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Innovation and Climate Change Policy

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by

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This paper examines the notion that more stringent climate change policy will induce innovation in environmentally friendly technologies. While past work has been concerned that such policies may stimulate such innovation at the expense of innovation elsewhere in the economy, the model presented here challenges the presumption that environmentally friendly innovation will itself be increased. It is demonstrated that a tighter emissions cap will reduce the scale of fossil fuel usage and that this effect will diminish incentives to improve fossil fuel efficiencies. At the same time, such policies may stimulate innovation that improves the efficiency of alternative energy but that the impact of carbon scarcity may feedback to diminish innovation incentives in this direction as well. Only for offsetting technologies that directly abate carbon pollution will there be a positive impact on the rate of innovation. These results have implications for the setting of climate change targets and the design of climate change policy. 

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1. Introduction

One of the givens in discussions of climate change policy and its implementation is that it will drive innovation in environmentally-friendly technologies. Consider, for example, the Stern Review (2007, p.xix): “Carbon pricing gives an incentive to invest in new technologies to reduce carbon; indeed, without it, there is little reason to make such investments.” Such statements are not controversial. Indeed, the main issue is whether ‘getting the prices right’ will be sufficient to spur environmentally-friendly innovation or whether, perhaps due to additional market failures with regard to innovation per se, additional support is needed (Arrow, et.al., 2008).

The logic associated with the notion that climate change policy will drive innovation has its origins in Hicks (1932):

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 to economising the use of a factor which has become relatively expensive … (p.124)

With regard to climate change policy, this concerns factors that utilise fossil fuels and are responsible for the generation of carbon emissions. By putting a price on carbon, such fuels become relatively expensive compared to alternatives. This will lead to a substitution from those fuels to alternatives but, so the theory goes, will also lead to the development and adoption of technologies that will economise on fossil fuel use – specifically, will generate more output per unit of fossil fuels burnt.

However, while it is true, holding output fixed, that a change in relative prices increases the returns to adopting and hence, developing technologies that yield more output per unit for the increasingly scarce factor, climate change policy will change output itself. Firstly, it will lead to less use of fossil fuels and, as technologies that augment this fuel also profit from the scale of its use, incentives to develop such technologies may be reduced. Secondly, climate change policy may lead to a decline in overall output as it reduces the overall scarcity of factors in the economy. This, in turn, may diminish incentives to develop environmentally-friendly technologies. Consequently, a fully general equilibrium approach to innovation in the face of

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1 This is a common implication that arises from the literature on endogenous growth (Romer, 1990; Aghion and Howitt, 1992).
climate change policy is required to evaluate these potentially competing effects.

The purpose of this paper is to provide this analysis. To do so requires, however, distinguishing between alternative environmentally-friendly technologies. For example, a more fuel efficient car is an example of a technology that improves the efficiency of fossil fuel use – allowing more output per unit of fuel. Such technologies are fossil fuel augmenting. In contrast, solar panels installed in buildings or wind power generation utilise alternative, non-emitting energy sources. While these allow more output per unit of fossil fuel as a matter of definition (i.e., they do not require fossil fuels), they utilise other inputs. Consequently, their efficiency is driven by distinct technological developments. These are termed alternative energy augmenting technologies.

Finally, there is a class of technologies that directly abates carbon pollution. This might occur at the point of emission such as carbon capture by electricity generators or this might involve a distinct process that sequesters carbon from the atmosphere. These are technologies that offset carbon pollution. Importantly, while there might be incentives, even in the absence of climate change policy, to develop technologies that augment fossil fuels or alternative energy, there is no demand for offset technologies without a carbon price as a necessary component.

Recent theoretical advances in understanding the bias of technological change in economic growth (Acemoglu, 2002; 2007) as well as the relationship to such bias to factor scarcity (Acemoglu, 2009) have provided a clear set of tools to analyse the impact of climate change policy on non-publicly supported technological change. I adopt those tools in this paper and reach several clear findings. First, more stringent climate change policy that puts a price on carbon reduces incentives to adopt and develop technologies that augment fossil fuel use. While the relative price of such fuels has increased, climate change policy is directed towards reducing emissions and hence, limiting fossil fuel use. This reduction in the scale of fossil fuel use, reduces the incentive to make such use more efficient.

Second, more stringent climate change policy may not increase incentives to adopt and develop technologies that augment alternative energy sources. While it is true that substitution towards the use of alternative fuels will provide an incentive to develop alternative energy augmenting technologies, if this substitution effect is weak relative to the economy-wide impact of greater fuel scarcity, innovation in this direction will be impeded. Put simply, the rewards to

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2 See Otto and Reilly (2008) for a discussion of these technologies.
innovation come not from current or future reductions in pollution but current and expected payments in the ‘real’ economy. Even if socially beneficial, climate change policy reduces the size of the ‘real’ economy and hence, may reduce the overall rate of innovation.

It is important to note that this result comes in the absence of any consideration of resource constraints on innovation that mean that differing research paths compete for scarce R&D resources although this is a feature of many growth models (Sue Wing, 2003). Allowing for these would only reinforce the results above. Similarly, it is assumed that there are no spillovers between the stock of knowledge achieved on one technological dimension and the productivity of innovation on another (cf: Goulder and Schneider, 1999). The inclusion of such spillovers would not change the overall results but would enhance the case for explicit public support of innovation.

Third, if climate change policy takes a form that rewards agents that undertake activities to offset carbon pollution – as it would by putting a price on carbon for emitters themselves or for others if offset activities can generate emissions permits – then stronger climate change policy will increase innovation in offset technologies. In this situation, the scarcity component increases both the carbon price that is the return to such activities as well as the demand for such activities by limiting its competition and, hence, leads to greater innovation in equilibrium.

These results have several important implications. First, climate change policy may enhance the case for public support of innovation in environmentally-friendly technologies (at least those that do not directly offset emissions). This is because the policy itself either reduces innovation incentives directly (as in the case of fossil fuel augmenting technologies) or diminishes the scale of economic activity making innovation harder to fund and earn a return.

Second, empirical analyses of the impact of climate change policies that do not model technological change as endogenous or who treat induced innovation as purely a function of relative price changes will understate the expected costs of abatement. This will have an impact on the targets for carbon and other emissions suggested by those models.3

Specifically, in the context of environmental regulation, the results here suggest that the well-known ‘Porter hypothesis’ is not likely to carry over to the broad economy-wide analysis

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3 Note that this conclusion stands in contrast to calibrated models of the impact of climate change policy that argue that such policy will induce innovation and hence, that the costs of abatement are over-stated (Popp, 2004). See also Goulder and Mathai (2000) who demonstrate that induced innovation reduces the need for more stringent environmental policy to maximise social welfare.
of climate change policy. The Porter hypothesis has varying forms but has come to refer to the notion that environmental regulation may enhance the competitiveness of firms subject to it by driving them to adopt more efficient technologies. Consequently, it is argued that environmental regulation could be productivity enhancing rather than harmful. Of course, it is acknowledged that the potential for this “win-win” situation on environmental regulation involves deviating from the usual economic assumption that firms are maximising inter-temporal profits. Here, I demonstrate that when firms maximise profits, for a national economy unilaterally adopting climate change policy, either, the effect of that policy is to diminish the rate of innovation or, even where it increases it, overall productivity declines.

Finally, given that offset technologies can be spurred by a higher carbon price, the greatest potential for this will arise if economic agents are able to generate emission permit credits as a result of such activities. At present, many emissions trading regimes (including the Kyoto protocol) explicitly exclude such activities. Consequently, innovation is left to the point of emission rather than broader pollution reducing avenues.

The outline of this paper is as follows. In the next section I review the literature on environmental policy and innovation. Section 3 provides the baseline model set-up while Section 4 provides an analysis of the impact of emissions caps on fossil fuel and alternative energy augmenting technological change. Section 5 then analyses offset markets and technologies. A final section concludes.

2. Literature Review

There have been a few antecedents considering the impact of climate change policies on innovation rates in a general equilibrium context. Aghion and Howitt (2008, Chapter 16) examine the allocation of innovation towards those that augment clean and dirty activities

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4 This is explicit in Porter and van der Linde (1995) who write that “[t]he possibility that regulation might act as a spur to innovation arises because the world does not fit the Panglossian belief that firms always make optimal choices.” (p.99) However, even taking this starting point, the Porter hypothesis has been a source of controversy (see Jaffe, Newell and Stavins, 2003 for a review). Nonetheless, even if there is disagreement about the overall impact of environmental regulation on productivity, there is widespread agreement that “[e]nvironmental regulation is likely to stimulate innovation and technology adoption that will facilitate environmental compliance.” (Jaffe, Newell and Stavins, 2003, Table 1) It is this second presumption that the present paper challenges.

5 There have been papers that have integrated pollution into models of endogenous growth including Smulders (1995) and John and Pecchenino (1994; 1997). However, these have not dealt with the issue of innovation direction as I do here. Popp, Newell and Jaffe (2009) provide a comprehensive review of the environmental economics and technological change literature; highlighting caps in that literature for those researchers on the economics of innovation to potentially fill.
where those activities are perfect substitutes. They demonstrate that environmental policy can push all production and innovation to be directed at clean technologies without any sacrifice in the long-run rate of growth although the economy is moved to a lower level of productivity following the policy’s introduction. This, however, is driven by the assumption of perfect substitutes. Here I relax that assumption explicitly although will, occasionally, examine that assumption as a limiting case.

Smulders and de Nooji (2003) construct a model similar to that of Acemoglu (2002) but applied to complementary labour and energy inputs. In their model, environmental policy reduces the rate of growth energy inputs which, in turn, can cause a rise in innovation directed towards improving energy productivity but a reduction in innovation towards labour productivity improvements (an innovation crowding out effect). Nonetheless, they demonstrate that the scarcity arising as a result of the reduction in energy supplies reduces overall output in the economy.\(^6\) Below, I similarly find that climate change policy reduces overall output examining a broader range of environmentally friendly technologies and no crowding out of innovation on other factors such as labour.

Sue Wing (2003) provides a model that acknowledges that the level of R&D directed towards a sector is a function of both relative prices and the scale of that sector. As prices and scales are related, the impact of a price change on the rate of innovation is ambiguous. Like Smulders and de Nooji (2003), he notes that the impact of climate change policy may be to depress the overall level of R&D. Given this, he explores what happens when climate change policy has this negative effect and concludes that it will have a significant impact on the mix of policies to deal with climate change. Finally, Sue Wing (2006a), examines the behaviour of a firm when a tax on polluting inputs is introduced. Using a similar production technology to the one I use below, he demonstrates that the firm’s total rate of R&D directed at its portfolio of inputs may fall as a result of that tax. As the production function of the firm in his model is similar to those of final good producers in Acemoglu (2002), some of his results (particularly, that innovation is biased away from the polluting factor) are mirrored in the general equilibrium analysis that I provide below.

There have been several analyses of technological innovation in environmentally

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\(^6\) van Zon and Yetkiner (2003) find a similar result for an ‘increasing variety’ model of endogenous growth although they show it can be reduced if the proceeds of an energy tax are recycled as a direct subsidy to R&D.
friendly technologies and their responsiveness to changes in energy prices. For instance, Newell, Jaffe and Stavins (1999) examine the energy efficiency of air conditioning over time as relative energy prices fluctuate. They discovered some significant correlation but also noted that other technologies also advanced even though they were not said to be influenced by energy prices. They also related the inducement to the introduction of suitable product labeling. Similarly, Popp (2002) examined patent applications and their rate of growth as a function of energy prices and found a positive and significant effect. The theoretical model developed here demonstrates that a change in relative prices is one effect and not necessarily the most important effect in driving induced innovation to climate change policy.

These studies have been used to justify the inclusion of induced technological change in climate change policy models of the economy. In each case, the impact of policy on innovation is assumed to be positive an assumption that some have argued has insufficient foundation (Sue Wing, 2006b). For example, Nordhaus (2000) assumes that changes in carbon intensity are a function of R&D expenditures which are themselves a positive function of carbon taxes. However, as noted in the introduction, the model in this paper, by looking beyond relative price changes and including changes in factor use, suggests that for certain types of technology, innovation rates may decline. Consequently, the assumptions of these models might be incorrect and, in fact, the welfare costs associated with climate change policy might be understated.

3. Model Set-Up and Initial Results

The model here is based on Acemoglu (2007). It is a simple general equilibrium model where competitive final good producers purchase factors from competitive markets but also specialized capital goods from monopoly suppliers. It is a static analogue of many endogenous growth models including Romer (1990) and Acemoglu (2002). Acemoglu’s (2007) focus is on labour market issues whereas here I concentrate on markets for polluting and non-polluting energy sources.

The two energy sources are ‘fossil fuel’ (emitting or dirty) fuel \( F \) and ‘alternative’ (non-fossil or clean) energy (e.g., solar) \( Z \). It is assumed that the capacity to produce each of these energy sources is fixed at \( F^* \) and \( Z^* \), respectively. This assumption is made for analytic simplicity and will be relaxed below.

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In the final good sector, each firm, \( i \in \mathcal{I} \), (where for convenience it is assumed that \( |\mathcal{I}| = 1 \)) has a production function:

\[
y_i = \alpha^{-\alpha} (1-\alpha)^{-1} \left( (\theta_1 F_i)^{\frac{\alpha}{1-\alpha}} + (\theta_2 Z_i)^{\frac{\alpha}{1-\alpha}} \right)^{\frac{1-\alpha}{\alpha}} q_i(\theta_1, \theta_2)^{1-\alpha}
\]

where \( F_i \subset \mathbb{R}_+ \) is \( i \)'s quantity of fossil fuels, \( Z_i \subset \mathbb{R}_+ \) is \( i \)'s quantity of alternative energy and \( \theta_1 \) and \( \theta_2 \) are technological choices to be described shortly. Aggregate output of all these firms is \( Y \); which is the numeraire good in this economy. \( \sigma \) is the elasticity of substitution between the two fuels and \( \gamma \) is a parameter that determines their returns to scale in production. As \( F \) and \( Z \) are competing sources of energy, it is also natural to assume they are substitutes (\( \sigma \geq 1 \)) and, as other inputs are fixed and not explicitly considered, that it has non-increasing returns in these inputs (\( \gamma \leq 1 \)). For output to be positive, the firm must also utilise an intermediate good, \( q_i(\theta_1, \theta_2) \), which is assumed to embody the technologies \( (\theta_1, \theta_2) \). Finally, the term \( \alpha^{-\alpha} (1-\alpha)^{-1} \) is a convenient normalization allowing us to focus on the role of \( \alpha \) is parameterising the importance of intermediate goods in production.

The intermediate good is supplied by a monopolist.\(^8\) This firm develops technology embodied in that good with the choice of \( (\theta_1, \theta_2) \subset \mathbb{R}_+^2 \). In effect, it is this firm that determines the efficiency of alternative energy sources. The cost of creating each \( \theta_s \) in terms of the final good is \( C(\theta_s) \) where \( C(.) \) is twice continuously differentiable, convex and strictly increasing. This means we can interpret a higher \( \theta_s \) with being associated with a more advanced technology. Once this technology is created, the monopolist can supply the capital good embodying that technology at a constant unit cost normalised to be \( 1 - \alpha \) units of the final good. It then sets a (linear) price for the supply of its good at \( \chi \).

Because fuel and final goods markets are competitive, each final good producer \( i \) takes technology and other prices as given and maximizes:

\[
\max_{F_i, Z_i, q_i} \pi(F_i, Z_i, q_i, \theta) = y_i(F_i, Z_i, q_i, \theta) - p_F F_i - p_Z Z_i - \chi q_i(\theta)
\]

An individual firm, \( i \)'s, demand for the intermediate good is:

\(^8\) This assumption is relaxed below without any change in the qualitative results to follow.
So the monopolist chooses price and technology to maximise:

\[
q_i(\chi, F_i, Z_i, \theta_1, \theta_2) = \alpha^{-1} \left( (\theta_1 F_i)^{\frac{\alpha}{\sigma}} + (\theta_2 Z_i)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} \chi^{-1/\alpha}
\]  

subject to (3). Given this, the analysis to follow will utilise the following equilibrium definition:

**Definition.** An equilibrium is a set of final good firm decisions \( \{F_i, Z_i, q_i\}_{i=3} \), technology choices \((\theta_1, \theta_2)\) and factor prices \((p_F, p_Z)\) such that \( \{F_i, Z_i, q_i\}_{i=3} \) solves (2) given \((p_F, p_Z)\) and \((\theta_1, \theta_2)\), and the technology and pricing decisions for each monopolist, \((\theta_1, \theta_2, \chi)\), solve (4) subject to (3).

This is a standard definition of a general equilibrium for this environment.

Importantly, note that (3) defines a constant elasticity demand function and so the price charged by the monopolist is, \( \chi = 1 \). Thus, (4) becomes:

\[
\max_{\theta_1, \theta_2} \Pi = \int_{i=3} \left( (\theta_1 F_i)^{\frac{\alpha}{\sigma}} + (\theta_2 Z_i)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} \chi^{-1/\alpha} d\Pi
\]  

With this set-up, Acemoglu (2007, Proposition 4) can readily be applied:

**Proposition 1.** Any equilibrium technology is a vector \((\theta_1^*, \theta_2^*)\) that is the solution to:

\[
\max_{\theta_1, \theta_2} \left( (\theta_1 F_i)^{\frac{\alpha}{\sigma}} + (\theta_2 Z_i)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} - C(\theta_1) - C(\theta_2)
\]

and any such vector gives an equilibrium technology.

This proposition provides a simple characterisation of the equilibrium technology and fuel use choices. In terms of the latter, the current available energy supply and capacity are symmetrically and fully utilised by final goods producers. Note also that by substituting (3) into (1), subtracting the cost of creating technology, \( C(\theta_1) + C(\theta_2) \), and total intermediate input production cost \((1-\alpha)\alpha^{-1} \left( (\theta_1 F_i)^{\frac{\alpha}{\sigma}} + (\theta_2 Z_i)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} \), the net output of the economy is:

\[
Y = \frac{\alpha}{1-\alpha} \left( (\theta_1 F_i)^{\frac{\alpha}{\sigma}} + (\theta_2 Z_i)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} - C(\theta_1) - C(\theta_2)
\]

**Social welfare**

The use of fossil fuels, \( F \), results in emissions with a function \( E(F) \) that is twice
continuously differentiable, increasing and convex. To simplify welfare characterizations, it is assumed that net output, $Y$, is consumed and $E$ represents the loss of utility in consumption units from emissions. As $Z$ is subject to free disposal, it is clear that any social optimum will involve all capacity for $Z$ being utilised. In addition, the use of intermediate inputs in final good production will involve usage as if those inputs were priced at marginal cost. Consequently, $q_i(F, Z, \theta_1, \theta_2) = \alpha^{-1} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{\frac{\alpha+1}{\alpha}} (1-\alpha)^{-1/\alpha}$. Thus, net output becomes:

$$Y = (1-\alpha)^{-1/\alpha} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{\frac{\alpha+1}{\alpha}} - C(\theta_1) - C(\theta_2)$$

(7)

Thus, a social planner will aim to solve:

$$\max_{F, \theta_1, \theta_2} (1-\alpha)^{-1/\alpha} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{\frac{\alpha+1}{\alpha}} - C(\theta_1) - C(\theta_2) - E(F)$$

(8)

This optimum is characterised by the following first order conditions:

$$(1-\alpha)^{-1/\alpha} \gamma \theta_1 (\theta_1 F)^{\frac{\alpha}{\alpha+1}-1} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{-\frac{\alpha+1}{\alpha}} = E'(F)$$

(9)

$$(1-\alpha)^{-1/\alpha} \gamma F (\theta_1 F)^{\frac{\alpha}{\alpha+1}-1} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{-\frac{\alpha+1}{\alpha}} = C'(\theta_1)$$

(10)

$$(1-\alpha)^{-1/\alpha} \gamma Z (\theta_2 Z)^{\frac{\alpha}{\alpha+1}-1} \left((\theta_1 F)^{\frac{\alpha}{\alpha+1}} + (\theta_2 Z)^{\frac{\alpha}{\alpha+1}}\right)^{-\frac{\alpha+1}{\alpha}} = C'(\theta_2)$$

(11)

This highlights two potential sources of distortions from the social optimum. First, there is a distortion in fossil fuel use that comes from a neglect of emissions by producers. It is apparent that the socially optimal use of fossil fuels will involve a choice of $F \leq \bar{F}$; however, a precise characterisation of when it is optimal for there to be a strict reduction in fossil fuel use cannot be done without more structure being put on the technologies available.

Second, there is a distortion to intermediate input use from monopoly pricing and another distortion because the technological choices of one intermediate input producer impacts positively on the demands for other intermediate inputs. The social planner removes the distortion and internalises such externalities. Thus, holding $F$ constant, the technologies chosen by intermediate input producers will be not advanced enough.

4. Impact of Emissions Permits

In this section, the impact of climate change policy on induced innovation is analysed. It
is assumed that such policy takes the form of an emissions trading scheme or, as it is commonly termed, a ‘cap and trade’ approach. This approach limits the total level of emissions in the economy. In the context of the model here, the level of emissions is uniquely determined by the consumption of fossil fuels. Consequently, if an emissions cap of $\bar{E}$, this would also potentially cap the use of fossil fuels to be no more than $\bar{E} \equiv E^{-1}(E)$. It will be assumed here that this cap is binding – that is, it is less than the availability of fossil fuels – and more stringent climate change policy will refer to a smaller $\bar{F}$. 

A ‘cap and trade’ approach is distinct from a carbon tax that does not limit emissions per say but places a price premium on carbon and hence, fossil fuel use. It is not the purpose of this paper to contribute on the continuing debate regarding these two policy approaches (save for a discussion in Section 5). Nonetheless, at the end of this section, I demonstrate how the same fundamental conditions that drive results for induced innovation as a result of a more stringent emissions cap also drive them for a higher carbon tax.

There are two broad types of innovation that are claimed to be likely to be induced by more stringent emissions targets. First, there are technologies that make fossil fuel use more efficient, most notably in automotive transport but also in terms of electricity production in general ($\theta_1$). Second, there are technologies that improve the productivity and efficiency of the use of alternative fuels ($\theta_2$). Most notably, these include solar power technologies that generate more power per unit of invested solar cells. Each of these is built into the production function specification above. Here we consider whether a more stringent emissions target (that is, a decrease in $\bar{F}$) will, in fact, induce more innovation or deployment of advanced technologies on each of these paths.

We are interested in the question of whether a tighter emissions target (reduction in $\bar{F}$) will lead to the creation of more advanced technologies that allow for a greater productive use of each fuel type (that is, whether $\theta_y$ is decreasing in $\bar{F}$). To build intuition, we first consider the choice of a fossil fuel, or $F$-augmenting technology (choosing $\theta_1$ and holding $\theta_2$ constant). Then we will consider the choice of a technology that augments the alternative energy source (choosing $\theta_2$ holding $\theta_1$ constant). Finally, we will consider the interactions between the technology choices.
**Fossil Fuel Augmenting Technological Change**

Utilising Proposition 1, the level of $\theta_i$ chosen is characterised by the first-order condition:

$$\gamma F(\theta_i^* F)^{\frac{1}{\sigma}} + (\theta_i^* Z)^{\frac{1}{\sigma}} = C'(\theta_i^*)$$  \hspace{1cm} (12)

Using this, it is straightforward to show that $\theta_i^*$ is decreasing in $F$ if and only if:

$$\frac{\sigma - 1}{\sigma}(\theta_Z Z)^{\frac{1}{\sigma}} + \gamma(\theta_i^* F)^{\frac{1}{\sigma}} < 0$$  \hspace{1cm} (13)

However, as $F$ and $Z$ are substitutes ($\sigma \geq 1$), this cannot occur. Consequently, $\theta_i^*$ is non-decreasing in $F$.  \hspace{1cm} (11)

The intuition for this result is straightforward. As in many endogenous growth models, innovation is driven by scale factors. In this case, the deployment of technologies that make fossil fuel use more efficient tend to have higher returns the greater the use of such fuels. Emission targets cap and reduce this use. This feeds back into a reduced demand for capital goods that complement the use of that fuel and hence, a reduction in the returns of the firm creating that technology.  \hspace{1cm} (12)

This has important implications for the interpretation of empirical research on induced innovation. For instance, Newell, Jaffe and Stavins (1999) investigate the impact of changes in relative energy prices on the efficiency of air conditioners. As such technological improvements mean that greater air conditioning output can be achieved per unit of electricity, it corresponds to a fossil fuel augmenting innovation. Newell, Jaffe and Stavins (1999) show that changes in the energy efficiency of air conditioners was significantly and positively correlated with relative energy prices and the introduction of product labeling but that the overall rate of technological

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10 Taking the derivative of the LHS of (12) and assessing when it is negative and using Theorem 2.8.1 from Topkis (1998).

11 If $F$ and $Z$ were complements then the reverse comparative static is possible. If $\beta_f = p_F F / p_Z Z$ is the equilibrium relative share of payments for fossil fuels over alternative energy, then it is straightforward to show that the LHS of (13) being positive implies that $\beta_f < \frac{\sigma - 1}{\sigma}$. Notice that this is more likely to be satisfied the lower is $\sigma$, the smaller is $\gamma$ (measuring returns to scale) and the lower is the fossil fuel share. This explains the origins of Smulders and van Nooij’s (2003) result that stronger environmental policy will stimulate innovation in environmentally friendly technologies. Initially, in their model, the energy share is low and so innovation is directed towards augmenting it rather than the complementary labour input. Hence, a similar condition is satisfied and climate change policy that creates energy scarcity increases innovation at improving energy productivity.

12 This mirrors the partial equilibrium result in Gans (1996) who demonstrated that the availability of technologies that increased the efficiency of fossil fuels would lead to more use of those fuels and a greater level of emissions/pollutants in the economy.
improvements in air conditioners was not correlated with energy prices. The model here predicts that positive correlation but that environmental policy will also have an impact on energy usage. This latter effect will cause a drain on innovation incentives. The inclusion of time-related dummies may well control the usage effect but what the analysis here stresses is that an improved understanding the relationship between environmental policy and induced technological change requires an empirical specification that captures more explicitly such scale issues.

**Alternative Energy Augmenting Technological Change**

We now turn to consider technologies that augment the alternative energy source \((Z)\) and the choice of \(\theta_2\). The chosen technology is characterised by the first order condition:

\[
\gamma \bar{Z} (\theta_2^* \bar{Z})^{\frac{\sigma-1}{\sigma}} \left( (\theta_1^* \bar{F})^{\frac{1}{\sigma}} + (\theta_2^* \bar{Z})^{\frac{1}{\sigma}} \right)^{\frac{\sigma-1}{\sigma}} = C'(\theta_2^*)
\]

(14)

And, it is now straightforward to show that \(\theta_2^*\) is decreasing in \(\bar{F}\) if:\textsuperscript{13}

\[
\gamma < \frac{\sigma-1}{\sigma}
\]

(15)

If this condition holds, \(F\) and \(Z\) are gross substitutes. Consequently, a restriction in the use of \(F\), causes an increase in the marginal product of \(Z\). This increases demand for technologies that complement the use of \(Z\) and hence, the profits of the provider of complementary intermediate inputs. Thus, the returns to innovating to increase the productivity of the alternative energy source are higher.

However, it is also possible that condition (15) does not hold. This happens if there are weaker diminishing returns to scale or \(F\) and \(Z\) are less substitutable. In this case, the reduction in \(F\) causes a small substitution towards \(Z\) use. Consequently, the scale of production of \(Y\) falls, reducing the demand for capital goods that complement energy use and with it, the incentives of the monopolist provider of those goods to augment either fuel technology.

The following proposition demonstrates that similar effects, only exacerbated, apply when both fuel augmenting technologies can be invested in.

**Proposition 2.** If \(\gamma \leq (>) \frac{\sigma-1}{\sigma}\). Then \(\theta_1^*\) is non-decreasing and \(\theta_2^*\) is non-increasing (increasing) in \(\bar{F}\).

\textsuperscript{13} Taking the derivative of the LHS of (14) and assessing when it is negative and using Theorem 2.8.1 from Topkis (1998).
The proof proceeds along the same lines as Acemoglu (2009, Theorem 3) noting that 
\[ \left( (\theta_1 F_1)^{\frac{\alpha}{\sigma}} + (\theta_2 Z)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} \] if \( \gamma \leq \frac{\alpha}{\sigma} \) is supermodular in \((\theta_1, -\theta_2, F)\) and if \( \gamma > \frac{\alpha}{\sigma} \) is supermodular in \((\theta_1, \theta_2, F)\).

This proposition demonstrates that a tighter emissions target will always lead to lower incentives to invest in the F-augmenting technology. Moreover, if it was possible for the F-augmenting technology to become “less advanced,” then a more stringent emissions target will lead to less productive use of fossil fuels.\(^{14}\) For Z-augmenting technologies, the result is contingent upon whether F and Z are gross substitutes or complements. If the latter, then tighter emissions caps actually reduces innovation incentives for this technology as well. Thus, fuel use in general would become less productive.\(^{15}\)

This result demonstrates that we cannot take induced technological innovation as a given if emissions policy is put in place. More stringent caps may encourage the use and innovation of technologies that enhance the efficiency of alternative or non-emitting energy sources (in particular, those that are less energy intensive but more substitutable with fossil fuels) but will likely discourage technologies that make fossil fuel use more efficient.

**Relationship to Climate Models**

As noted in the introduction, models of climate change tend to be complex and incapable of purely analytical characterisation. Consequently, their predictions are ascertained from numerical simulation with a combination of estimated and assumed parameters.

At the heart of many of these is a production function and where innovation is modeled an impact of that innovation on that function. Proposition 2 (and its general form by Acemoglu, 2009) demonstrates that it is the qualitative properties of production functions and the interaction between factors of production and innovative technologies that drives whether the exogenous reduction in the use of a fuel or some other change drives or reduces equilibrium

\(^{14}\)In a dynamic model with on-going innovation, the analogue of this result would be a slowing down of the rate of technological progress along each technological path (Acemoglu, 2002).

\(^{15}\)Note that this result does not rely on intermediate inputs being supplied by a monopolist. If instead, duopolist supplied alternative intermediate inputs each specialised to one fuel or another leading to a production function of the form: \( y_i = \alpha^{-\alpha} (1-\alpha)^{-\alpha} \left( (\theta_1 F_1)^{\frac{\alpha}{\sigma}} + (\theta_2 Z)^{\frac{\alpha}{\sigma}} \right)^{\frac{\sigma}{\alpha}} \left( q_i(\theta_1)^{-\alpha} + q_i(\theta_2)^{-\alpha} \right) \), then Acemoglu (2008) demonstrates that Proposition 2 would continue to hold with technology choices the Nash equilibrium of a game between the duopolists.
innovation. Here, therefore, I extract representative production functions from existing climate change models to understand the impact of climate change policy on innovation in those models.

A number of models posit innovation as directly impacting on production in the following manner:

\[
y_i = L_i^{1-\alpha} q_i^{1-\alpha} \left( \theta^{\sigma_{-\gamma} + F_i^{\sigma_{-\gamma}}} \right)^{\gamma^{-\gamma}}
\]  

This is the (basic) form of the production function in the ENTICE model (Popp, 2004) and also in Goulder and Schneider (1999).\(^{16}\) In this situation, the technology as well as fossil fuels are in input into the production of energy. Acemoglu (2009) demonstrates that the impact of an exogenous change in \(F\) on the optimal \(\theta\) is driven by the properties of the function \(G(\theta, F_i) \equiv \left( \theta^{\sigma_{-\gamma} + F_i^{\sigma_{-\gamma}}} \right)^{\gamma^{-\gamma}}\); notably whether it has increasing differences in \((\theta, F_i)\) or not. Note that:

\[
\frac{\partial^2 G}{\partial \theta \partial F_i} = \gamma(\gamma \sigma_{-\gamma} - 1) \frac{\sigma_{-\gamma}}{\sigma} \left( \theta^{\sigma_{-\gamma} - 1} + F_i^{\sigma_{-\gamma} - 1} \right)^{\gamma^{-\gamma} - 1}
\]

If \(\sigma < 1\), the technology and fossil fuel are complements, and this expression is positive implying that a reduction in \(F\) will have a negative impact to innovation. On the other hand, if \(\sigma > 1\), the technology is a substitute for fossil fuel use in producing energy. Nonetheless, innovation will only increase with \(F\) if \(\gamma < \sigma_{-\gamma}\); otherwise it may fall (for the same reasons as the result in Proposition 2).

Popp (2004) assumes \(\sigma\) is around 1.6 and consequently, so long as the energy share of production is less than 0.38, more stringent climate change policy will stimulate innovation of this form. Popp (2004, p.751) states that the calibration of these parameters was specifically to generate qualitative results consistent with micro-level empirical findings that shocks to fossil fuel availability generated improvements in innovation. Suffice it to say, the results here demonstrate that it may be important to estimate the parameters directly for the purpose of general equilibrium modeling of the impacts of climate change.

Another class of models does not consider technological change to be purely factor

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\(^{16}\) The model of Van Zon and Yetkiner (2003) is a special case with \(y_i = \theta L_i^{1-\alpha} q_i^{\alpha(1-\gamma)} F_i^{\gamma} \).
augmenting but to also directly impact on the costs of abatement – that is, technologies that extract pollutants from the atmosphere. I will return to discuss these in Section 5 below where I discuss technologies of that form.

Impact on Output

The claim, associated with the Porter hypothesis, is that environmental regulation can lead to induced innovation and, overall, improve rather than reduce productivity. The results thusfar demonstrate that when it comes to an emissions cap, tighter caps far from guarantee induced innovation. However, where $\gamma < \frac{\alpha - 1}{\sigma}$ then a more stringent cap can induce $Z$-augmenting innovation. In situations where $\theta_1$ cannot be reduced, this has the potential to lead to higher output. However, this depends upon whether the magnitude of the improvement in $\theta_2$ and its impact on output outweighs the direct reduction in output that arises when $F$ is reduced.

The following proposition characterises the impact on output.

**Proposition 3.** Suppose that $\theta_1$ is fixed, then $Y$ is decreasing in $F$.

**PROOF:** Let $G(F, Z, \theta_1, \theta_2) = \left( (\theta_1 F)^{\frac{\sigma}{\gamma}} + (\theta_2 Z)^{\frac{\gamma}{\sigma}} \right)^{\frac{\gamma}{\sigma}}$. Then

$$\frac{dY}{dF} = \frac{2 - \alpha}{1 - \alpha} G_F + \frac{2 - \alpha}{1 - \alpha} G_{\theta_2} \frac{d\theta_2^*}{dF} - C'(\theta_2^*) \frac{d\theta_2^*}{dF}$$

Noting that, in equilibrium, $G_{\theta_2} = C'(\theta_2)$, this will be positive if and only if $(2 - \alpha)G_F G_{\theta_2} > G_{\theta_2} G_{\theta_2 F}$. Some substitution demonstrates that this is equivalent to:

$$(-2 + \alpha)(\theta_2 Z)^{\frac{\gamma}{\sigma}} - (\theta_2 F)^{\frac{\gamma}{\sigma}} (1 + (1 - \alpha)(1 - \gamma)\sigma) > 0$$

which can never hold. Specifically, $G_F / G_{\theta_2}$ is less than $\partial(G_F / G_{\theta_2}) / \partial \theta_2$.

Thus, a tighter emissions cap, even with induced innovation, will always result in a reduced level of output.

This is important in considering the optimal emissions cap. Leaving the technology choice to the market, the second best emissions cap would be determined by:

$$\frac{dY}{dF} = E'(F)$$

Note that the smaller is the left hand side, the more stringent the desired emissions cap. Induced innovation can result in this occurring but the analysis here has demonstrated that the impact of this might be lower than others have expected. Consequently, this implies that the emissions cap
that maximises social welfare is likely to be correspondingly higher in the absence of other instruments to promote technological innovation.

**Elastic alternative energy supply**

As discussed above, we have made simplifying assumptions that have made the supply of alternative energy sources perfectly inelastic. However, it may be the case that the capacity to generate such alternative energy might be endogenous, even in the short-run. To analyse this, we take the CES functional form and focus, for notational ease, on the case of perfect substitutes (i.e., as $\sigma \to \infty$). Thus, we use:

$$y_i = \alpha^{-\alpha} (1 - \alpha)^{-1} (\theta_1 F_i + \theta_2 Z_i)^{\gamma \alpha} q_i^{1-\alpha}$$

(20)

where we now specify that $\gamma < 1$ (there is diminishing returns to scale in energy use alone). Given this, the demand for alternative energy is determined by its marginal product:

$$\frac{\partial y_i}{\partial Z_i} = \alpha^{-\alpha} (1 - \alpha)^{-1} \gamma \alpha \theta_1 (\theta_1 F_i + \theta_2 Z_i)^{\gamma \alpha - 1} q_i^{1-\alpha}$$

(21)

Suppose that the unit cost of alternative energy is $c_Z \frac{1}{Z} Z^2$. Then, using (3) and $\chi_s = 1$, the total quantity of alternative energy consumed will be:

$$Z^* = \max \left[ \theta_2 \frac{\gamma}{(\gamma \alpha \theta_1)} \left( \frac{c_Z}{(1-\alpha)\gamma \alpha} \right)^{\frac{1}{\gamma \alpha}} - \frac{\theta_1}{\theta_2} F, 0 \right]$$

(22)

Notice that, an increase in $\theta_1$ ($\theta_2$) reduces (increases) $Z^*$. Substituting these back gives the objective function of the monopolist when choosing technology:

$$\left( \frac{c_Z}{(1-\alpha)\gamma \alpha} \right)^{\frac{1}{\gamma \alpha}} - C(\theta_1) - C(\theta_2) \quad \text{if} \quad \left( \frac{c_Z}{(1-\alpha)\gamma \alpha} \right)^{\frac{1}{\gamma \alpha}} \geq \theta_1 F$$

$$\left( \theta_1 F \right)^{\frac{1}{\gamma \alpha}} - C(\theta_1) - C(\theta_2) \quad \text{otherwise}$$

(23)

What this means is that as $F$ falls, $\theta_1$ falls until a point where alternative energy is used. At this point $\theta_1$ no longer changes with $F$ and falls to zero while $\theta_2$ jumps to a positive level but beyond that does not change with $F$. Thus, aside from a regime switch, the supply substitution drives a shift in the mix of energy from fossil fuels but otherwise has little effect on innovation.

**Carbon Tax**

Instead of an emissions cap, a carbon tax can be put on emissions that raise fossil fuel costs by $\tau$ per unit. This, in turn, reduces demand for fossil fuels and qualitatively has a similar
impact to an emissions cap.

The following proposition formalises this for the case where both $Z$ and $F$ supply are elastic that is, the unit cost of $Z$ is $c_Z \frac{1}{2} Z^2$ while the unit cost of $F$ becomes $\tau F + c_F \frac{1}{2} F^2$.

**Proposition 4.** Suppose that $\sigma \to \infty$. $\theta_i'$ is non-increasing in $\tau$. For $\tau$ sufficiently high, $\theta_2'$ is non-decreasing in $\tau$. For $\gamma$ sufficiently high and $\tau$ sufficiently low, $\theta_2'$ is non-increasing in $\tau$.

**Proof:** Let $Q = \theta_1 F_i + \theta_2 Z_i$ be the total fuel use in efficiency units. A final good producer equates the marginal product of fuel $\alpha^{-a} (1-\alpha)^{-1} \gamma \alpha Q^{\alpha-1} q_i^{1-a}$ to the price of an efficiency unit of that fuel, $p_\varnothing$, where:

$$p_\varnothing = \min_{F,Z \text{ s.t. } Q=1} \tau F + c_F \frac{1}{2} F^2 + c_Z \frac{1}{2} Z^2 = \frac{c_F c_Z + \theta_2 \tau^2}{2(c_F \theta_2^2 + c_Z \theta_1^2)}$$  \hspace{1cm} (24)

This gives an equilibrium choice of $Q = \left( \frac{2 c_F c_Z}{(1-\alpha)c_F c_Z + \theta_2 \tau^2} \right)^{1/\gamma}$. In addition, observe that the energy choices that minimise energy costs holding $Q$ fixed are:

$$Z = \frac{c_F Q \theta_2 + \theta_1 \theta_2}{c_F \theta_2^2 + c_Z \theta_1^2} \text{ and } F = \frac{c_F Q \theta_1 - \theta_2 \tau}{c_F \theta_2^2 + c_Z \theta_1^2}$$  \hspace{1cm} (25)

Substituting $Q$ into these, the monopolist’s objective function for technological choices becomes: $\left( \frac{2 c_F c_Z}{(1-\alpha)c_F c_Z + \theta_2 \tau^2} \right)^{1/\gamma} - C(\theta_1) - C(\theta_2)$. Taking derivatives, it is easy to see that the mixed partial derivative of this expression with respect to $(\theta_1, \tau)$ is negative, $(\theta_2, \tau)$ is positive if $\tau^2 > \frac{c_F c_Z (1-\gamma) \theta_2}{\gamma \theta_1 \theta_2}$, and $(\theta_1, \theta_2)$ is negative if $\tau^2 > -\frac{c_F c_Z (1-2\gamma)}{c_F (1-\gamma) \theta_2^2 + c_Z \gamma \theta_1^2}$. Note that as $\gamma$ becomes 1, each of these reduces to: $\tau > \frac{\theta_2}{\theta_1}$. Hence, for $\tau$ sufficiently low, $\theta_2'$ is non-decreasing in $\tau$.

With an emissions cap and perfect substitutes, a tighter cap always led to innovation in alternative energy augmenting technologies. Proposition 4 demonstrates that with a carbon tax this is not necessarily the case. If that carbon tax is modest, then even if there are constant returns to scale in energy use, an increase in that tax could reduce innovation in alternative energy sources. In that situation, the carbon tax does not generate much substitution between fuels but leads to a relatively large decrease in energy use.\(^{17}\) Consequently, scale effects dominate and innovation is reduced regardless of factor bias.

\(^{17}\) Note that this result does not speak to the ‘caps versus taxes’ debate in climate change policy. In the baseline results on an emissions cap, I only examined cases where the cap was binding and so, when there is perfect substitution, alternative energy use never fell. Here for a small carbon tax, the first order impact is on energy use and the substitution is only second order. Consequently, alternative energy use can fall in this case, in turn, causing a reduction in alternative energy augmenting innovation.
5. **An Offset Market and Technology**

Thusfar, this paper has considered innovations that enhance the efficiency of either fossil fuels or alternative energy. However, as noted in the introduction, a third class of environmentally-friendly technologies is often discussed that involves abatement or offsetting of pollutants in the atmosphere. Such technologies include abatement at the point of emission (including carbon sequestration and storage) as well as reforestation and other means of extracting carbon from the atmosphere.

One advantage of a ‘cap and trade’ environmental policy is that while overall emissions might be capped, the source of the use of those emissions is flexible. In particular, if carbon can be captured then a greater amount of carbon can be used as fuel. The price of carbon permits is both a cost to those using carbon-based fuels and a payment to those capturing carbon. The issue here is what would such an emissions trading regime mean for the mix of directed technological change if we considered this in the industries that captured as well as used carbon?

To consider this, let $\tau$ be the traded price of carbon in any period. The demand for permits is determined by the outcome of (2), that is:

$$\alpha^\alpha (1 - \alpha)^{-1} \gamma \theta (\theta F_i) \theta^{\frac{\alpha}{\alpha + 1}} \left( \theta \bar{F} \frac{\alpha}{\alpha + 1} + (\theta_2 \bar{Z}) \theta^{\frac{\alpha}{\alpha + 1}} \right)^{\frac{\alpha}{\alpha + 1}} = \tau$$

(26)

It is assumed that there are various offset activities that might be undertaken. These are done competitively with the level of emissions reduced, in fossil fuel, units being, $f$. If we assume that the total supply cost of $f$ is $\frac{1}{2} \theta_3 f^2$, then, in equilibrium, if the total number of permits is capped at a level, $\bar{F}$, that yields, in the absence of offsets, a positive, then $\tau = \theta_3^{-1} f$.

This results in an equilibrium level of fossil fuel consumption:

$$\hat{F}(\theta_1, \theta_2, \theta_3, \bar{F}) = \bar{F} + \hat{f}(\theta_1, \theta_2, \theta_3, \bar{F})$$

given by:

$$\alpha^\alpha (1 - \alpha)^{-1} \gamma \theta (\theta (\bar{F} + \hat{f})) \theta^{\frac{\alpha}{\alpha + 1}} \left( \theta (\bar{F} + \hat{f}) \theta^{\frac{\alpha}{\alpha + 1}} + (\theta_2 \bar{Z}) \theta^{\frac{\alpha}{\alpha + 1}} \right)^{\frac{\alpha}{\alpha + 1}} = \theta_3^{-1} \hat{f}$$

(27)

Note that $\hat{f}$ is increasing in $\theta_1$ and $\theta_3$, non-decreasing (decreasing) in $\theta_2$ if $\gamma \geq (\leq) \frac{\sigma_1}{\sigma_2}$ and non-increasing in $\bar{F}$.

Holding technology fixed, notice that moving from any situation whereby fossil fuel

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18 Utilising Milgrom and Roberts (1994, Theorem 1).
availability was such that the effective price of permits would be zero, say \( \overline{F}_0 \), to a situation whereby the price is positive, say \( \overline{F}_1 \), involves a reduction in equilibrium fossil fuel use; that is, \( \overline{F}_0 > \overline{F}_1 + \hat{f}(\overline{F}_1) \). This because the supply curve for fossil fuels will be reduced as a result of the positive permit price and the positive marginal costs associated with providing offsets.

Consequently, by Proposition 2, the equilibrium technology choices of \( \theta_1 \) and \( \theta_2 \) will adjust based on the qualitative predictions of that proposition. Specifically, the fossil fuel augmenting technology choice will be reduced while the alternative energy technology may increase or decrease depending upon other parameters. However, the magnitude of these technological responses will be less given that offsets will mitigate the actual constraint on the use of fossil fuels for the same targeted emissions level.

There will be incentives to expand \( \theta_3 \) – the cost of offset emissions – whether it be by an investment from a monopoly provider of intermediate inputs or directly from a supplier of offsets who can capture the surplus in the permit market. That expansion will increase the equilibrium level of offsets being traded but, even holding other technologies fixed (and limiting \( \theta_3 > 0 \)), this activity will be insufficient to overturn the result that \( \overline{F}_0 > \overline{F}_1 + \hat{f}(\overline{F}_1, \theta_3) \) as the supply of offsets still involves a positive marginal cost. That said, in the absence of a permit market that allows offset supply, there is no incentive to conduct research into means of offsetting emissions. Consequently, this direction of technological change will unambiguously advance as a result of a tighter emissions cap.

The specification above has two interpretations. First, it could be that the offset technology is integrated into the capital of final good producers. In this case, \( \hat{f} \) represents abated pollution. This type of innovation can be induced by an emissions cap or a carbon tax. The difference between the two is innovation in offset technology, reduces permit prices and so will result in less of a response than what might occur with a carbon tax where the carbon price itself is fixed regardless of innovation that occurs. Second, it could be that the offset technology is part of an alternative activity and not so integrated. In this situation, a carbon tax would not induce any offsets or innovation while an emissions trading scheme that allowed offsets generated to expand the supply of permits would generate it.\(^{19}\) As noted earlier, most emissions

\(^{19}\) Gerlagh and van der Zwaan (2006) also note the potential ineffectiveness of taxes in this regard.
trading schemes that have been implemented or proposed have excluded an offset route and, thus, have bypassed this source of potential innovation.

As a final note, as anticipated earlier, many climate change models considering the role of innovation include technologies that would be characterised here as offset, rather than factor augmenting. For instance, in Nordhaus (2002), emissions are a function of output, for example, $E_i = y_i / \theta$ and thus, facing a permit price of $\tau$, final output producers would earn, net of other payments, $y_i(1 - \frac{\tau}{\theta})$. Notice that $\frac{\partial y_i(1-\theta\tau)}{\partial \theta \tau} = y_i \frac{1}{\theta \tau}$ and thus, more stringent climate change policy increases $\theta$; thereby, reducing the intensity of emissions generated per unit of output. A similar effect occurs in Goulder and Schneider (1999) and Buonanno, Carraro, and Galeotti (2003) who each model innovation as reducing the emissions generated by output as well as impacting on final good production in ways discussed earlier. However, by not separating the two technological paths, in each case, they likely bias towards reducing the impact of climate change policy on innovation.

6. Conclusion

One of the key variables in determining and analysing the impact of climate change policy is the expected rate and direction of innovation that arises from more stringent application of emission caps or carbon taxes. This paper has provided a general equilibrium analysis of this impact and has found that the general presumption that stronger climate change policy will, at the very least, stimulate incentives to develop environmentally friendly technologies cannot be taken as given. Indeed, there is a generic bias away from fossil fuel augmenting technological change. Only for offset technologies do the scale and price impacts of climate change result in enhanced incentives. However, whether these are stimulated is a matter of policy design.

The model here is a simple specification and in reality the evaluation of the impact of climate change policy must take a broader multi-sector approach. Nonetheless, the goal here is to stimulate further and more explicit integration of the economic forces impacting on innovation into climate change models.
7. References


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