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Abstract

Conventional wisdom argues that environmental policy is less costly if environmental policy induces the development of cleaner technologies. In contrast to this argument, we show that the cost of environmental policy (a reduction in emissions) may be larger with induced technical change than without. To explain this apparent paradox, we analyze three main issues. The first key issue is whether the new technology increases or reduces the marginal cost of abatement. While most analyses in environmental economics consider it natural that marginal abatement costs fall as new technology is developed, we argue that technological change may instead increase the productivity of polluting inputs, and thus marginal abatement costs. The second issue is whether environmental policy increases or decreases total investment and innovation. Even when stricter environmental policy induces some pollution-saving technological change, it may do so at the cost of a reduced overall rate of innovation, which crowds out production and consumption, and thus makes environmental policy more costly. Finally, the presence of additional distortions drive wedges between the social and private valuation of investment and pollution that may provide incentives for induced technological change with welfare-deteriorating effects.

JEL-Code: H230, O380, Q550, Q580.

Keywords: environmental policy, innovation policy, induced technical change, pollution-saving technical change, pollution-using technical change, crowding-out, second-best policy.

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1 Introduction

With the global concentration of carbon dioxide (CO_2) steadily inching towards 450 parts per million (ppm)[1], and the continuing failure on the part of the world's governments to reach a comprehensive agreement on how to tackle green-house gas emissions, changes in technology are being advocated with increasing urgency as the solution to the problem of climate change. If technology is the *deus-ex-machina* that will save the planet, stringent environmental policy is often seen as the necessary lever to get the machinery in motion. The received wisdom on environmental policy and innovation depicts a scenario where, as policy makes polluting inputs more expensive, profit-driven innovators devise new ways to economize on the use of such inputs. Accordingly, while environmental policy aims at internalizing pollution damages, it also generates incentives to develop new technologies, which once in place reduce the opportunity cost of environmental policy.

This perspective on induced innovation, while admittedly comforting, contrasts sharply with the historical record, which shows that time and time again new, more efficient technologies have led to environmental degradation, and it raises one fundamental question. In a world where externalities and distortions are pervasive and the second best is the norm, should we really expect environmental policy to always induce technologies that reduce the cost of pollution control? The theory of second-best suggests that the opposite situation, one in which induced technological change instead operates against environmental improvements, might be just as likely. It should not be taken for granted that the technological response to an environmental policy shock would necessarily reduce the opportunity cost of pollution reductions.

In this paper, we revisit the interaction between environmental policy and induced technological change (ITC), offering a more comprehensive view than previously done in the literature.[2] Indeed, a full assessment of these issues requires the use of a broader menu of available technological improvements than usually encountered in the literature, a thorough analysis of feedback effects, and of how environmental policy interacts with other distortions and second-best policies. We show that within this extended framework, changes in technologies induced by environmental regulation may (partially) offset the benefits of the policy itself, and as a result ITC potentially makes environmental policy less effective or more costly.

The literature so far has not adopted such an encompassing view, but several elements have already been developed, and we naturally build on them. Indeed, a long literature exists that deals with the question how endogenous technological change affects the cost of environmental policy. In a partial equilibrium context, Gerlagh (2007), for example, tackles this issue within a static framework, while dynamic analyses are presented by Goulder and Mathai (2000), Nordhaus (2002), Parry et al. (2003), Popp (2004), and Sue Wing (2006), among others.[3]

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[1] According to IPCC (2007b), this concentration would be consistent with a 50/50 chance of a global temperature increase less than 2°C above pre-industrial levels (IPCC, 2007b, chapter 10, p. 826). The seasonal adjusted value recorded for June 2012 at the Manua Loa observatory was 393.48 ppm, the annual average rate of increase over the last 10 years was roughly 2 ppm/year (`http://www.esrl.noaa.gov/gmd/ccgg/trends/`). Notice, however, that Hansen et al. (2008) consider the critical level consistent with the preservation of the current earth's climate to be below 350 ppm.

[2] *Endogenous* and *induced* technological change are just two different labels for the same phenomenon. The expression 'endogenous technological change' is more common in the economic growth literature, whereas environmental economists tend to favour 'induced technological change'. We use the two terms interchangeably.

[3] These papers can be considered as part of the literature on environmental policy and innovation, which is thoroughly surveyed in Loeschel (2003), Jaffe et al. (2003), and Popp et al. (2009). The literature on instrument choice and induced technological change based on static models (e.g. Milliman and Prince, 1989; Fischer et al., 2003; Requate and Unold, 2003; Perino and Requate, 2012) is also closely related to our topic,

The typical assumption made in these contributions is that investment in new technologies lowers the marginal cost of reducing emissions, i.e. the marginal abatement cost (MAC). As a consequence, environmental policy that increases investment necessarily lowers abatement costs, and induces additional emissions reductions. Recent contributions, however, have discussed the contrasting case in which new energy technologies (e.g. alternative technologies to produce electricity with different emission intensities) reduce total abatement costs, while increasing the marginal cost of abatement over some range of abatement activities (Baker et al., 2008; Bauman et al., 2008).[4] Amir et al. (2008) provide a general and illuminating taxonomy of technologies, and show that marginal abatement costs can indeed rise with innovation in several circumstances.

While this effect of innovation may appear surprising to most environmental economists, it is in line with standard views on the aggregate effect of innovation, and thus cannot be considered as an anomaly. Indeed, most theoretical growth models, as well as empirical growth accounting studies point to the fact that growth is driven by sustained innovation and total factor productivity (TFP) growth.[5] Increases in TFP, however, increase the marginal productivity of all inputs, including polluting ones. In other words, reducing pollution becomes more costly the higher the TFP. This implies that the cost of environmental policy increases with TFP.

Both on theoretical and empirical grounds, then, it is crucial to compare innovations that increase the MAC – which we call "brown" technologies – to those that instead reduce it – "green". In the case where technology is brown, additional investment leads to higher emission levels for a given tax rate. In this case, it is natural to ask how environmental regulation affects abatement costs via its effects on technical change. In two recent contributions, Perino and Requate (2012) and Brechet and Meunier (2012) show that, for a given tax rate, there will be less technology adoption under brown technology, compared to the green technology scenario. Their result is consistent with growth models, in which overall innovation rates can be depressed by emissions reductions, even though innovators are able to choose between brown and green innovations (e.g. Smulders and de Nooij, 2003).

In partial equilibrium firm-level analyses of abatement activities, successful innovations must lower total abatement costs, as firms would never adopt the technology otherwise. Heal and Tarui (2010) however, show, in an industry-wide analysis, that abatement costs could increase in the presence of externalities. More generally, allowing for interactions between the choice of abatement and other firms' decisions, innovation might well end up increasing the total cost of abatement. This is natural as firms care about overall profit maximization, rather than focussing on the minimization of a particular type of costs, e.g. abatement costs. Hence, innovation may lead to higher levels of pollution and abatement costs, while at the same time increasing profits, which is what makes the innovation attractive in the first place. This description of the innovation process, whereby new technologies lead to more pollution, well represents the impact of some of the most disruptive changes in technology over the last two hundred years. The adoption of steam powered pumps and looms in the nineteenth century, the introduction of internal combustion engines at the beginning of the twentieth, the capillary diffusion of petrochemical plastics and fertilizers after World War II, the emer-

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but it focuses much less explicitly on exogenous vs. endogenous technological change.

[4] Bauman et al. (2008) consider various examples of technologies that increase marginal abatement costs in an energy context, taking technical change exogenous. Thus, they do not deal with induced technical change. Hence, their paper is close in spirit to the literature on the "rebound effect" which studies the response of emissions to exogenous changes in technology.

[5] Empirical investigations of economic growth unanimously identify total factor productivity improvements as the main driver behind sustained growth (see Caselli, 2005, for an overview).

gence of intercontinental flights in the 1960's, or the rise of the personal computer and other information and communication technologies that started in the 1980's all led to staggering increases in firms' profits and social welfare. Such technological breakthroughs, however, came at the cost of large increases in the use of fossil fuels and the associated polluting emissions. One must conclude that standard analyses of innovation done by environmental economists neglect a very large portion of the menu of possible technological innovations. In line with this discussion, in what follows we allow for a more general description of technological improvements, such that in equilibrium technological change may prove to be either pollution-using or pollution-saving. This will turn out to be one of the crucial ingredients for our analysis, and one that has not been previously systematically investigated in this literature.

Another key aspect that needs to be recognized is that general equilibrium effects play a relevant role in the interplay between environmental policy and technological change. Since emission cuts reduce output, and hence the market size of potential investment projects, changes in environmental regulation may crowd out investment and innovation, raising the cost of environmental policy (see the theoretical analyses by Smulders and de Nooij, 2003; Di Maria and Smulders, 2004; Sue Wing, 2006; Di Maria and van der Werf, 2008; Gerlagh, 2008; Gans, 2011; Acemoglu et al., 2012). This starkly contrasts with the view that environmental policy triggers innovation in clean technology. Moreover, the induced changes in technology might not only affect aggregate income, but also change the composition of demand.[6] As a consequence the willingness to pay for environmental quality could change, which has significant implications in a setting where environmental policy is endogenous. The explicit inclusion of general equilibrium effects, and of endogenous changes in the stance of environmental regulation, is another of the important ways in which our analysis differs from most work in the area.

External effects also play a role in the way in which environmental policy and ITC interact. First, technological spillovers may affect the cost of environmental policy. Both in general equilibrium and integrated assessment models typically social returns to R&D are bigger than private ones, so that increases in R&D are normally welfare improving (e.g. Goulder and Schneider, 1999; Nordhaus, 2002; Popp, 2004; Gerlagh, 2007). If environmental policy induces a shift of R&D efforts away from sectors with relatively low social returns and into those with high returns, welfare gains can be large.[7] In our model, technological spillovers play an important role not so much because environmental policy can correct the misallocation of research efforts, but rather because environmental externalities interact with technology ones. A second type of externality is relevant to our discussion. Changes in environmental quality may affect the productivity of other factors, for example, air pollution increases morbidity and decreases labour productivity. We incorporate this externality in our discussion, and show that this distortion may either compound or dampen the positive impact of environmental policy on aggregate welfare.

As should be clear from our discussion so far, our analysis explicitly discusses a number of distortions that introduce 'wedges' between the social and private valuation of investment

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[6] The importance of feedback mechanisms between economic activity and externalies for the analysis of the cost of policy interventions has been the object of a long literature. See Carbone and Smith (2008) for an interesting recent contribution and a review of the related literature.

[7] This type of models generally finds moderate to large positive effects of ITC in calibrated numerical models. Similarly to the partial equilibrium models mentioned above, these models focus on describing technological progress in alternative energy sectors, while providing detailed descriptions of energy generation. Innovation and investment in other directions, especially those of a pollution-using nature, tend therefore to be neglected. This leads to results that may be biased in favour of aggregate pollution-saving technological change.

and pollution, and prevent the decentralized allocation from being fully optimal. In this situation, it should not be surprising that ITC may increase the cost of environmental policy. More surprisingly, we are able to show that in a dynamic setting ITC increases the cost of environmental policy (reduces the efficient level of environmental quality), even in the absence of additional distortions apart from the one the policy is designed to correct. This result arises because the costs and benefits of the corrective policy accrue at different points in time, as do the costs and benefits of ITC. Hence, in the presence of discounting, environmental policy becomes more costly under ITC.

The main contribution of this paper is to present a tractable model that allows us to disentangle all of the effects discussed above. In our model the direction of technical change is the endogenous result of investment decisions by innovators and of the nature of technological innovations: innovators react to environmental policy by either decreasing or increasing investments in projects that may increase or decrease the demand for polluting inputs. We show that the induced change in technology can either bolster the effectiveness of environmental policy or partially undo the regulator's efforts. This latter – unconventional – result turns out to arise under completely standard assumptions. In particular, it may arise when environmental quality affects production as an externality, when environmental and technology policy are uncoordinated, or when the cost and benefits of environmental policy are not synchronized over time, in the presence of discounting.

The nuanced conclusions on the impact of ITC that we obtain in this paper contrast sharply with the almost universal belief that ITC makes environmental policy cheaper. The Intergovernmental Panel of Climate Change (IPCC) epitomize this crystallized consensus when they attach a high degree of confidence[8] to the statement that "*Long-term stabilization scenarios highlight the importance of technology improvements, advanced technologies, learning-by-doing, and induced technological change, both for achieving the stabilization targets and cost reduction*"(IPCC, 2007a, Chapter 3, page 172). Similar positions have been expressed in the well-known *Stern Review* (Stern, 2006). A North American perspective is offered by Goulder (2004), while a modelling view is discussed at length in the Innovation Modelling Comparison Project in Edenhofer et al. (2006). An extreme representation of this tenet is offered by Acemoglu et al. (2012), who show that environmental policy only needs to be temporary to prevent environmental collapse by redirecting technological change.

The policy implications of our analysis are striking. The role of technological progress in facilitating the working of environmental policy measures should not be taken for granted, as environmental policy might end up being less effective or more expensive than previously thought. Ambitious environmental policy efforts that rely on significant shifts in the existing technological paradigm need to be complemented by carefully designed measures to ensure that the incentives that emerge for investors as not misaligned relative to those of the social planner.

We build our analysis in steps, starting from a static framework with exogenous policy. In subsequent sections we endogenize environmental policy, and finally recast our analysis in a first-best dynamic framework. Section 2 presents the static model where both pollution and technology are endogenous. Section 3 defines the central concepts of our analysis: green and brown technology, crowding-in and crowding-out of investment, and pollution-using and pollution-saving technical change. In Section 4, we study the role of ITC when environmental policy is exogenous. In Section 5, environmental policy is set optimally, but the externalities in investment are not necessarily resolved. In Section 6, we study the dynamic version of the

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[8] By this we mean that the statement is given a "high agreement, much evidence" status in the executive summary.

model, with fully optimal policy. Finally, Section 7 concludes.

2 The framework of analysis

In our economy, the final good is produced using one polluting input, P, and man-made (knowledge) capital H. To capture the idea that pollution may also *indirectly* reduce the overall productivity of the production process, as a negative externality for individual producers, we allow production to depend also on environmental quality, N. Formally, we have:

$$Y = y(N, P, H). \tag{1}$$

We assume that $y_P > 0$, $y_{PP} < 0$, $y_H > 0$, $y_{HH} < 0$, $y_N \geq 0$,$y_{NN} \leq 0$, $y_{HN} > 0$, $y_{PN} > 0$, where the latter two assumptions mean that increases in N are total-factor productivity enhancing.[9] We do not restrict the sign of y_{PH}. A positive sign corresponds to capital-pollution complementarity, whereas a negative sign implies capital-pollution substitutability.

Capital can be accumulated through costly investment. The amount of investment, I, needed to achieve a given level of technology, H, increases in a convex way with this technology level, and is influenced by knowledge spillovers K. Accordingly, we let the function describing the cost of investment be

$$I = i(H, K). \tag{2}$$

where we assume $i_H > 0$, $i_{HH} > 0$, and $i_K < 0$. Knowledge spillovers come from investment in the aggregate economy, in the spirit of Arrow (1962) and Romer (1986). In the context of a representative firm, this implies:

$$K = k(H). \tag{3}$$

We allow for two possibilities, when $k_H > 0$ the cost of investment decreases with the level of H, indicating positive spillovers, e.g. learning by doing. A negative derivative, $k_H < 0$, implies negative spillovers, e.g. because of patent races or fishing-out (cf. Jones, 1995).

Our modelling of environmental quality links the flow of pollution to the level of environmental quality, N, as follows

$$P = e(N). \tag{4}$$

In this context, $e(N)$ can be interpreted as the sustainable emissions (or pollution) level, i.e. the level for which environmental quality remains stable. The variables N and P are susceptible to the usual range of interpretations: in a natural resource setting N can be seen as the resource stock (e.g. the fish biomass) and P as the harvest rate (the catch, in the fishery example); in a classic pollution setting P is the flow of pollutants, and N the ambient quality. We will mostly use this latter interpretation in what follows. Here, it is natural to assume that environmental quality deteriorates with pollution, and that the deterioration occurs at an increasing rate. Formally, this implies that $e_N < 0$ and $e_{NN} < 0$.[10]

In this economy, consumers derive utility from their consumption of the final good, and from their enjoyment of the natural environment. We can write this as

$$U = u(C, N; \phi), \tag{5}$$

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[9] Throughout the paper we use lower case letters to denote functions, and subscripts to indicate partial derivatives, such that, e.g. $\partial z(X, Y)/\partial X = z_X$, $\partial^2 z(X, Y))/\partial X \partial Y = z_{XY}$.

[10] Since $N = e^{-1}(P)$ is a decreasing function of P, its concavity implies the concavity of $e(N)$.

where C is the level of consumption, and N the level of environmental quality defined above. We conform to standard assumptions by letting $u_i > 0$, $u_{ii} < 0$, for each input $i = C, N$, and $u_{CN} = u_{NC} \geq 0$. We use ϕ in the utility function to parametrize the relative preference for environmental quality. An increase in ϕ raises the marginal willingness to pay for environmental quality, $\omega(C, N; \phi) \equiv u_N/u_C$, thus representing a 'greening' of preferences.

Finally, total output can be used either to acquire consumption goods or for gross investment, such that the equilibrium on the goods market requires:

$$Y = C + I. \tag{6}$$

3 Marginal abatement costs and the nature of technological change

In what follows, we focus on how a shock to the economy (specifically, a tightening of environmental policy or a greening of preferences) affects the representative firm's investment decisions, the consumer's welfare levels, and the optimal choice of environmental policy. Our main goal is to identify the role of technological change in this context. Thus, we distinguish between the case where technology is exogenous from the situation in which the shock to the economy leads to changes in technology, i.e. the ITC case.

Making use of the production function in (1), we can classify technologies in a transparent way, depending on their impact on polluting emissions. Our classification is aimed at capturing the idea that one should classify as '*green*' only technology whose more widespread utilization causes, *cœteris paribus*, a fall in the demand for polluting inputs. In contrast, technologies whose increased use leads to a higher demand for pollution need to be classified as '*brown*'. Since the demand for polluting inputs is derived by equating the marginal product of pollution (y_P) to the price (or cost) of pollution, and given that a larger use of any given technology implies an increase in H, a technology can only be classified as green if further investment in H reduces the marginal productivity of the polluting inputs. Hence, we can formally define green and brown technologies as follows:[11]

Definition 1. (Colour of technology) *Technology is said to be* green *whenever $y_{PH} < 0$, and* brown *whenever $y_{PH} > 0$.*

This definition has an immediate interpretation in terms of the marginal cost of pollution abatement, MAC, defined as the loss in output from a marginal reduction in pollution when taking as given all other inputs in production:[12]

$$\text{MAC} \equiv y_P = \frac{\partial y(N, P, H)}{\partial P}. \tag{7}$$

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[11] Notice that here and in the rest of the paper we abstract from the case in which technological change is pollution neutral, i.e. we rule out the case $y_{PH} = 0$. In this case, by Young's theorem we would have $y_{HP} = 0$, and changes in pollution (and environmental policy) would not affect the stock of knowledge; which would devoid the concept of ITC of any poignancy.

[12] Once we define a baseline level of emissions (often referred to as the business-as-usual, BAU, level), we can measure total abatement in either physical or value terms. Baseline emissions are defined as the level that would arise in an unregulated 'benchmark' economy, and are the level of emissions at which the marginal product of the polluting input equals the benchmark cost of emissions, presumably zero, i.e. $P_0 : y_P(P_0, \cdot) = 0$. In the presence of an emission charge τ, actual – regulated – emissions are simply $P_1 : y_P(P_1, \cdot) = \tau$. Abatement in physical terms is the difference between actual and baseline emissions $(P_0 - P_1)$, while the cost of abatement is the amount of net output forgone by reducing emissions from their baseline level to their actual one, i.e. $y(P_0, \cdot) - y(P_1, \cdot)$.

One can then use the partial differential of the MAC expression above with respect to technological change,

$$\mathrm{dMAC}|_{\mathrm{d}P=0} = y_{PH}\mathrm{d}H, \tag{8}$$

to conclude that investment in green technology reduces marginal abatement costs, while investment in brown technology increases them.

Whether marginal abatement costs actually fall or increase as a consequence of an economic shock, however, depends on both the sign of y_{PH}, and that of $\mathrm{d}H$. The former depend on the characteristics of the production technology $y(.)$, while the latter is determined endogenously, since the decision how much to invest hinges upon the trade-off between the cost of investment and its returns. Thus, shocks to the economy have the potential to either increase or decrease the level of investment, leading to the '*crowding-in*' and '*crowding-out*' of investment, respectively.

In much the same spirit as for Definition 1 above, we can now classify technological change (i.e. a change in H), as follows:

Definition 2. (Nature of technological change) *Any change in technology that leads to a decrease in the marginal cost of abatement, i.e.* $y_{PH}\mathrm{d}H < 0$, *is said to be* pollution-saving*. Any change in technology that leads to an increase in the MAC , i.e.* $y_{PH}\mathrm{d}H > 0$, *is said to be* pollution-using*.*

By extension, any shock to the economy that reduces the MAC is said to induce pollution-saving technological change.

We can conclude this discussion by noting that pollution-saving technological change may emerge either as a result of the crowding-in of green technology, or as a consequence of the crowding-out of brown technology. The same *caveat* applies to pollution-using technical change that may arise when brown technologies are crowded-in, or when the investment in green technologies falls.

As discussed in the introduction, the effects of technology on the MAC (i.e. the sign of y_{PH}) can be either positive or negative. In the rest of this paper we allow for both possibilities, and derive our conclusions conditional on this sign. We show that, depending on whether technology is green or brown, the impact of ITC on economic and environmental outcomes may vary dramatically.

4 Exogenous environmental policy under induced technical change

Our analysis of the impact of ITC on the environmental and economic consequences of environmental policy starts with what can be considered the workhorse model of environmental economics, i.e. a static set-up with exogenous policy. Within this framework we consider the impacts of a marginal tightening of environmental policy, with and without induced technological change.

4.1 Investment decisions and environmental policy

Let the profits, π, of the representative firm be given by

$$\pi = y(N, P, H) - i(H, K) + \sigma H - \tau P, \tag{9}$$

where we normalize the price of the final good to 1 such that $y(\cdot)$ represent revenues, $i(\cdot)$ is the cost of investment, σ is a subsidy to innovation.[13] The last term in (9) represents environmental policy, where τ is the 'price' of pollution: the pollution tax, or the permit price in the case of an emission trading system. We assume that the negative externalities from pollution are initially not fully internalized, either because the tax is set too low, or because the overall cap in the trading scheme has been set too high. We assume that further distortions are avoided in that the tax/permit auction revenues are lump-sum rebated to households.

The representative firm chooses its level of pollution, P, and its innovation intensity, H, to maximize profits, taking as given environmental quality N, the pollution price τ, the innovation subsidy σ, and the economy-wide knowledge stock, K. The resulting first-order necessary conditions are:

$$y_P = \tau, \tag{10}$$

$$y_H = i_H - \sigma. \tag{11}$$

Equation (10) states that the marginal cost of abatement equals the price of pollution. Equation (11) says that the marginal returns to investment equal the marginal cost of investment.

Using (4) and (3) to substitute away the function arguments N and K in y and i, the first order conditions (10) and (11) can be rewritten as functions of P and H only:[14]

$$\widetilde{m}(P,H) \equiv y_P(e^{-1}(P), P, H) = \tau, \tag{12}$$

$$\tilde{r}(P,H) \equiv y_H(e^{-1}(P), P, H) - i_H(H, k(H)) + \sigma = 0. \tag{13}$$

Here, $\widetilde{m}$ expresses the representative firm's willingness to pay for polluting inputs, y_P, as a function of P and H only, while $\tilde{r}$ does the same for the marginal net return to investment, $r \equiv y_H - i_H + \sigma$.

Totally differentiating (13), we find $\tilde{r}_P \mathrm{d}P + \tilde{r}_H \mathrm{d}H = 0$, from which we can immediately derive the following expression for the effect of a change in environmental quality on investment:

$$\frac{\mathrm{d}H}{\mathrm{d}P} = \underbrace{\frac{1}{i_{HH} + i_{HK}k_H - y_{HH}}}_{\zeta} \underbrace{\left(y_{HP} + \frac{y_{HN}}{e_N}\right)}_{\tilde{r}_P}. \tag{14}$$

The positive term ζ in this last expression can be interpreted as a gauge of induced technological change.[15] Indeed, the case in which technology doesn't respond to changes in pollution can here be represented by letting the marginal cost of investment rise infinitely fast (i.e. $i_{HH} \to \infty$). In this case we have $\lim_{i_{HH}\to\infty} \zeta = 0$, and $\mathrm{d}H/\mathrm{d}P = 0$.

Given that ζ is positive, the sign of $\tilde{r}_P$ determines the sign of (14). Hence, $\tilde{r}_P$ signals whether changes in environmental policy encourage or discourage investment in new technology. If

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[13] We model innovation support as a subsidy per unit of H. Alternatively, one could consider a subsidy per unit of investment cost, which would complicate the analytical expressions without changing the results.

[14] Throughout the paper we will use 'tilded' symbols to identify expressions that depend on P and H (and parameters) only. We first solve variables in terms of P and H (and parameters) only, before we derive closed form solutions. This allows us to transparently compare the solution conditional on a fixed H (the exogenous technology case), to the solution with endogenous H (i.e. the ITC case).

[15] The positiveness of ζ is required to guarantee that the initial equilibrium defined by (10) and (11) is stable. In the presence of 'large' positive technological spillovers – i.e. when $i_{HK}k_H < 0$ is small enough to make ζ negative – any small deviation (a "tremble" in game theoretic parlance) by any firm from the original investment plan that satisfies the first- and second-order conditions would lead to a different equilibrium. Full details of the formal argument are available from the authors upon request.

$\tilde{r}_P$ is positive firms invest more when they are allowed to pollute more, and – conversely – invest less in response to a tightening of environmental policy. A positive sign of $\tilde{r}_P$ implies that environmental policy *crowds out* investments in new technology.

The mechanism behind this result is simple. Investment incentives are driven by the (net) marginal returns to investing in new technologies (i.e. increasing H), the $\tilde{r}$ defined above. To isolate the impact of environmental policy on investment, differentiate $\tilde{r}$ keeping technology fixed for the time being:

$$\mathrm{d}\tilde{r}|_{\mathrm{d}H=0} = \tilde{r}_P \mathrm{d}P = \left(y_{HP} + \frac{y_{HN}}{e_N} \right) \mathrm{d}P. \tag{15}$$

The second term in parentheses captures the fact that a decrease in pollution, increases environmental quality, N, which boosts TFP – see (1) – and increases the incentives to invest in knowledge capital, H. Since $y_{HN} > 0$ and $e_N < 0$, it is apparent that a more stringent environmental regulation ($\mathrm{d}P < 0$) tends to encourage investment via the environmental production externality. The direct effect of pollution on the productivity of the capital stock – measured by the term y_{HP} – is less straightforward. It depends on whether knowledge is a substitute or a complement for polluting inputs, i.e., on whether technology is green or brown (see Definition 1). Under green technology, P and H are substitutes and a reduction in pollution makes investment in H more attractive, further encouraging investment. Thus, in this case investment is necessarily crowded in by a tightening of environmental policy as the two terms in parentheses in (15) reinforce each other. Conversely, in the presence of brown technology pollution and technology are complements so that a lower level of pollution makes investment less worthwhile. Thus, brown technology tends to be crowded out by more stringent environmental regulation. Indeed, from (15) one can conclude that brown technology can be crowded in only if the production externality effect dominates the direct 'complementarity' effect.

We can now summarize the discussion above in the following preliminary result on the nature of technological change:

Lemma 1. (Direction of technological change) *In the static model with induced technical change, a marginal reduction in pollution induces* pollution-using *technological progress if and only if* $y_{PH}\tilde{r}_P < 0$*, which requires* $0 < y_{PH} < -\frac{y_{HN}}{e_N}$*. Otherwise, the induced technological progress proves to be* pollution-saving*.*

Proof. Definition 2 states that pollution-using technological change requires $y_{PH}\mathrm{d}H > 0$. Rewriting yields $y_{PH}\frac{\mathrm{d}H}{\mathrm{d}P}\mathrm{d}P > 0$. Using (14), we get $y_{PH}\tilde{r}_P\zeta\mathrm{d}P > 0$. Under our assumptions of ITC (i.e. $\zeta > 0$) and pollution reduction (i.e. $\mathrm{d}P < 0$) pollution-using technical change requires $y_{PH}\tilde{r}_P < 0$. From the expression for $\tilde{r}_P$ given in (15) and the assumption that $y_{HN}/(e_N) < 0$, one can immediately conclude that pollution-using technological change only arises when $y_{PH} > 0$, and $y_{PH} + \frac{y_{HN}}{e_N} < 0$. □

Thus colour of technology and direction of the crowding-in/out effect jointly determine the direction of technological change in this context. The sign of $y_{PH}\tilde{r}_P$ clearly signals this direction. When technology is green, a marginal tightening of environmental policy unequivocally crowds in investment – see (14) – and MAC falls. This corresponds to pollution-saving technical change. If technology is brown, investment may be crowded out (if the environmental production externality is 'small enough'), and again MAC falls, leading to technological change being pollution saving. When brown technology is crowded in because of a large environmental production externality, however, the MAC increases and technological change turns out to be pollution using.

Two things are worth noting here. First, pollution-saving technological change may emerge as a result of environmental policy reducing investment in brown technology, rather than as the consequence of an increase in green R&D activities. This channel is crucially different from the conventional view held by most environmental economists and policy makers that we discussed in the introduction. Second, while from an aggregate perspective it seems counterproductive to pollute more in reaction to a cleaner environment, the mechanism at play here is perfectly rational from the point of view of the individual agents which operate under the influence of external effects. The intuition behind the last, surprising case discussed in the previous paragraph is that, as environmental quality increases, investment rises since investors observe an increase in the net rate of return. This increase is brought about by a surge in TFP driven by improvements in environmental quality, that is large enough to offset the production-depressing effects of the more stringent environmental regulation. In turn, the higher innovation level leads to more demand for pollution, given the existing complementarity between P and H in this brown technology scenario. Clearly, the private and social incentives to pollute and invest are not aligned in this case, as $\tilde{r}_P$ and $MAC_H = y_{PH}$ have opposite signs. One can interpret this as a 'perverse' Le Chatelier effect, whereby adjustments in the 'fixed factor', technology in this case, undermine the effectiveness of environmental policy.

4.2 A marginal tightening of environmental policy

Using the results derived above, we now address the impact of ITC on the effectiveness and the cost of environmental policy. Totally differentiating (12), we derive the following expression for the effect of a change in environmental quality on investment:

$$\frac{\mathrm{d}\tau}{\mathrm{d}P} = \underbrace{\left[y_{PP} + \frac{y_{PN}}{e_N}\right]}_{<0} + y_{PH} \underbrace{\frac{\mathrm{d}H}{\mathrm{d}P}}_{\zeta \tilde{r}_P} . \tag{16}$$

The term in brackets summarizes the change in MAC due to a change in pollution, for given technology (i.e. without ITC), while the second term, $y_{PH}\mathrm{d}H/\mathrm{d}P$, captures the effect of induced technological change. If technological change would not react to changes in pollution, this term would be zero, as ζ would be zero in this case. Under ITC, however, ζ is positive, and a positive sign for $\tilde{r}_P$ implies that a reduction in pollution triggers pollution-saving technological change, while a negative sign indicates that a more stringent environmental policy induces pollution-using technological change.

We now can prove the following proposition on the implications of ITC for the cost and effectiveness of a marginal tightening in environmental policy:

Proposition 1. **(Cost of environmental policy)** *In the static model, whenever* $y_{PH}\tilde{r}_P < 0$*, i.e.* $0 < y_{PH} < -\frac{y_{HN}}{e_N}$*, ITC implies*

i. a larger increase in the private marginal cost of environmental policy due to a marginal tightening of the cap on pollution;

ii. a smaller pollution reduction following a marginal change in the exogenous pollution charge.

Proof. Assume that $0 < y_{PH} < -\frac{y_{HN}}{e_N}$. From the proof of Lemma 1, we know that this implies $y_{PH}\tilde{r}_P < 0$. Substituting (14) into (16), and letting $y_{PH} = y_{HP}$[16] one gets:

$$\mathrm{d}\tau/\mathrm{d}P = y_{PP} + y_{PN}/e_N + \zeta y_{HP}(y_{HP} + y_{HN}/e_N).$$

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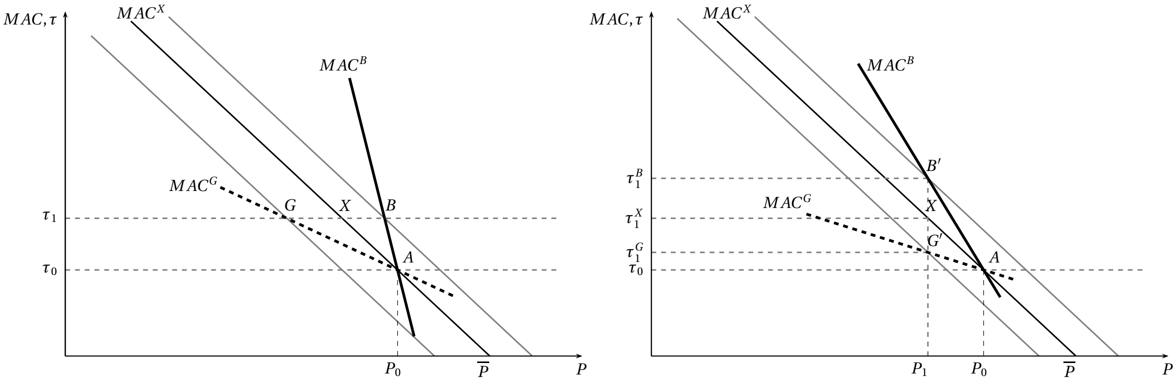
[16] By Young's theorem, this holds if we assume that the production function has continuous second-order



(a) a price instrument (b) a quantity instrument

Figure 1: Exogenous policy under induced technological change

From the previous assumption it then follows that $\frac{\mathrm{d}\tau}{\mathrm{d}P}\big|_{\zeta>0} < \frac{\mathrm{d}\tau}{\mathrm{d}P}\big|_{\zeta=0} < 0$, proving the first statement. To prove the second, simply notice that the last inequality implies $0 > \frac{\mathrm{d}P}{\mathrm{d}\tau}\big|_{\zeta>0} > \frac{\mathrm{d}P}{\mathrm{d}\tau}\big|_{\zeta=0}$. ☐

Thus, when induced technological change proves pollution-using, the traditional conclusion that ITC makes environmental policy less expensive/more effective is turned on its head. A simple graphical illustration helps grasp the intuition behind the result. Figure 1, illustrates the impact of ITC on policy outcomes. At the initial equilibrium, point A in the graphs, the pollution price is τ_0, and the level of pollution P_0. The slope of the MAC curve in the initial equilibrium is given by (16); as we only focus on marginal changes, we ignore second order effects that change the slope of the MAC curve, and draw straight lines.

Consider how environmental policy operates when technology is completely exogenous and ITC doesn't occur (i.e. let $\zeta = 0$). In this case, either an exogenous increase in the pollution charge from τ_0 to τ_1, say, or a reduction of the number of permits auctioned in the cap-and-trade system from P_0 to P_1 produce the same outcome, and the new equilibrium obtains at a point like X, along the MAC^X – for exogenous technological change – curve.

Under ITC, instead, the outcome depends on the interaction between the nature of technology, the firm's incentives to invest, and the type of instrument chosen by the regulator. The standard case discussed in the literature features green technologies. As discussed above, when technology is green a more stringent environmental policy induces crowding-in of investment, so that the MAC curve shifts down. The exact new equilibrium level depends on the choice of the instrument. Under exogenous taxation – see Figure 1(a) – as the tax raises to τ_1 pollution falls more than in the exogenous technology case, and the new equilibrium is reached at point G. The perceived abatement cost curve – the dashed line MAC^G (for green technology) – is now flatter, due to ITC. Figure 1(b), instead, presents the equilibrium emerging from a quantity instrument. In this case, at the new equilibrium, point G', the pollution level is the same but the permit price is lower under ITC. Similar outcomes occur when technology is brown but the production externality small. In this case it is the crowding-out of investment that leads to the downward shift of the MAC curve: technological change is pollution-saving due to a fall in investment. Consider, however, what happens when technology is brown ($y_{PH} > 0$) and the production externality large (such that $\tilde{r}_P < 0$). In this

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derivatives, which seems the natural benchmark assumption. Since we only consider marginal changes, it is sufficient to assume local differentiability. This rules out a situation where firms are constrained because they pollute at maximum pollution levels (the zero-abatement pollution level), as is possible in the well-known formulation by Stokey (1998).

case the tightening of environmental policy crowds in new investment. This has the effect of making pollution more productive (given that it is a complementary input to investment), and raises the opportunity cost of reducing it. The net effect is that the MAC curve shifts upwards in this case. The perceived MAC schedules under ITC – the bold MAC^B (for brown technology) lines in the graphs – are now steeper than when technology doesn't adjust. When the regulator uses a pollution charge, as in Figure 1(a), less pollution reduction occurs at the new equilibrium (at point B), relative to the exogenous technology case. When the regulator chooses a quantity instrument, see Figure 1(b), the permit price increases much more than in the exogenous technology scenario (see point B'). Since τ in equilibrium equals the marginal cost of pollution reduction, induced pollution-using technical change makes environmental policy more costly.

4.3 Welfare changes

Proposition 1 discusses the implications of ITC for the effectiveness and the cost of environmental policy. The natural next step is to investigate how the welfare consequences of a marginal tightening of the stance of environmental are influenced by the presence of ITC. Totally differentiating (5), using (4), (6), and the first-order conditions (10) and (11), we get the following expression for the change in welfare, in terms of consumption equivalents:

$$\frac{\mathrm{d}U}{u_C} = -\left\{ \underbrace{\left[\frac{1}{-e_N}\left(\frac{u_N}{u_C} + y_N\right) - y_P\right]}_{(\tau^* - \tau)} - \underbrace{\left(- i_K k_H - \sigma\right)}_{(\sigma^* - \sigma)} \underbrace{\frac{\mathrm{d}H}{\mathrm{d}P}}_{\zeta \tilde{r}_P} \right\} \mathrm{d}P. \tag{17}$$

This expression captures the fact that there are two types of externalities at work, the environmental one operating on utility and productivity, and the knowledge spillovers that affect the cost of investment. The term in square brackets gauges the degree to which the environmental externalities are correctly addressed at the initial equilibrium by measuring the difference between the optimal pigouvian tax, which fully internalizes the damages to production and the loss of utility,

$$\tau^* \equiv \frac{1}{-e_N}\left(\frac{u_N}{u_C} + y_N\right), \tag{18}$$

and the actual environmental tax (or the permit price in the cap-and-trade case), τ. Here, we recover the standard result that a pollution reduction is welfare-improving as long as the marginal environmental benefits are not correctly internalized at the initial equilibrium. Recall that we have assumed that the tax is initially too low relative to the damages of pollution to production and utility, i.e. $\tau < \tau^*$.

The second term in the curly bracket captures the investment inducing effects of a change in the allowed level of pollution. Whenever $\mathrm{d}H/\mathrm{d}P \neq 0$, welfare is also affected via the knowledge spillovers, provided that there is a wedge between the social and private returns to investment. Since the social cost of investment is $i_H + i_K k_H$, while the private costs are $i_H - \sigma$, the second bracketed term is the difference between private and social returns. If the term is positive, the initial equilibrium is characterized by underinvestment, because the technology subsidy falls short of the technology spillovers, i.e. $\sigma < -i_K k_H \equiv \sigma^*$. In the presence of underinvestment, the crowding in of investment through environmental policy – i.e. $\mathrm{d}H/\mathrm{d}P = \zeta \tilde{r}_P < 0$, see (14) – leads to a welfare gain.[17]

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[17] Clearly, the opposite is also true. In the presence of overinvestment, a crowding-out of investment due

The role of ITC becomes even more pervasive when we consider environmental policy conducted via a price instrument rather than via a quantitative restriction. In this case, there is yet another channel through which ITC interacts with environmental policy. To see this, multiply and divide the right-hand side of equation (17) by $\mathrm{d}\tau$ to get:

$$\frac{\mathrm{d}U}{u_C} = -\left\{ (\tau^* - \tau) - (\sigma^* - \sigma)\,\zeta \tilde{r}_P \right\} \frac{\mathrm{d}P}{\mathrm{d}\tau}\mathrm{d}\tau. \tag{19}$$

From (16) we know that $\mathrm{d}P/\mathrm{d}\tau = (y_{PP} + y_{PN}/e_N + y_{PH}\zeta\tilde{r}_P)^{-1}$. We can conclude that under price regulation ITC also influences welfare via its impact on the effectiveness of environmental policy discussed in Proposition 1.

Thus, ITC affects the welfare impact of environmental policy through two 'wedges', representing two separate but interacting channels. First, via the pollution-saving or pollution-using nature of technological change, ITC affects environmental quality, which is underprovided by assumption. Second, through the crowding-in/out of investment, ITC affects technology, which – depending on the subsidy – might be either underprovided or overprovided. The following proposition summarizes the possible outcomes.

Proposition 2. (Welfare effect of environmental policy) *In the static model, the presence of ITC...*

i. ...decreases the welfare gains from a marginal reduction in pollution, if and only if $(\sigma^* - \sigma)\tilde{r}_P > 0$*, which implies* $(\sigma^* - \sigma)y_{PH} > (\sigma^* - \sigma)y_{HN}/(-e_N) > 0$*;*

ii. ...decreases the welfare gains from a marginal increase in the pollution tax, if and only if $-(y_{PP} + y_{PN}/e_N)\frac{\sigma^*-\sigma}{\tau^*-\tau} < y_{PH} < \frac{y_{HN}}{-e_N}$ *or* $\frac{y_{HN}}{-e_N} < y_{PH} < -(y_{PP} + y_{PN}/e_N)\frac{\sigma^*-\sigma}{\tau^*-\tau}$.

Proof. Ad *i*: from (17) it is immediate to see that $\frac{\mathrm{d}U}{\mathrm{d}P}\big|_{\zeta=0} < \frac{\mathrm{d}U}{\mathrm{d}P}\big|_{\zeta>0} < 0 \Leftrightarrow \zeta(\sigma^* - \sigma)\tilde{r}_P = \zeta(\sigma^* - \sigma)(y_{PH} + \frac{y_{HN}}{e_N}) > 0$. Since $\zeta > 0$ under ITC, the statement of the proposition immediately follows.

Ad *ii*: Substitute (16) into (19). It is a simple matter of algebra to show that $\frac{\mathrm{d}U}{\mathrm{d}\tau}\big|_{\zeta=0} > \frac{\mathrm{d}U}{\mathrm{d}\tau}\big|_{\zeta>0}$ $\Leftrightarrow \frac{\tau^*-\tau}{y_{PP}+y_{PN}/e_N} < \frac{(\tau^*-\tau)-(\sigma^*-\sigma)\zeta\tilde{r}_P}{y_{PP}+y_{PN}/e_N+y_{PH}\zeta\tilde{r}_P} \Leftrightarrow [(\sigma^*-\sigma)(y_{PP}+y_{PN}/e_N)+(\tau^*-\tau)y_{PH}]\tilde{r}_P < 0$. Substituting the definition of $\tilde{r}_P$ and evaluating, we find the inequalities above. ☐

Under ITC, when the regulator chooses a quantity instrument to reduce pollution (i.e., she lets $\mathrm{d}P < 0$), the policy affects environmental quality and investment. In this case, the value of the environmental quality improvement is independent of the technology response, as it equals $-(\tau^* - \tau)\mathrm{d}P$, and ITC only impacts on welfare through its effect on the firms investment decisions. It induces an additional gain when investment is crowded in ($\tilde{r}_P < 0$) starting from a situation of underinvestment (i.e. $(\sigma^* - \sigma) > 0$), or when, starting from a situation of overinvestment ($(\sigma^* - \sigma) < 0$) environmental policy crowds out knowledge accumulation (i.e. $\tilde{r}_P > 0$). However, it induces an additional loss when crowding out occurs in an already underinvesting economy, or crowding in in a inefficiently overinvesting one (in these two cases $(\sigma^* - \sigma)$, and $\tilde{r}_P$ have the same sign), and leads to a reduction in the welfare gains from environmental improvements, as stated in the Proposition above.

When the regulator resorts to a price instrument to reduce emissions (i.e. she lets $\mathrm{d}\tau > 0$), ITC not only interacts with the investment wedge, $(\sigma^* - \sigma)\mathrm{d}H$, but also with the environmental one, $(\tau^* - \tau)\mathrm{d}P$. The size of the environmental benefit is now compounded if the induce technological change is pollution-saving, and dampened if it is pollution-using. As

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to changes in environmental policy would boost welfare. This latter case, however, appears less empirically relevant at the aggregate level.

a result, even when the tax increase crowds out much needed investment in the presence of under-subsidized investment, ITC might still increase welfare gains since it has now the capacity to magnify environmental benefits.

To summarize, Proposition 2 shows that ITC can reduce the welfare gain from environmental policy under both types of technology, green or brown, and under both types of policy, quantity-based or price-based. This occurs because the environmental and the investment externality go in opposite directions. If we only allow for a situation of underinvestment ($\sigma^* > \sigma$), however, ITC can never reduce welfare under the assumption of green technology. The straightforward reason is that with green technology, environmental policy necessarily crowds in investment, adding to the welfare gain by partially internalizing the technology spillover. However, when technology is brown, crowding out might offset the benefits from environmental quality improvements. Once again, we find that the optimistic conclusions found in the environmental economics literature might be traced back to modelling choices.

5 Uncoordinated environmental policy

Having analyzed the case where environmental policy is set exogenously in a static context, in this section we investigate the possibility that the environmental regulator (the Environmental Protection Agency – EPA for short) may attempt to use environmental policy to maximize social welfare, which can take the form of either a pollution tax or a direct cap on pollution. Realistically, however, we assume that the EPA is not charged with regulating the optimal level of innovation in the economy. As a consequence, knowledge spillovers are not necessarily internalized. We label this *uncoordinated* environmental policy since the EPA is not coordinating its policy with other regulators, and in particular, not with the regulator in charge of investment.[18]

The EPA's objective is to maximize utility (5), subject to the environmental and budget constraints, (4) and (6), and taking H as given. Formally, we have:

$$\begin{aligned}\max_{C,N}\ & U = u(C,N;\phi)\\ s.t.\ & C = y(P,N,H) - i(H,k(H)),\\ & P = e(N).\end{aligned}$$

The first-order conditions for this problem can be combined to obtain,

$$y_P = \frac{1}{-e_N}\left(\frac{u_N}{u_C} + y_N\right). \tag{20}$$

This equation is the familiar condition for optimal environmental policy, as it equates marginal abatement costs to the marginal social benefits from environmental quality improvements, equivalently referred to as social marginal cost of emissions or the marginal damage. To obtain an expression in terms of P and H only, we first need to express C in terms of these two variables only. Using (1), (2), (3), (4), and (6), we get:

$$\tilde{c}(P,H) \equiv y(e^{-1}(P),P,H) - i(H,k(H)) = C. \tag{21}$$

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[18] Note that this is different from the second-best situation in which the EPA uses a single instrument – environmental policy – to internalize multiple externalities, viz the environmental externality and the investment one.

Substituting the definition of $\omega(C, N; \phi)$ into the right-hand side of (20), and using (4) together with the expression for $\tilde{c}$ above, we write the right-hand side of (20) as

$$\tilde{\tau}^*(P, H; \phi) \equiv \frac{1}{-e_N(e^{-1}(P))} \Big[\omega(\tilde{c}(P, H), e^{-1}(P); \phi) + y_N(e^{-1}(P), P, H)\Big]. \tag{22}$$

Now we can use (20) expressed in terms of P and H only using (12), and (22), to obtain an expression for the the *net* marginal benefits from environmental quality, $\tilde{n}$ say, that need to be zero at the optimum:

$$\tilde{n}(P, H; \phi) \equiv \tilde{\tau}^* - \widetilde{m} = 0. \tag{23}$$

Comparing (20) – or, equivalently, (23) – and (10), it is clear that the optimal environmental policy can be implemented by setting the pollution tax, τ equal to $\tilde{\tau}^*$. Hence, the difference between the current model and the one in the previous section is that the marginal abatement costs are no longer equated to an arbitrary exogenous pollution tax, but to the marginal social benefits from pollution reduction. Our results in this section will stem from the fact that also the marginal benefits depend on the knowledge stock H, which is still determined by the equalization of the private marginal costs and benefits of investment, equation (13).

There are several reasons why technical change may affect the marginal benefits of environmental policy. For example, it may increase the productivity of environmental quality (i.e. $y_{NH} > 0$), leaving the economy more exposed to the potential damages from environmental degradation; or, it may increase consumption and, as a consequence, the demand for environmental quality (as the marginal utility of consumption falls, the representative consumer's marginal willingness to pay for environmental quality $\omega = u_N/u_C$ rises). Hence, technological change – including ITC – may call for more stringent environmental policy, compared to the case without (induced) technological change. On the other hand, any change in technology that lowers marginal abatement benefits leads to less stringent environmental policy. This second scenario may arise, for example, if investment is crowded out. In such case the economy is less productive, and there is less to protect by avoiding environmental degradation. Similarly, if there is crowding out of consumption, environmental policy becomes less desirable.

5.1 Technological change and green demand

The necessary first step in our analysis is to formally discuss how changes in investment affect the social marginal benefits from environmental policy. To do this, we partially differentiate the right-hand side of equation (22), and find:

$$\tilde{\tau}^*_H = \frac{1}{-e_N} \left\{\omega_C \tilde{c}_H + y_{NH}\right\}. \tag{24}$$

Using (21) and (13), we find how consumption is affected by investment:

$$\tilde{c}_H = y_H - i_H - i_K k_H = \sigma^* - \sigma, \tag{25}$$

which implies that, at an optimum, consumption increase with investment only if the investment subsidy is below the socially optimal level. Substituting the last expression in (24), one immediately gets

$$\tilde{\tau}^*_H = \frac{\omega_C(\sigma^* - \sigma) + y_{NH}}{-e_N}. \tag{26}$$

This expression informs us that the social marginal benefits from environmental policy are affected by investment both via the knowledge spillover wedge, and the production externality. This expression can be either positive or negative, but, in the presence of underinvestment, the sign is necessarily positive.

We can use this expression to transparently analyze the sources of a technology-induced higher demand for environmental quality. First, if the subsidy to investment is initially too low, such that investment is underprovided, an increase in knowledge capital (higher H) makes consumers richer, and increases their consumption level. As a consequence of the increase in consumption, the willingness to pay for environmental quality also rises, as the environment is a normal good ($\omega_C > 0$). Second, an increase in the knowledge stock directly makes the economy more productive, increasing the opportunity cost of pollution: the economy has more to lose from environmental degradation ($y_{NH} > 0$).

In equilibrium, the effect of ITC on the optimal level of pollution is determined by the net effect of changes in the marginal benefits of environmental quality and in the marginal cost of abatement. To gauge this overall effect we can look at the impact of investment on the *net* marginal benefits from environmental quality, defined in equation (23). Using (26), (12), and (15), we can express the change in net benefits for given P and H as:

$$\tilde{n}_H = \frac{\omega_C(\sigma^* - \sigma) + y_{NH}}{-e_N} - \widetilde{m}_H = \frac{\omega_C(\sigma^* - \sigma)}{-e_N} - \tilde{r}_P. \tag{27}$$

If this expression is positive, investment increases the demand for environmental quality, so that can we say that technology induces *green demand*. Hence, $\tilde{n}_H > 0$ identifies green-demand-inducing technology, while $\tilde{n}_H < 0$ characterizes a situation where technology reduces the demand for environmental quality. The last equality in (27) reveals the drivers of this result: investment increase the demand for environmental quality if the impact of the uncorrected investment spillovers outweights the investment incentives effect measured by $\tilde{r}_P$.

5.2 A marginal greening of preferences

We are now ready to investigate the impact of ITC in the conduct of environmental policy. To do so, we devise a simple experiment that parallels the exogenous increase in the policy stringency studied before. We imagine that environmental services become more valuable to consumers, i.e. the equilibrium value of u_N/u_C becomes exogenously (and marginally) larger, starting from an initial equilibrium in which environmental policy was set optimally. Our aim here is to compare changes in environmental quality in response to such a shock, with and without ITC. If environmental quality increases less under ITC, we can conclude that ITC makes environmental policy more 'costly' to implement.

Formally, our experiment amounts to a marginal increase in the shift parameter ϕ, that increases the consumer's willingness to pay for environmental quality, i.e. we assume

$$\mathrm{d}\phi = \mathrm{d}\left(\frac{u_N}{u_C}\right)\Bigg|_{\mathrm{d}C=\mathrm{d}N=0} > 0. \tag{28}$$

The general equilibrium effect of such preference shift on the level of environmental policy can be derived using the first order condition the firms uses to decide on investment, (11), and the one according to which the environmental regulator decides on the optimal level of environmental quality, (20). By expressing both of them in terms of variables P and H only, we end up with a system of two equations in two unknowns that solve for $\mathrm{d}P$ and $\mathrm{d}H$. Using (4), one easily obtains $\mathrm{d}N$.

As shown in section 4.1, (11) can be rewritten as (13), while we have shown above that (20) can be rearranged to yield (23). Taking total differentials of the resulting expressions with respect to P, H and ϕ, solving for $\mathrm{d}P$, and then using (4) to solve for $\mathrm{d}N$, we obtain:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \left(\frac{1}{e_N}\right)^2 \frac{1}{\tilde{n}_P + \zeta \tilde{r}_P \tilde{n}_H} \tag{29}$$

where $\tilde{n}_H$ and $\tilde{r}_P$ are defined in (27) and (14), respectively, while to get $\tilde{n}_P$ we use (12), (22), and (23), to find

$$\tilde{n}_P = -e_{NN}\frac{\tau^*}{e_N^2} - \left(\frac{1}{e_N}\right)\left[\omega_C\left(\frac{y_N}{e_N} + y_P\right) + \frac{\omega_N}{e_N} + y_{PN} + \frac{y_{NN}}{e_N}\right] - \frac{y_{PN}}{e_N} - y_{PP} > 0. \tag{30}$$

Recognizing that the term $\zeta \tilde{r}_P \tilde{n}_H$ in (29) captures the role of ITC on the optimal level of environmental quality, we can immediately derive the following result,

Proposition 3. (Uncoordinated environmental policy) *In the static model with uncoordinated environmental policy, induced technical change reduces the demand for environmental quality following a marginal greening of preferences, if and only if* $\tilde{r}_P \tilde{n}_H > 0$*, implying* $\frac{\omega_C}{-e_N}(\sigma^* - \sigma) + \frac{y_{HN}}{-e_N} < y_{PH} < \frac{y_{HN}}{-e_N}$ *or* $\frac{y_{HN}}{-e_N} < y_{PH} < \frac{\omega_C}{-e_N}(\sigma^* - \sigma) + \frac{y_{HN}}{-e_N}$.

Proof. From (29), it follows that $\left.\frac{\mathrm{d}N}{\mathrm{d}\phi}\right|_{\zeta=0} > \left.\frac{\mathrm{d}N}{\mathrm{d}\phi}\right|_{\zeta>0} \Leftrightarrow \tilde{r}_P \tilde{n}_H > 0$. Substituting the expressions for $\tilde{r}_P$ from (13), and $\tilde{n}_H$ from (27), and solving returns the inequalities presented above. □

This results clarifies that ITC can increase the cost of environmental policy via its impacts on both firms' incentives to invest in new technology, and on the consumers' demand for environmental quality. A graphical illustration of the optimality condition in (20) helps to understand the intuition behind the last result.

Figure 2 illustrates condition (23): the MAC curve represents the firm' willingness to pay for pollution, $\widetilde{m}$, which is also the marginal abatement cost, y_P, as before, while the MD curve represents the social marginal damage of pollution, or equivalently the social marginal benefits of environmental quality – i.e. $\tilde{\tau}^*$. The vertical distance between MD and MAC gives the net marginal benefit of pollution reduction $\tilde{n}$. The optimal level of pollution is found at the intersection of the MAC and MD curves so that $\tilde{n} = 0$. The initial equilibrium is at point A, where the stock of knowledge is H_0, pollution is at level P_0, and preferences haven't shifted yet, that is $\phi = \phi_0$.

Now consider what the exogenous shift in preferences does to the equilibrium. The parameter ϕ increases to ϕ_1 indicating a relative greening of societal preferences. The MD curve shifts up, as ω increases – see (22) – and a new equilibrium emerges, indicated by X to recognize that so far technology is assumed exogenously given. With ITC two things happen. First, the MAC curve shifts, as analyzed at length in the previous section. The picture captures the case where the MAC curve shifts down due to pollution-saving technical change, and the perceived MAC curve – the dashed line in Figure 2 – is flatter than under exogenous technological change. Second, the MD curve shifts as well, this is the effect formalized in equation (26). The picture refers to a situation where the MD shifts down, leading to a steeper (perceived) MD curve – the bold line in the Figure. The new equilibrium obtains at point E, where the fall in pollution is smaller under ITC.

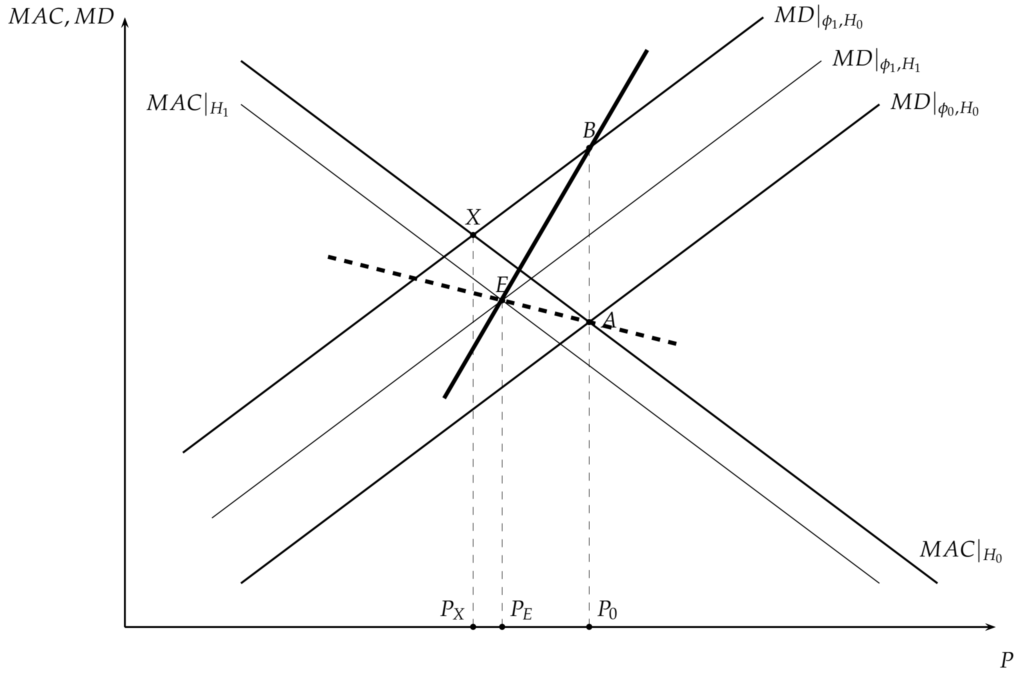

Figure 2: The optimal level of environmental quality under ITC

A situation like the one depicted in Figure 2 and presented in Proposition 3 is consistent with different possibilities. Begin with the case of underinvestment ($\sigma^* > \sigma$). In this case an exogenous shift in preferences that leads to additional demand for environmental quality might bring about a crowding-out ($\tilde{r}_P > 0$) of investment when technology is brown (Lemma 1), hence the drop in MAC. The crowding-out of already scarce investment reduces consumption, raising the marginal utility of consumption and lowering the willingness to pay for environmental quality, thus the shift down in MD as technology adapts ($\tilde{n}_H > 0$). This eventually results in less stringent environmental regulation under ITC. Notice that, in contrast, under green technology and underinvestment a greening in preferences unequivocally makes environmental policy more stringent. We know that the increased demand for the environment necessarily crowds in investment ($\tilde{r}_P < 0$), which increases consumption and environmental demand ($\tilde{n}_H > 0$). Thus, the equilibrium level of environmental quality is necessarily larger under ITC than in the case of exogenous technology.

Now turn to the case of over-investment ($\sigma^* < \sigma$). In this case, even under green technology we may obtain the result of the Proposition: if the preference shift crowds in ($\tilde{r}_P < 0$) additional investment above the already excessive level, consumption may fall, which reduces the marginal willingness to pay for environmental quality ($n_H < 0$), making environmental policy more costly under ITC.

Finally, consider the case where the investment subsidy is initially set optimally ($\sigma^* = \sigma$). In this case, our uncoordinated policy provides the social optimum: the EPA corrects the environmental externality at the same time as another regulatory agency is internalizing knowledge spillovers. Under these circumstances, ITC necessarily makes environmental policy more stringent, allowing us to conclude that in the static framework it is the wedge between private and social returns to investment that (potentially) increases the cost of environmental policy through ITC.

6 Environmental policy in a dynamic framework

In this section we show that in a dynamic framework ITC may increase the cost of environmental policy, not because of additional externalities outside of the control of the environmental regulator, but because of a wedge of a different nature between the costs and benefits of the investment decision. In the fully optimal dynamic model that follows, the wedge, rather than being in terms of private vs. social cost, emerges in terms of short-run vs. long-run costs. In brief, in this section we move from a static to a dynamic framework and from a second-best to a first-best world. We focus on the steady state of the system, as this is sufficient for the point we want to make here.

The problem we investigate here is one where the optimal level of consumption, emissions and investment have to be chosen. The objective is to maximize the present value of the discounted flow of utility,

$$W = \int_0^\infty u(C(t), N(t); \phi) e^{-\rho t} \mathrm{d}t, \tag{31}$$

where ρ is the social discount rate. The maximization is performed subject to the production function (1), the budget constraint (6), together with the laws of motion of the capital stock[19] and environmental quality, i.e. the dynamic counterparts of (2) and (4):

$$\dot{H}(t) = g(I(t), H(t)), \tag{32}$$

$$\dot{N}(t) = e(N(t)) - P(t). \tag{33}$$

where $g_I > 0$, $g_H < 0$, and $g(I, H)$ is concave. From the necessary conditions for a maximum, we can derive the following no-arbitrage conditions:

$$r = \frac{u_C/u_N + y_N}{y_P} + e_N + \frac{\dot{y_P}}{y_P}, \tag{34}$$

$$r = g_I y_H + g_H - \frac{\dot{g_I}}{g_I}, \tag{35}$$

$$r = \rho - \frac{\dot{u_C}}{u_C}, \tag{36}$$

which in the steady-state reduce to

$$y_P = \frac{1}{\rho - e_N} \left(\frac{u_N}{u_C} + y_N \right), \tag{37}$$

$$\frac{1}{g_I} = \frac{y_H}{\rho - g_H}. \tag{38}$$

These equations are the steady-state counterparts of (20) and (11), respectively. The former equates the marginal cost of pollution reductions to the net present value of the marginal benefits arising from a larger stock of environmental quality. The latter equates the marginal investment cost to the net present value of the marginal benefits of a bigger knowledge stock.

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[19] We consider a planner who internalizes knowledge spillovers, which can therefore be left implicit in the accumulation function, i.e. $g(I, H) \equiv \breve{g}(I, H, k(H))$ where the right-hand side separates out spillovers from own stock effects. Note that the conventional (physical) capital accumulation equation, $g(I, H) = I - \delta H$, is also nested in our specification, in which case we have $g_I = 1$ and $g_H = -\delta$.

6.1 A marginal greening of preferences

As in section 5, the policy shock we investigate is a marginal greening of the agent's preferences, i.e. an increase in ϕ.

Let $\tilde{i}(H)$ be the steady state investment level that solves $\dot{H} = 0$, so that

$$\tilde{i}_H = -\frac{g_H}{g_I}. \tag{39}$$

We use this equation and (4) to write the first-order steady state condition for investment, (38), as the following function of P and H only:

$$\tilde{r}^*(P, H) \equiv y_H(e^{-1}(P), P, H) - \frac{\rho - g_H(\tilde{i}(H), H)}{g_I(\tilde{i}(H), H)} = 0, \tag{40}$$

so that $\tilde{r}^*_P = \tilde{r}_P$, see (15), while

$$\tilde{r}^*_H = y_{HH} + \frac{y_H}{g_I}\left(g_{II}\tilde{i}_H + g_{IH}\right) + \frac{1}{g_I}\left(g_{HI}\tilde{i}_H + g_{HH}\right) \equiv -\frac{1}{\zeta^*} < 0. \tag{41}$$

The optimal long-run investment response to changes in pollution is derived from totally differentiating (40) and using (41), to get

$$\frac{\mathrm{d}H}{\mathrm{d}P} = \zeta^* \tilde{r}_P. \tag{42}$$

Analogously to ζ, ζ^* has the property that if investment is infinitely costly, there is no induced technical change and $\lim_{g_I \to 0} \zeta^* = 0$.

Using (1), (4), and (6), together with the steady state condition $\dot{H} = 0$, we can express consumption as the following function of P and H,

$$\tilde{c}^*(P, H) \equiv y(e^{-1}(P), P, H) - \tilde{i}(H) = C. \tag{43}$$

The effect of investment on consumption in the long-run is then:

$$\tilde{c}^*_H = y_H - \tilde{i}_H = \frac{\rho y_H}{\rho - g_H} > 0, \tag{44}$$

where the inequality follows from (38). It is immediately apparent that here, in contrast to the static model, an increase in investment always increases consumption. The reason is that the costs of investment has to be borne before the full benefits of investment, which take time to accrue. Given the positive rate of discount, the planner finds it optimal to invest less than the level that would maximize the steady-state level of consumption, as a matter of dynamic efficiency. In this sense, discounting introduces yet another wedge between the costs and benefits of investment in the steady state, similarly to what happened in the static model with underinvestment. In this context, however, we observe 'underinvestment' only in as far as we experience a less than maximum level of consumption in the steady state.

As illustrated in Section 5, in equilibrium the effect of ITC on the stance of optimal environmental policy is determined by the combined shift of the steady-state marginal damage and marginal abatement cost curves. The effect of these combined shifts can be assessed by the effect of investment on the steady state *net* marginal benefits of environmental quality,

$n^* \equiv (\rho - e_N)^{-1}(u_N/u_C + y_N) - y_P$. Reducing n^* to a function of P and H only, one can write (37) as

$$\tilde{n}^*(P,H;\phi) \equiv \frac{1}{\rho - e_N(e^{-1}(P))}\left[\omega(\tilde{c}^*(P,H), e^{-1}(P);\phi) + y_N(e^{-1}(P),P,H)\right] + \\ - y_P(e^{-1}(P),P,H) = 0. \tag{45}$$

Computation of the partial derivative with respect to H yields:

$$\tilde{n}^*_H = \frac{1}{\rho - e_N}\left(\frac{\rho\omega_C y_H}{\rho - g_H} + y_{NH}\right) - y_{PH}. \tag{46}$$

Demand for environmental quality increases with investment because of the increased willingness to pay on the part of consumers it induces. It decreases, however, due to the opportunity cost of environmental policy, namely the reduction in innovation captured by the y_{PH} term. When technology is green, there is no conflict and H always induces more green demand. When technology is sufficiently brown, however, the demand for environmental quality may fall with H as environmental policy becomes too costly.

Similarly to the procedure in Section 5.2, totally differentiating (40) and (45), solving for dP and using (4) allows us to derive an expression for the change in the optimal level of environmental quality, following a marginal greening of preferences:

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \left(\frac{1}{-e_N}\right)\left(\frac{1}{\rho - e_N}\right)\frac{1}{\tilde{n}^*_P + \zeta^*\tilde{r}_P\tilde{n}^*_H}. \tag{47}$$

It is now easy to prove our final result.

Proposition 4. (Optimal environmental policy) *In the steady state of the dynamic model, ITC leads to a less stringent environmental policy, if and only if $\tilde{r}_P\tilde{n}^*_H > 0$, implying $\left(\frac{\rho\omega_C y_H}{\rho - g_H} + y_{HN}\right)\frac{1}{\rho - e_N} < y_{PH} < \frac{y_{HN}}{-e_N}$ or $\frac{y_{HN}}{-e_N} < y_{PH} < \left(\frac{\rho\omega_C y_H}{\rho - g_H} + y_{HN}\right)\frac{1}{\rho - e_N}$.*

Proof. According to (47), $\left.\frac{\mathrm{d}N}{\mathrm{d}\phi}\right|_{\zeta=0} > \left.\frac{\mathrm{d}N}{\mathrm{d}\phi}\right|_{\zeta>0} \Leftrightarrow \zeta^*\tilde{r}_P\tilde{n}^*_H > 0$. Substituting the expressions for $\tilde{r}_P$, and $\tilde{n}^*_H$, and solving the ensuing expressions returns the inequalities presented above. ☐

There are two scenarios in which ITC leads to less stringency. In both cases, a higher preference for environmental quality reduces pollution. In the first scenario, corresponding to the first pair of inequalities in the Proposition, this makes more investment attractive because of a strong TFP effect ($\tilde{r}_P < 0$). The ensuing higher level of investment reduces the demand for environmental quality because it is too costly to be green ($\tilde{n}^*_H < 0$). In the second scenario, which corresponds to the second pair of inequalities above, the lower pollution level reduces investment since pollution and investment are complements (and the TFP effect is small, such that $\tilde{r}_P > 0$). In this case, the lower level of investment lowers demand for environmental quality since it reduces the willingness to pay for environmental improvements ($\tilde{n}^*_H > 0$).

Finally, it is interesting to notice the role of discounting. It is easy to see that, as ρ tends to zero,[20] the ITC term in (47) collapses to $-\zeta^*\tilde{r}_P^2$, which is unambiguously negative. Hence, in the absence of discounting, ITC never reduces the level of environmental quality chosen at the optimum, i.e. it never makes a negative contribution to the cost of environmental policy.

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[20] Note that, formally, ρ can never be identically zero or the indefinite integral in (31) would not converge.

This is intuitive in this context. Indeed, a zero discount rate implies that it is optimal to maximize steady-state utility. The benefits from the investment in technology have the same present value whenever they accrue, and the steady-state consumption level is maximized (for given levels of pollution). As a result, changes in investment have no first-order effects on consumption, so that ITC cannot affect the marginal benefits of environmental policy through reducing the households' willingness to pay (u_N/u_C).[21]

7 Discussion and conclusion: of wedges and policy

It is commonly argued that technological change is good for the environment as it reduces the cost of achieving pollution reduction targets by making abatement cheaper. That this might not be the case, however, can be easily illustrated with simple examples. Consider, for example, a remote area of outstanding natural beauty that attracts tourists who pay tour-operators to arrange their trips. Tourism generates profits that depend on the level of environmental quality. If the area is designated as a natural park and protected, the level of environmental quality is likely to improve, at least initially. Increasing demand on the part of tourists leads to higher profits for the tourism industry. The higher productivity of the environment, however, makes it profitable for tour-operators to invest additional resources to improve facilites for guests, and accessibility to the park.[22] This is induced technological change in this context. Following the investment, however, the increased flow of tourists exerts additional pressure on the environment, and ends up reducing environmental quality below the level that would have prevailed without the induced innovation. A similar story can be told about climate change. Climate change reduces productivity, so mitigation efforts increase the rate of return to investment. As a consequence, successful climate change policy leads to more investment in production capacity and transportation, for example. As demand for (fossil) energy increases, the pollution reduction effects of climate policy are dampened, relative to a situation without ITC.

The examples above emphasize how ITC may turn out to be pollution-using, an idea that was already clear to William Jevons, who over 150 years ago wrote "*if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each.*"(Jevons, 1866, chpt.VII, par.7).[23] The existing consensus view on the role of ITC abstracts from this aspect and thus concludes that ITC necessarily reduces the cost of environmental policy (Goulder, 2004; Edenhofer et al., 2006; Stern, 2006; IPCC, 2007a; Acemoglu et al., 2012, for example). Our discussion in this paper recovers Jevons' intuition, and provides several new insights into the relationship between ITC and (the cost of) environmental policy that have important consequences for the design of environmental policy.

Our first result has been to show that ITC can increase the cost of environmental policy

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[21] This can be seen easily by totally differentiating the budget constraint and the steady-state condition for knowledge accumulation, $\dot{H} = 0$ to find $\mathrm{d}C = y_P \mathrm{d}P + y_N \mathrm{d}N + \frac{\rho y_H}{\rho - g_H} \mathrm{d}H$. When $\rho \to 0$, this reduces to $\mathrm{d}C = y_P \mathrm{d}P + y_N \mathrm{d}N$.

[22] You may think of using snowmobiles to improve winter access to Yellowstone National Park, as an example. See, `http://www.nps.gov/yell/planyourvisit/winteruse.htm`.

[23] Jevons's words did not refer to a policy-induced change in technology, but rather to an exogenous efficiency improvement – a modelling choice still common in the 'rebound effect' literature, see (Binswanger, 2001). In our discussion, however, we have shown that similar effects emerge when the change in technology is induced by policy.

when technological change is pollution-using, which implies that the marginal cost of pollution abatement increases following the introduction of new technology (Proposition 1). It is worth pointing out here that pollution-using technical change is far from a special case. Baker et al. (2008) discuss several cases of technological progress that leads to increases in the marginal costs of abatement, at least for relatively high abatement levels. Their climate-change related examples include several intermediate technologies,[24] such as increases in the efficiency of coal- and gas-fired electricity generators, carbon capture and sequestration (of less than 100% of emissions), and cost reduction of efficient gas-fired generators. In the transportation sector their list includes better and less expensive hybrid vehicles and bio-diesel. Bauman et al. (2008) present empirical evidence showing that fuel switching in response to increasing regulation led to an increase in marginal abatement costs for SO_2 in electricity generation in Korea between 1970 and 1998. Interestingly, all of these technological improvements form part of the portfolio of technological options usually discussed in connection to ITC. Our results here contrast sharply with those of other contributions in the literature (e.g. Goulder and Schneider, 1999; Goulder and Mathai, 2000; Sue Wing, 2006; Gerlagh, 2007), quite simply because such analyses abstract from the possibility of pollution saving technical change by assuming that technology is green, in which case ITC is necessarily pollution-saving.

Proposition 2 discusses the welfare costs of ITC under exogenous policy, analyzing both the case where a quantity instrument is used, and the case when a price instrument is favoured. In this part of the paper we emphasized the complex interactions existing between environmental externalities and technology spillovers. We show, for example, that the potential environmental benefits from crowding out brown technologies might be more than offset if investment is underprovided, as is the case when positive technological spillovers are not fully internalized. Our analysis transparently reveals the crucial role played by incompletely internalized external effects, and sheds additional light on differences across estimates of the value of ITC in CGE models. For example, Buonanno et al. (2003) neglect the role of market failures in R&D, and obtain larger estimates for the impact of ITC on the cost of environmental policy than Popp (2004), who explicitly recognizes the divergence between the social and the private returns to innovation.

Our third result focuses on the importance of general equilibrium effects in this debate. Proposition 3 emphasizes that ITC affects the consumers' marginal willingness to pay for environmental quality improvements. As the willingness to pay changes, so do the relative costliness of environmental policy and the equilibrium level of environmental quality. We show that shifts in both the MAC curve and the marginal damage curve are crucial to the final outcome, and that a negative role for ITC may emerge even when technological change is pollution-saving from the point of view of the representative firm. One key difference exists between our analysis and the existing literature. In our general equilibrium model, changes in investment affect income and consumption and hence, through shifting the demand for environmental quality, affect marginal damages. Most of the existing literature, however, frames this question in a partial equilibrium context, typically assuming that the marginal benefits from pollution reduction are (the present value of) the marginal pollution damages, that only depend on environmental magnitudes (pollution stock, environmental quality, etc.). In the context of our model, this would imply that marginal damages depend on N, but not H. By construction, then, ITC would not be able to affect environmental policy via changes in marginal damages, and the general equilibrium effects we find here are neglected. For example, both Goulder and Mathai (2000) and Heal and Tarui (2010) posit a social loss

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[24] Baker et al. (2008) define 'intermediate technologies' somewhat endogenously as "technologies that have lower emissions than Business-as-Usual technologies, but will be substituted away from in the case of very high abatement" [ibid.,p.2806].

function that is additively separable in abatement costs and damages, where the latter only depend on cumulative emissions. The sharp contrast between the unambiguously positive effect of ITC in partial equilibrium models, and our much more nuanced conclusions highlights the importance of considering general equilibrium effects when gauging the relevance of ITC for environmental policy.

Our last result in this paper takes our analysis within a dynamic framework. Having underlined the crucial role played by additional uncorrected externalities, i.e. the existence of 'wedges' between the private and the social valuation of different types of goods, we focus on a fully optimal dynamic general equilibrium model to make one last important point. Proposition 4 shows that within the fully-optimal dynamic model, the 'wedge' through which ITC affects the cost of environmental policy emerges due to the decision maker's positive rate of time preference. Discounting puts a higher weight on short-run costs relative to long-run benefits. ITC reduces the short-run costs of environmental policy if technology is green, but might increase them if technology is brown – either through reducing consumption or through magnifying the fall in the returns to investment. Hence, although ITC allows for additional opportunities to address environmental problems (i.e. through innovation), it not necessarily makes environmental policy more attractive.

Overall our analysis paints a rather different picture of the link between ITC and the cost of environmental policy from the one commonly found in the literature. We find that a less than flattering role can emerge for ITC when technology and pollution are complements and pollution reductions lead to increases in investment activity, or when additional distortions are present in the economy, that haven't been fully internalized, or, finally, when investment costs have to be faced ahead of the benefits accruing to the agents. Arguably, all these situations are far from uncommon, and represent a more realistic description of actual economies than the stylized static first-best models so common in this literature.

Our analysis has relevant policy implications since, far from being the *deus ex-machina* that enables the achievement of ambitious environmental targets, induced innovation might increase the cost of environmental regulation. Our research shows that a comprehensive approach to environmental problems – i.e. one which takes into account the productive impact of increases in environmental quality, the need to correct technology spillovers, and the type of technologies that are likely to emerge from the purposive activity of innovators – is needed to take full advantage of the potential benefits of ITC, and avoid the possible costs it entails.

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