regulations that dictate the specific actions each industry must take to reduce their emissions, and cap-and-trade regulations—while existing carbon regulations are often inefficient. A recent study estimated existing CO_2 abatement policies, including those recently proposed by the Obama administration and later revoked by President Trump, would reduce carbon emissions by 20 percent relative to no action. However, more than two-thirds of the reduction in emissions would occur after 10 years. The study also concluded that the rules cost the economy nearly 1 percent of GDP.[7]

One reason these policies can be expensive is every industry is at least indirectly responsible for emissions, many large sources of which—including transportation, construction, and electricity generation—are closely linked to modern life. When the sources of pollution are few and the technology needed to achieve certain environmental goals is already available at a reasonable cost, it might make sense for government to simply mandate companies to adopt it. But the prospect of closely regulating every major source of carbon emissions, both now and in the future, is beyond the ability of even the nimblest regulator.

The two most common market solutions are an emissions cap with tradable permits, and a carbon tax. Under an emissions cap, the government requires companies to obtain a permit before emitting carbon and sets a limit on the amount of carbon permits available. Companies can buy and sell permits in the market. The initial permits are often given away rather than auctioned off in order to reduce the cost of compliance. This dramatically reduces the revenues available to the government but may also reduce political opposition from existing companies.

With a carbon tax, the government levies a tax on all emissions. In theory, if the tax equals the market clearing price for a given cap on market permits, the two policies should result in the same outcome. With permits, the government is setting the quantity of emissions and letting the market dictate the price, whereas a tax sets the price of emissions and leaves the quantity up to the market. Although a carbon tax leaves open the possibility emissions will be higher than planned, it also holds out the hope they will be lower, especially if they induce more innovation.

Although policy discussions have tended to center around cap-and-trade plans, most economists favor a carbon tax. There are several reasons for this. The tax utilizes the same price signal industrial supply chains are already familiar with. In addition, it is easier to administer, with the government simply implementing a tax on fuels based on their carbon content. In contrast, the process of issuing emissions permits for hundreds of thousands of different companies is daunting to say the least. Moreover, a cap-and-trade regime is very difficult to apply to small-source polluters (e.g., a dry cleaner or someone using their lawn mower), whereas a carbon tax affects all activities.

A carbon tax also gives the government a chance to address different market failures in the discovery of new technologies to combat warming. Firms conduct research when the profits they receive are greater than the cost of conducting the research. However, it is widely agreed that the social benefits of corporate research are significantly greater than the private benefits firms are able to capture.[8] For example, one survey of this subject points to evidence that the social return on research is 30 to 70 percent per year, whereas the private returns are only 6 to 15 percent.[9] Unfortunately, firms do not take the social benefits into account. As a result, they conduct far less research than is socially optimal.

The problem is even greater in the case of technology to reduce emissions, wherein the benefits are more social. Moreover, when new technology comes at a higher cost, companies may not adopt it even if it significantly reduces emissions. A carbon tax partially addresses this by increasing the cost of dirty energy and, in the process, raising the private benefits of research on energy efficiency and low-carbon energy. However, the social benefits are still likely to exceed the private ones, resulting in too little research. As one paper found: "Because the benefits of environmental technologies tend to accrue to society at large, rather than the adopter of such technologies, market forces alone provide little incentive for developing environmental technologies."[10] As such, research on clean energy may have an even greater social value than research in most other industries.[11] First, until recently, comparatively less research had been done on alternative energy and other clean technologies. The lower knowledge base may mean a higher proportion of high-value innovations remain to be discovered. It is not unreasonable to assume the marginal value of research into a particular technology will decrease over time.[12] Second, energy technology influences the economics of many other sectors of the economy because it is a ubiquitous input. A logical solution is to reduce the after-tax cost of discovering and adopting new innovations.

THE POLITICS OF A CARBON TAX

Many demographic groups, including Hispanics and young voters, increasingly want to see action on climate change.[13] In the past, conservatives were highly skeptical of the need to control emissions—but that may be changing. A recent poll shows 19 percent of conservative Republicans believe the "climate is changing and human activity is contributing a lot to the change."[14] The concept of clean energy enjoys even broader support: 84 percent of registered voters, including 72 percent of Republicans and 68 percent of conservative Republicans, support action to accelerate the development and use of clean energy.[15]

Polling indicates political support for a carbon tax may be growing.[16] A recent survey found that Americans are willing to see their energy bills go up by $177 per year, an average of 14 percent, through a carbon tax.[17] It also concluded that Americans prefer the revenues be invested in clean energy, infrastructure, and compensating displaced miners, which could be done either through direct spending programs or tax incentives. There was less support for reducing individual taxes or paying a dividend to households. Another survey found that only 34 percent support a carbon tax when the use of the revenues is unspecified. Support jumped to 56 percent (43 percent of Republicans) when the tax was revenue-neutral. The largest gains in support came from Republicans.[18] Support was highest, 60 percent, when the revenues went to fund R&D for renewable energy programs.

THE BASICS OF A CARBON TAX

What would an ideal carbon tax look like? Three criteria seem important. The first is certainty. As both a practical and political matter, policymakers need to retain a degree of flexibility to adjust the amount of the tax in response to new knowledge and outcomes from the tax. But unless companies are confident carbon prices will remain substantially higher in the long term, their incentive to engage in research to find cleaner technologies or make long-term investments to implement them will be weaker.

The second criterion is comprehensiveness. The tax should be levied early in the supply chain, at the wellhead or mine. Its impact would then flow to all firms and consumers downstream. Rebates would need to be given for fuel that is used as a feed stock in a process that does not produce emissions, such as the making of chemicals and plastics. A report by the Congressional Research Service estimated 80 percent of U.S. greenhouse emissions (including methane and nitrous oxide) could be taxed through payments by 2,300 entities.[19] These entities would then pass the burden of the tax on to others in the supply chain. Other sources, including farm and cattle operations, forestry, and landfills, would be harder to tax.

Finally, the tax should be adjusted at the border. Exporters of dirty fuel should be able to get a rebate, with importers of that fuel paying a tax based on the emissions associated with the product. Border adjustability would prevent double taxation and minimize the competitive impact of the United States imposing a tax unilaterally. However, it would not make sense for adjustments to also include energy-intensive products, even if those products face international competition. Calculating the correct amount of tax or rebate on thousands of products made using different production methods and different intermediate goods would be impractical.[20]

Estimates of the optimal size of a carbon tax suffer from a significant problem: Many of them recommend an initial carbon tax of $10–$20 that then rises slowly thereafter. A number of observers believe this will be too low to achieve the emission reductions most experts think are necessary to prevent the most severe damages from climate change.[21] Environmentalists therefore call for a much higher tax rate. However, it is very difficult to justify the economic costs of a high tax rate unless the model uses a very low discount rate to value environmental benefits that will not occur until decades from now. Whether to do this is fundamentally a moral and political decision. There is also very little evidence of public support for a high initial rate, which makes it politically difficult to achieve. As a result, significant future reductions in emissions depend heavily on a rapid pace of energy innovation to bring down prices and improve the performance of clean energy.

Because carbon emissions are often associated with the production of fine particulates, sulfur dioxide, and other pollutants, a carbon tax will produce other environmental benefits models often do not measure. These "co-benefits" can be substantial, perhaps even outweighing the benefits from reduced global warming. One study found these benefits alone would justify a carbon tax of $36 per ton, provided the revenues were used productively. This suggests a carbon tax of $50 per ton could be imposed without reducing total welfare in net present value terms.[22]

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THEORIES OF TECHNOLOGICAL CHANGE

How does technological change happen? How can government influence it? The earliest studies of technological change identified it simply as the increase in output that could not be explained by an increase in one of the factors of production, most commonly capital and labor.[23] Because it was unexplained, it was often assumed to occur independently of public policy.

Some models still adhere to this practice, although many of them assume the process naturally contains a degree of autonomous energy efficiency improvement (AEEI) that benefits the economy regardless of public policy. Others may simply assume one or more specific "backstop" technologies, such as nuclear power or solar energy, will naturally become more efficient over time until they reach a price point that allows them to replace current technology. Under this model, innovation is, as Robert Solow once quipped, "manna from heaven."

A growing number of economists have come to understand the nature of technology and how much it responds to public policy choices. Joseph Schumpeter laid out a theory in which technological change is divided into three steps, each of which is critical to the final influence on social welfare.[24] *Invention* occurs with the development of a new product or process. However, most inventions never influence the economy—and if they do, they do so only over long periods. *Innovation* occurs when this new product or process is commercialized into something others can use. The final critical stage is *diffusion*, or the spread of the innovation such that its social impact is increased. The level of diffusion typically follows an S-shaped curve, with adoption growing slowly at first, speeding up once it crosses a critical mass, and then slowing again as full adoption is approached.[25] Each stage is necessary for technological change to have an effect on society. Termed "endogenous growth theory," it posits innovation can happen on both the supply and demand side, and that on the supply side, government policies, such as funding for R&D, can play a key role in determining the course and pace of innovation.

At least three theories seek to explain how, within firms, technological change happens.[26] The *evolutionary approach* assumes firms satisfice instead of maximize profits.[27] As long as firms are successful and earn a targeted rate of return, they pursue their current practices. Investment in R&D is driven by rules of thumb that have been successful in the past. Economic pressure may cause firms to implement randomly chosen new products or processes. Firms that choose successful technologies expand, while those that do not go out of business. Because these models assume firms do not maximize their performance, it is theoretically possible for the government to mandate technologies that, if adopted, would both improve social welfare and reduce costs. However, this assumes the government can successfully identify and implement these policies when the private sector either cannot or will not. This is a significant hurdle in practice.

The *path dependence* theory assumes certain technologies can benefit from factors other than their merits versus other technologies.[28] These forces include familiarity, the presence of large sunk costs, and network effects. Path dependence can lead to "lock-in"— a society staying with an incumbent technology even though a better one is available. The ultimate choice of technology may depend on random factors in history rather than the maximization of economic welfare. But while it is clear such forces may influence technological developments in the short run, clear cases of inferior technologies being locked in for long time periods are hard to identify.[29] So too are cases in which the government does a better job of identifying successful technologies than the private sector.

Both of these theories have some explanatory power. Firms do not always maximize profits, even when uncertainty is taken into account. Indeed, firms with too much or too little market power can limit innovation: In the first case, firms lack the competitive incentive to invest in risky innovation. In the second, they lack the necessary resources.[30] Certain technologies, including many in the energy sector, do benefit from network effects and high fixed costs. However, neither theory is as powerful as induced innovation in explaining firm development and adoption of technology.

THE THEORY OF INDUCED INNOVATION

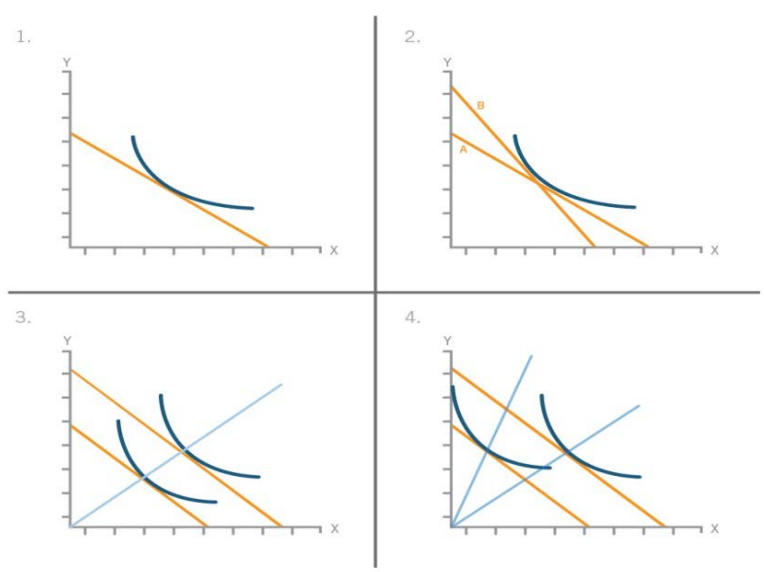
The basic concept of induced innovation, which predicts innovation will respond to market forces, has been around for a long time. One of the earliest formal descriptions of it comes from *The Theory of Wages* by John Hicks: "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed at economizing the use of a factor which has become relatively expensive."[31]

The effect of induced technological change can be seen in the four panels contained in figure 1. Panel 1 shows a typical isoquant made up of all of the existing technologies that can produce a given amount of a good. To a certain extent, manufacturers can substitute the two goods in response to price or other constraints. Manufacturers will choose the particular mix of inputs that minimizes the total cost of producing the good. The x- and y-axes can represent the quantities of two inputs needed to produce the good. We could also define the x-axis as representing the environmental cost of producing the good, with the y-axis representing an index of all other inputs. Environmental damages represent a cost to society and, to the extent they are passed on to producers, affect its choice of technology. The orange line shows the ratio of prices. Producers will choose the combination of inputs that is a tangent to this line.

The basic concept of induced innovation, which predicts innovation will respond to market forces, has been around for a long time.

Panel 2 shows the effect of an increase in the price of input x (pollution). The manufacturer moves to a new point on the isoquant that substitutes input y for input x. It is important to note this price change can be caused by many events, including a government tax on input x or regulations that artificially restrict its supply. If the x-axis represents the environmental cost of producing the good, then the shift to a new point on the isoquant could be caused by regulatory action that increases the manufacturer's cost of pollution.

Figure 1: How Induced Innovation Works



Panel 3 shows the effect of technological progress, which produces a new isoquant nearer to the origin of the chart. It is now possible to produce the same amount of the good at a cheaper price, using fewer total inputs. Absent any other changes in the economy, technological progress could be expected to follow a neutral path, not favoring any particular input or industry. This would result in a proportional decrease in demand for all inputs. Absent an explicit policy to encourage innovation, it is likely some of this would still occur as a natural course of business. This would be especially true for highly competitive industries whose customers are very responsive to price.

Panel 4 shows the effect of induced technological change in response to a carbon tax. In this case, a rise in the price of carbon spurs additional innovation that again moves the isoquant closer to the origin. However, the new technology clearly favors a reduction in input x, which is the amount of environmental damage. This is in addition to the price effect shown in panel 2. Consumers, facing a higher price for environmental damage, will look for solutions that pollute less. At the same time, suppliers have an incentive to find innovations that are relatively more efficient in the use of input x.

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The conclusions of academic studies on induced innovation are affected by a number of assumptions about how technology advances and the relative effect of various economic forces. As a result, the specific approach taken in modeling technological change is one of the most important influences on the results of climate change analysis.[32] The problem is even more severe when, to calculate the optimal carbon tax over time, researchers try to integrate assumptions about the relationships between net emissions and global warming; the amount of warming and economic activity; and the effect of public policy on emissions. The result of these integrated assessment models depends heavily on the specific assumptions that go into the model, especially the discount rate used to value expected benefits decades into the future.[33]

The simplest theories are limited to the price-induced shifts previously described in panel 2. They assume public policy affects the choice between existing technologies, but does not influence the development of new ones.

A second approach assumes the stock of knowledge is a key input into the production process.[34] This stock may or may not depreciate over time, and is increased in large part by investments in R&D, which respond in part to the relative price changes caused by public policy. The theory assumes an increase in the price of energy motivates firms to invest more in energy-saving research and development. Key assumptions include the price elasticity of energy-saving research, the degree to which an increase in energy-saving research crowds out existing R&D, and the size of social spillovers from private research.

There are, however, significant lags between R&D investments and the widespread diffusion of a new technology. This could justify a much lower tax rate in the near term, provided it rises rapidly in the medium and long term.[35] Assuming companies mainly respond to their long-term expectations about the tax rate, a low short-term rate would minimize the social costs of imposing the tax, without significantly reducing the incentives to conduct research on alternative technologies, provided companies remain confident the tax will increase and they will be able to earn sufficient returns on developing cleaner technology in the long term. Once the benefits of new technology occur, the reduced economic costs of a given carbon tax justify raising it.

A third approach focuses on the effect of learning.[36] Unlike R&D, learning effects do not require the investment of large resources and do not crowd out other research. Instead, the models assume production costs fall as the output associated with a particular technology increases (learning by doing) and the technology's value to consumers increases the more it is used (learning by using). Both imply the presence of increasing returns (i.e., returns go up as more is produced or consumed), which can lead to path dependency and lock-in. The presence of learning also tends to reduce the amount of a tax necessary to achieve a given level of emissions abatement. However, the effect is usually to increase the optimal tax in the near term and lower it in the long term. The rise in near-term taxes speeds up the benefits from increased returns to scale, giving society more years to enjoy them. Because it assumes induced innovation does not crowd out other investments in innovation, this approach probably overstates its benefits.[37]

Induced innovation can affect the level and timing of a carbon tax in many ways. In the simplest view, an improvement in carbon-saving technology should lower the cost of achieving a given reduction in emissions. Assuming the carbon tax rate is driven by the desire to prevent global temperatures from rising by a given amount, induced innovation would justify a lower tax rate without threatening this goal. However, it is also possible policymakers would want to devote the social savings from induced innovation to achieving an even greater amount of emission reductions, which would require a higher tax rate than originally planned, but incur the same economic costs because of the benefits of induced innovation.

The government's commitment to higher taxes may not be time-consistent, however. If company research depends strongly on long-term expectations, the government will need to commit to high tax rates in the future. But if induced innovation produces dramatic improvements in energy efficiency, the government may be able to lower the tax rate while still achieving the original emissions goals—although this would deprive companies of the full benefits of developing the new technology, as demand would be reduced. Because companies can foresee the temptation to reduce rates, their motivation to invest heavily in energy R&D may be decreased.

It is also possible to argue that near-term carbon taxes should be high in the short term and then fall over time, at least in real terms. If innovation responds relatively quickly to permanent price signals and builds on itself, then it may be wise to advance as much innovation as possible, giving society extra decades to take advantage of it.[38] Once the innovations that allow for a leveling off of temperature change have been widely adopted, the tax rate can fall without fear of rising emissions.

An additional complication arises from energy's pervasive role in modern economies. A rise in prices or efficiency normally leads to less of a good being used. This is certainly true of the direct effect of rising energy prices. However, because energy is such a pervasive input, a dramatic improvement in energy efficiency will reduce fossil fuel energy prices, leading to greater demand. This secondary impact, known as the Jevons Paradox or "rebound effect," can make it hard to reduce overall consumption of dirty energy through increases in efficiency alone.[39] In this case, dramatic breakthroughs in alternative forms of energy that deliver the same amount of power with fewer carbon emissions become especially important.

PRIOR STUDIES ON INDUCED INNOVATION IN ENERGY MARKETS

A number of economic studies have tried to measure the responsiveness of innovation in the energy sector. A large fraction of the carbon reductions that need to occur will happen in the energy markets. Most of these studies take advantage of the sharp increases in the price of energy that accompanied the oil crises of the 1970s and 1980s, and therefore give some indication of how energy technology might respond to a carbon tax.

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Popp

David Popp examined patent data from 1973–1999 (a period spanning both oil crises) to measure crowding out of research.[40] He found no evidence of crowding out between sectors and discovered increases in energy R&D—including government R&D—did not draw R&D resources away from unrelated sectors. He did find that higher R&D patenting gradually resulted in fewer patents of other types. However, this appears to be the result of companies appropriately maximizing profits rather than financial constraints that limit the total amount of R&D they can perform. At least within the refining industry, the innovations that are dropped deal primarily with increasing the production of fossil fuels, which is presumably desirable.

Finally, Popp found that alternative energy patents tend to be cited by the same firms more frequently and by a wider range of other technologies than other patents. This indicates the innovations behind the patents may be generating greater social value than those that are displaced. However, the patents are no more valuable than those pertaining to refining and drilling, indicating the research most likely to be dropped is roughly as valuable as the new clean research that is replacing it.

Newell

Richard Newell et al. looked at the energy efficiency of room air conditioners, central air conditioners, and gas water heaters from 1973–93.[41] In addition to their sudden price increases, these products were subject to new energy efficiency regulations from the Department of Energy. The authors found that both energy prices and government regulations affected the energy efficiency of the three products. However, there were also substantial improvements in efficiency that seemed to be autonomous.

They concluded there was a substantial positive relationship between changes in the relative price of energy of the sort that would occur from a carbon tax and the rate of improvements in energy efficiency. This responsiveness increased after the federal government required manufacturers to label the energy efficiency of their products, which also allowed consumers to make more intelligent choices about the features of different models. Depending on the product, the results suggest that induced innovation accounted for between one-quarter and one-half of the total increase in energy efficiency during the two decades. Autonomous advances in technology seem to explain up to 62 percent of improvements in air conditioners, but none for gas water heaters.

Calel

In a recent paper, Raphael Calel argued previous cap-and-trade programs, such as markets for sulfur dioxide and lead in the United States, did not spur significant innovation because companies could comply with new standards at a relatively low cost merely by adopting existing technology. They therefore did not have a strong incentive to invest in finding new technologies even though doing so would have allowed them to avoid purchasing permits on the market.[42] However, Calel discovered the experience might be different with climate change. Most people believe significant technological advancements will be necessary to substantially reduce greenhouse emissions at a moderate cost. Assuming any attempt to price carbon tries to achieve a significant reduction in emissions, the option of achieving those emissions at a moderate cost merely by accelerating the adoption of existing methods or making them more efficient will not work. Industries will have to invest resources in finding new, much cleaner technologies.

Relatively few studies have attempted to estimate an optimal price for carbon both with and without induced innovation.

Earlier studies found that the European Union's Emissions Trading System (ETS) was not leading to more innovation. Calel compared a group of British companies that were subject to ETS with a similar group that was not and measured the difference in both patenting activity and R&D expenditures between the two groups. He found that ETS had not encouraged widespread adoption of off-the-shelf technology, but had encouraged low-carbon patenting and R&D investment for the long term. The growth rate in low-carbon patenting doubled from 9 to 18 percent, and low-carbon R&D spending quadrupled between 2006 and 2012. Both overall patenting and total spending on R&D also increased, indicating a lack of crowding out. In fact, Calel found some evidence of crowding-*in*, indicating the overall effect on innovation might be twice the direct effect on low-carbon R&D. These results were buttressed by the fact that companies expecting higher future prices on carbon were more likely to innovate.

STUDIES OF INDUCED INNOVATION IN RESPONSE TO GLOBAL WARMING POLICIES

Economists have also studied induced innovation directly in response to climate change policies. To a large extent, these studies have focused on theoretical models of how knowledge is produced in an economy. Relatively few have attempted to estimate an optimal price for carbon both with and without induced innovation. Those that do contain a number of assumptions that lack solid empirical support, resulting in a wide variation in both the pace and magnitude of optimal climate policy. These studies nevertheless shed light on the issues involved in setting the right tax rate. They are also attracting notice from policymakers. The Intergovernmental Panel on Climate Change pointed out:

> One drawback of exogenous TC [technological change] is that it ignores potential feedback between climate policy and the development of new technologies. Models with endogenous TC address this limitation by relating technological improvements in the energy sector to changes in energy prices and policy. These models demonstrate that ignoring induced innovation overstates the costs of climate control.[43]

Nordhaus

Robert Nordhaus was one of the first to attempt to measure the optimal value of a carbon tax, with and without induced innovation.[44] Measuring both the reductions in CO_2 and the global mean temperature, he found the effects from the additional innovation induced by the carbon tax were only about half the size of the effects that occurred due to the price changes alone, which assumes no extra innovation. The decline in carbon intensity is quite modest in the early decades: The fall in emissions due to induced innovation is about 6 percent over the first 50 years and 12 percent after a century. Overall, induced innovation is likely to reduce emissions about one-eighth of the amount necessary to stabilize emissions when subjected to a tax that tries to maximize social welfare, taking into account the social damage from global warming, as well as any cost of reducing emissions. His estimate of this optimal tax had it start at $16.50 per ton in 1995 and rise to almost $100 per ton by 2095 (in 2018 prices). Global temperatures still would rise by over 3°C.

The results seem to be driven by the fact that, even with the induced effects, energy R&D is too small compared with the size of other corporate investments to radically change the direction of technology. This outcome is also heavily influenced by Nordhaus assuming research is subject to a finite cap. Although he estimated that energy research rises 8 percent in response to a 10 percent increase in the price of energy, and that the social value of this research is 4 times its cost, all of this additional research comes at the expense of research in other parts of the economy. In his words, "When we calculate the social costs of increasing the research in the environmental sectors, we must reckon the loss in research outputs in the non-environmental sectors."[45] This sharply limits the net contribution induced research can make to lowering the total cost of a given carbon tax.

Goulder and Mathai

A study by Lawrence Goulder and Koshy Mathai looked at optimal carbon abatement both with and without induced innovation, and found that induced innovation lowers the amount of the optimal taxes in the short run.[46] The research tested two scenarios: The first assumed the tax rate was equal to the marginal social cost of additional carbon emissions; the second assumed the tax was set to reach a given, stricter emissions level. Goulder and

Mathai concluded that the exact impact of induced innovation depends on whether additional knowledge is gained through R&D or from learning by doing.

In the case of research, induced innovation allows for the shifting of some abatement to the future by temporarily lowering tax rates in the near term, because a decrease in the tax rate reduces the economic cost of the new tax without substantially reducing induced innovation, which takes time to develop. In the long run, the tax rises because induced innovation lowers the cost of reductions in carbon emissions. It therefore makes sense to buy more emission reductions. However, when advances come from learning by doing, the impact on timing is ambiguous because knowledge accumulation today leads to economies of scale that make future advances cheaper. With either R&D or learning, induced innovation reduces the economic cost of a carbon tax, allowing higher abatement levels to be achieved with the same economic impact.

Induced innovation lowered the discounted average cost of abatement by 30 percent.

The authors discovered induced innovation lowered the discounted average cost of abatement by 30 percent. The exact effect normally depends on the assumed amount of knowledge spillover private research creates for the rest of society, the rate of technological change that would occur without a carbon tax, and whether innovation is caused by research or learning. The tax rates that maximize social welfare for both R&D and learning are similar, starting at about $22 per ton. By 2100, that figure could rise to about $35 per ton. However, the tax rate needed to achieve a carbon concentration of 550 parts per million by volume (commonly assumed to limit temperature increases to 2° C) is much higher, starting at just a few dollars today, but is expected increase to around $50 by 2055, $100 by 2065, and over $200 by 2075.

Acemoglu et al.

Daron Acemoglu and others developed a model in which firms can invest in either a clean or dirty sector.[47] Firms have conflicting incentives. Their propensity to invest is higher for more productive sectors that have higher prices, and a larger market share. Because of this, dirty technology can get locked-in if it has an initial advantage. In this case, delaying action to reduce emissions can prove costly because doing so strengthens the advantage of the incumbent technology. Instead, a harder tax "push" may be needed to displace existing technologies and allow cleaner ones to spread. Climate policy must address the two market failures involving climate emissions and private research, as well as a possible third one. If producers have some monopoly power, the competitive pressure to adopt existing clean technology will be reduced. For this reason, the optimal policy will always involve both a carbon tax and subsidies for clean research. Subsidies for either developing or adopting green technology speed its diffusion through the economy.

Optimal policy depends on a number of factors. If the dirty resource is finite, then its price should rise as the resource becomes scarcer, lowering the amount of a carbon tax needed to switch the economy over to clean technology. Although many have predicted the imminent arrival of "peak oil" and its subsequent scarcity, all fossil fuels have been subject to periods of low to moderate prices, indicating natural supply shortages are not likely anytime soon.

The results also depend on the elasticity of substitution between the two technologies. If the elasticity is high enough, the model shows the optimal policy involves using subsidies to immediately switch R&D to clean technology in order to generate new breakthroughs. This can be followed by a gradual switch of all production to clean inputs, after which a tax is no longer necessary.

Popp

David Popp also tried to use data on both energy technology and global warming to estimate the actual costs of carbon abatement with and without induced technology.[48] He estimated two scenarios. The first attempted to maximize global welfare by selecting a carbon tax that equalized the marginal costs and benefits of reduced carbon emissions (including reduced climate change). The second scenario chose a tax that would restrict emissions to 1995 levels. Because his model only measured improvements in energy efficiency—not potential increases in alternative fuels—it likely understated the gain from a carbon tax. Popp found that equalizing marginal costs and benefits increases welfare (including environmental benefits) by $3.28 trillion in current dollars. Induced technology increases this gain to $3.59 trillion or 9.4 percent, but it does not result in significant environmental benefits beyond those already achieved by the carbon tax. The optimal carbon tax would start at $19.46 per ton in 1995 and rise to $134.06 by 2105 (in 2018 dollars) while reducing emissions by only 5.4 percent over the next century.

Like many other models, Popp's estimate of the socially optimal tax does not prevent global temperatures from rising above the 2°C limit advocated by many environmentalists, and has global temperatures rising by 2.5 degrees Celsius in 2105 and 3.7 degrees in 2205, compared with a base case of 2.6 and 4.0 degrees, respectively. The second scenario, which involves restricting emissions to 1995 levels, would impose a net cost to society, even when induced innovation is factored in. Emissions would need to decline by 29.5 percent, causing global consumption to fall by $15.68 trillion (in 2018 dollars) by 2205.

Di Maria and Smulders

It is possible more stringent carbon taxes could have a perverse effect on carbon abatement, especially if policymakers cannot implement the optimal policy. Corrado Di Maria and Sjak Smulders built a model in which it is possible for induced innovation to *increase* the cost of emission reductions.[49] Tougher regulation could dramatically increase the cost of using energy, causing profits to fall, and leaving firms with less money to invest in new technology. This could happen if policymakers underestimate the full social benefits from innovation while providing excessive support to existing dirty energy, such as coal or oil. Doing so would make it more profitable for companies to stay with existing technology rather than search for new breakthroughs. In their model, stricter regulation always increases innovation and reduces the stock of capital in the economy. Since the model assumes capital and technology are complements rather than substitutes (because the value of a given amount of technology is more in a larger economy), the fall in total capital also reduces the optimal amount of new technology, at least partially offsetting the effect of the carbon tax.

DOES INDUCED INNOVATION CROWD OUT OTHER RESEARCH?

One problem often left unsolved in the literature involves determining the net impact of induced innovation on the total research an industry conducts. Higher carbon prices should cause some companies to invest more in low-carbon innovation, leading to social gains. But if companies pay for this research by cutting the amount they invest in other R&D, the social gains may be reduced or even eliminated. Likewise, increasing the demand for scientists and engineers could raise their prices, reducing R&D in other firms and industries. But the effect is not necessarily bad. To the extent investment in clean technologies crowds out research in dirty technologies, the result may be a reduction in the size of the tax needed to achieve a given level of emissions as well as additional environmental benefits.[50] However, this is likely to be a very small effect. The overall question of crowding out is important because assumptions about the magnitude of crowding out explain much of the difference between models regarding the amount of induced innovation that might occur.[51]

There are good arguments for believing crowding out should not be a serious problem. First, because many of the industries developing clean technologies are not spending money on R&D for other technologies, if a carbon tax increases the demand for better clean technologies, these firms invest more rather than divert existing R&D. Moreover, at a societal level, there is little reason to believe the supply of scientists and engineers is fixed. Higher wages for scientists should increase the supply, either through domestic education responses or through high-skill, STEM immigration, leading to the reestablishment of the prior equilibrium between supply and demand.

USING THE REVENUES FROM A CARBON TAX

Even a modest carbon tax could raise a significant amount of revenue. The Congressional Budget Office (CBO) recently estimated that a tax starting out at $25 per metric ton and rising in real terms by 2 percentage points each year would generate revenues of $437 billion in the first 5 years and $977 billion in the first 10.[52] Although CBO did not try to calculate the socially optimal tax, this level certainly is in the ball park of most related studies.

Policymakers would then have to determine what to do with the income: reduce the budget deficit, cut taxes, or increase spending. A wide range of social priorities could account for a share of the funds. This report confines its review to a revenue-neutral carbon tax, meaning all revenues from the tax are used to reduce existing taxes of one type or another.

The choice of which existing taxes to reduce or eliminate would depend on what social priorities are most pressing. There are three main possibilities. The first is to reduce individual taxes, especially for low-income taxpayers. It is widely agreed that a carbon tax would be regressive. Although wealthier taxpayers would probably end up paying more per individual, the tax liability would represent a larger share of low-income individuals' income. To compensate for that, individual taxes could be reduced either across the board or mainly for low-income workers.

There are at least two problems with this approach. The first is that if Congress lowers taxes for all households, including middle- and higher-income households, it would neither accomplish much in the way of fairness nor result in appreciably higher economic growth. However, limiting the tax cut to low-income workers would necessitate a phase-out range of income during which marginal tax rates would be artificially high. A second problem is that many low-income workers do not owe income taxes. Congress could allow a credit against payroll taxes, or it could create a refundable credit, although some people would not consider this to be strictly revenue-neutral. A uniform refundable credit would be similar to the idea supported by a number of large companies and prominent officials to use the proceeds of a rising carbon tax to provide dividend payments to all Americans on a per capita basis.[53] The idea is similar to the annual payments from the Alaska Permanent Fund, which recently exceeded $1,000 per resident.[54]

Limiting the tax cut to low-income workers would necessitate a phase-out range of income during which marginal tax rates would be artificially high.

A second alternative is to reduce specifically those taxes that have the greatest negative effect on economic growth. All taxes impose some economic drag on the economy (not counting the offsetting growth that may result from spending). But some taxes impose a heavier drag than others. Many studies show corporate taxes have a larger negative effect on economic growth than those on individuals.[55] This is partially because corporations represent a second level of taxation in addition to individual income taxes, and partly because firms have a greater ability to minimize taxes by changing their activity or moving to a different location. One report issued prior to recent tax legislation estimated that a significant cut in the corporate rate (from 35 percent to 16 percent), together with a repeal of recent energy regulations, would increase GDP by 2 percent, increasing per-household incomes by nearly $3,000.[56] The Congressional Budget Office estimated the impact of a cap-and-trade policy needed to reduce emissions by 15 percent. Using the proceeds to reduce corporate income taxes rather than providing lump-sum rebates to households lowered the negative effect on GDP by half.[57] Lower corporate taxes would in turn lead to higher worker wages.[58] Hafstead et al. showed that a carbon tax of $45 per ton (2013 dollars) instituted in 2016 and rising by 2 percent a year would reduce total consumption by 0.25 percent from what it would otherwise be in 2030. Using the revenues to reduce the corporate income tax rate by 6 percentage points would reduce the fall in consumption to 0.18 percent. At this level, the social costs of the combined policy would be less than the benefits from the emissions reductions, implying an increase in social welfare.[59] Other studies have reached a similar result.[60]

A major problem with this strategy is Congress recently reduced corporate taxes as part of a broader tax reform bill, with the federal corporate rate falling from 35 percent to 21 percent. This weakens the case for further reducing the corporate tax rate. Unfortunately, Congress did not find offsetting revenue increases or spending cuts to pay for all of the reform. As a result, federal deficits will rise by more than $1 trillion over the next decade. Revenues from a carbon tax could be used to reduce these deficits, putting the nation's finances on sounder footing. But, given that the corporate tax cuts have already been enacted, paying for them with a new tax might be less popular than lowering other existing taxes. It would also not satisfy a strict definition of revenue neutrality.

The final alternative is to use the tax revenues to reduce other taxes on investment and provide greater incentives to conduct R&D. Doing so would address the second market failure, which causes firms to underinvest in both machinery and R&D. A large number of studies found the social benefits of both business research and investments in machinery and equipment are much higher than the private benefits companies are able to capture.[61] But companies invest in research and capital equipment (e.g., machinery, equipment, and software) only until the private benefits equal the cost to the company; they do not take social benefits into account. As a result, society would be much better off if companies conducted substantially more research and invested more in capital goods. One way to do this would be by lowering the after-tax cost of R&D and capital goods.

Efforts to raise the after-tax benefits of research should not be limited to clean energy research. This is because policies to address knowledge spillovers are more effective if they address all spillovers, not just those pertaining to clean energy.[62] Limiting tax reductions to clean energy research would unnecessarily limit the benefit of directing carbon revenues to R&D, which is primarily to reduce the economic burden of the carbon tax.

The traditional R&D tax credit saves companies a portion of their costs associated with the qualified research they conduct above a historic baseline. Although the credit is now a permanent part of the tax code, the recent tax reform bill did not make it more generous. In fact, because the bill also required companies to amortize the costs of their research, it made the tax credit less effective. Moreover, the generosity of the U.S. credit has fallen from 1st to 25th among Organization for Economic Cooperation and Development (OECD) countries over the past 25 years.[63] Because of the credit's complexity, companies increasingly use the Alternative Simplified Credit (ASC), which provides a credit of 14 percent. Congress should use revenues from the carbon tax to increase this rate to at least 40 percent.[64]

Congress could also create a true innovation box that gives companies a substantially lower tax rate on any income derived from intellectual property, provided the research and production accompanying the property were conducted in the United States.[65] Several countries have already created similar boxes.

The tax reform bill also attempted to encourage investment by letting companies deduct the full cost of capital machinery in the first year. Unfortunately, this provision expires in five years. Carbon revenues could be used to extend it indefinitely or, even more effectively, create an investment tax credit.

An earlier report by ITIF proposed a 15-year carbon tax of $15 per ton.[66] The proposal would have devoted 80 percent of the revenues to business tax incentives that encourage investment and growth. The recommendations included raising both the base and the rate of the ASC; expanding and increasing the R&D credit for collaborative research; including workforce training expenses in the ASC; and creating an investment tax credit for purchases of machinery and equipment. ITIF suggested the remaining revenues be put into a trust fund to support spending on clean energy innovation initiatives. The latter suggestion could also be accomplished through the tax code by designing an appropriate tax credit.

Studies estimating the effect of induced innovation consistently show that a policy combining a carbon tax with subsidies to R&D and capital equipment investment results in more economic growth than when the revenues are not devoted to R&D, without sacrificing environmental benefits.[67] Supporting broad R&D and capital investment efforts by using carbon revenues to reduce the after-tax cost of research and capital goods investment would benefit the entire economy by increasing the economic spillovers resulting from research and capital investment. Any incentives devoted to energy research or capital goods acquisition would have the additional benefit of increasing the amount of induced innovation of clean energy, further reducing the cost of achieving a given reduction of carbon emissions.

Studies estimating the effect of induced innovation consistently show that a policy combining a carbon tax with subsidies to R&D and capital equipment investment results in more economic growth than when the revenues are not devoted to R&D.

CONCLUSION

Concerns about climate change have been present for a long time and are driven by two simple facts. First, pumping more carbon dioxide and other greenhouse gases into the atmosphere should result in a warmer atmosphere. Second, human activity is likely to produce a doubling of CO_2 concentrations within a short time. There is a strong consensus that the resulting changes would impose large costs on society, although the bulk of these costs would not take place for decades.

Despite this argument, political opposition has latched on to a number of scientific uncertainties to prevent much action. This is in contrast to successful international efforts to deal with ozone depletion.[68] Two developments over the last decade may have changed the momentum for climate action. First, in technologies as diverse as storage batteries, electric motors, solar cells, and wind power, price declines and quality improvements have occurred faster than many forecasters assumed. Second, national governments seem to be more committed to taking advantage of these innovations. Whereas past international agreements focused on minimizing the cost of emission reductions by parceling out reduction requirements, current negotiations seem more focused on the commercial opportunity presented by low-emissions technology, and are therefore aimed at implementing policies to take advantage of it.[69] The Paris Agreement may merely represent this change in attitude rather than drive it.

As a result, it is becoming clear the United States will eventually take stronger actions to reduce greenhouse emissions. Indeed, according to the U.S. Supreme Court, the Clean Air Act requires the Environmental Protection Agency to implement regulations if it determines carbon dioxide represents a threat to human health.[70] Most economists believe a carbon tax would be an efficient policy tool that would address the market failure associated with global warming emissions by attaching a price to the environmental damage caused by carbon emissions. The higher costs of carbon-intensive activity would spread throughout the supply chain and give all producers and consumers an incentive to reduce emissions, while at the same time increasing the incentives for companies to develop better and more cost effective clean energy technologies.

Indeed, there is strong evidence that a carbon tax would also induce an increase in clean technology innovation beyond what would otherwise occur. And this induced innovation would lower the cost of achieving a given level of emission reductions. If the proceeds from the tax were used to increase the tax incentives for conducting R&D and investing in machinery and equipment, economic growth would actually accelerate because it would address a second market failure: the social benefit from research and capital goods investment is much greater than the private benefit companies receive. As a result, society would be much better off if companies conducted more R&D and invested in more machinery and equipment than is strictly profitable for them to do. Global warming aside, such a policy would be strongly beneficial for productivity and economic growth.

A carbon tax, at reasonable levels, with the revenues dedicated to reducing after-tax research and capital investment, is likely to not only reduce carbon emissions but do it in a way that grows the overall economy.

Both logic and scholarly research point in a clear direction: A carbon tax at reasonable levels, with the revenues dedicated to reducing the after-tax cost of research and capital investment, is likely to not only reduce carbon emissions but do it in a way that grows the overall economy.

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