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Optimal Timing of Climate Change Policy: Interaction Between Carbon Taxes and Innovation Externalities

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Abstract This paper addresses the impact of endogenous technology through research and development (R&D) on the timing of climate change policy. We develop a model with a stock pollutant (carbon dioxide) and abatement technological change through R&D, and we use the model to study the interaction between carbon taxes and innovation externalities. Our analysis shows that the timing of optimal emission reduction policy strongly depends on the set of policy instruments available. When climate-specific R&D targeting instruments are available, policy has to use these to step up early innovation. When these instruments are not available, policy has to steer innovation through creating demand for emission saving technologies. That is, carbon taxes should be high compared to the Pigouvian levels when the abatement industry is developing. Finally, we calibrate the model in order to explore the magnitude of the theoretical findings within the context of climate change policy.

Keywords Climate change · Environmental policy · Technological change · Research and development

JEL Classification H21 · O30 · Q42

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1 Introduction

In the coming decades radical policy interventions are necessary to bring a halt to the continuing increase in the atmospheric greenhouse gas concentrations when the aim is to prevent a potentially dangerous anthropogenic interference with the global climate system, see, e.g., [IPCC \(2007\)](#) and [Stern Review \(2007\)](#). Though most scientists agree on the need for some abatement in the coming decades, there is a debate on whether the major share of these efforts should be pursued from the beginning, or whether the largest share of abatement efforts should be delayed to the future. Three reasons stand out among advocates of delayed action. First, due to the discounting of future costs, saving our abatement efforts for the future will allow us to increase our efforts considerably at the same net present costs. Second, delaying emission reduction efforts will allow us to emit larger cumulative amounts of greenhouse gases, and thus to abate less in total, due to the natural depreciations of the atmospheric greenhouse gas concentrations. Third, delaying abatement efforts will allow us to benefit from cheaper abatement options that are available in the future, and also to develop these options through innovation. The first two arguments have taken firm root in the literature, thanks to—among others—the analysis by [Wigley et al. \(1996\)](#).¹ The third argument, however, based on presumed technological advancements in abatement options, has raised a lively debate among economists studying technological change in relation to climate change, and more generally, environmental policy.

There are arguments for accelerating abatement efforts rather than delaying them. Energy system analyses have clear empirical evidence for so-called experience curves suggesting that new low-carbon energy technologies, which will define the major long-term options for carbon dioxide emission reduction, need to accumulate experience for costs to come down sufficiently to make these technologies competitive.² Based on these experience curves, the more general argument is made that there is a need for up-front investment in abatement technologies to make them available at low prices, and thus, technological change would warrant early abatement action rather than a delay ([Ha-Duong et al. 1997](#); [Grübler and Messner 1998](#); [van der Zwaan et al. 2002](#); [Kverndokk and Rosendahl 2007](#)). Models exploring the experience curves are typically referred to as learning by doing (LbD) models.³ Many energy system models add another reason for a smooth transition towards clean energy supply, which is that diffusion of new technologies need the turnover of all existing vintages and therefore takes a considerable time ([Knapp 1999](#)). A too rapid switch of the capital stock towards an entirely new technology is considered unrealistic ([Gerlagh and van der Zwaan 2004](#); [Rivers and Jaccard 2006](#)).

Objections have been raised to these arguments. Though experience and diffusion curves have a strong empirical basis, many economists consider it a mechanistic view on technological development hiding the incentive-based structures that determine the level of research efforts by innovators. They prefer models with an explicit treatment of research and development (R&D) as the engine of innovation, and they have found that modelling innovations through R&D can lead to potentially very different outcomes on optimal timing of abatement policy. An important difference between LbD and R&D models is that the latter category of models does not assume from the outset that the technology needs to be used for its costs

¹ They used these arguments to make the case that emission paths developed by the [IPCC \(1995\)](#) for ceiling atmospheric carbon dioxide concentrations tended to put too much effort up-front, while a delayed abatement response would be more cost-efficient.

² See [Lieberman \(1984\)](#) for an early contribution focused on the chemical industry, and [Isoard and Soria \(2001\)](#) for a recent empirical analysis for energy technologies.

³ [Manne and Richels \(2004\)](#), however, find that LbD has almost no effect on the efficient timing of abatement.

to fall. Thus, through R&D, future cheap abatement options may be made available without the need to use these abatement options while costs are still high. In an R&D model, it is then most efficient to focus mainly on R&D in the early stages of abatement policy, without employing the technologies, and to apply them only after the costs have sufficiently come down. Indeed, [Goulder and Mathai \(2000\)](#) found this pattern as an optimal environmental policy and they concluded that whereas LbD may warrant an advance of using abatement technologies compared to a situation without technological change, the presence of R&D unambiguously implies a delay in the use of such technologies.

The first objective of this paper is to extend the discussion on the timing of abatement to include the timing of climate change instruments. That is, we will not only ask the question as to whether the possibility of R&D implies a delay or advance of abatement, but rather, we will ask whether optimal carbon taxes are ahead of or delayed with respect to Pigouvian taxes and whether research subsidies should be constant, decreasing or increasing over time. This is the first research question.

Second, we will extend the analysis of optimal climate change policy with R&D to a second-best context, i.e., when we have several imperfections, but insufficient policy instruments available to correct them all. Caution is needed when results—such as the delay in optimal abatement thanks to R&D—depend on first-best assumptions, since such a first-best innovation-abatement solution can be reached only when policy makers have a rich instrument set available. R&D market imperfections may be different for climate change specific technologies such as, say, energy saving innovation and non-carbon emitting energy sources, compared to other technologies. In that case, policy makers need to have an instrument available tailored to climate change-related R&D to bring emission reduction R&D efforts to their socially optimal level. However, while innovation subsidies certainly exist, it is hard for a government to commit to subsidise all new innovations that create positive spillovers, as well as to identify these spillovers, see, e.g., the discussion in [Kverndokk et al. \(2004\)](#). [Gerlagh et al. \(2008\)](#) also show that with a finite patent lifetime, optimal innovation policy depends on the stage of the environmental problem, which may also be uncertain to the policy makers. In the absence of such tailored climate-change R&D instruments, policy makers may use a common R&D instrument such as R&D subsidies over all sectors, and a generic climate change instrument such as carbon taxes or emission permit markets to target climate change goals. Since energy related R&D makes up only a small portion of economy-wide R&D expenditures, we consider it a natural assumption that R&D subsidies are exogenous to the climate change policy problem, and consequently, the policy maker has to rely on one instrument, say the carbon tax, to steer both abatement levels and climate change-specific R&D efforts. Since now the carbon tax affects both abatement efforts and innovation, the functioning of the innovation market within the energy sector, i.e., how the gap between private and social returns on R&D develops, becomes of crucial importance for determining the efficient level of the carbon tax. The second research question is thus how the optimal carbon tax should develop, relative to the Pigouvian tax, in a second-best setting.

For our study we develop an R&D model in line with the endogenous growth literature and assume that R&D efforts are based on market-based incentives through patents. Patents have different welfare implications. They give an incentive for innovation as they protect the holders from others directly using their innovation in production, but they also create a static inefficiency as patents allow monopolistic supply by the patent holder. A long patent lifetime increases the incentives for innovation but increases the static inefficiency.⁴ At the same time,

⁴ The optimal patent lifetime has been analysed in several papers such as [Judd \(1985\)](#), [Chou and Shy \(1993\)](#) and [Iwaisako and Futagami \(2003\)](#).

patents disclose the knowledge base underlying the innovation, which then can be used by rivals to develop substitute technologies. These properties can lead to intricate connections between R&D dynamics and climate change policy (cf. [Encaoua and Ulph 2004](#)), and we need to see how they alter the first-best timing results.

We expect that an R&D model may present similar results as the LbD models when we study innovation in a second-best R&D setting with finite lifetime of patents. Whereas in a first-best R&D model with an infinite patent lifetime, it is possible that innovators develop new technologies and continually improve these without them to be used in production, in a second-best R&D model with finite patent lifetime, innovations will only occur when they are used in production before the patent's expiration date. This mechanism is similar to the mechanism in LbD models, where technology only advances if it is used. Thus, the representation of finite lifetime of patents in an R&D model will lead to the required use of abatement technologies in earlier periods to guarantee that innovators can earn back the costs of R&D.

The argument above makes clear that a finite patent lifetime creates an appropriation problem for innovators who cannot fully capture the social value of their innovations in the long future. Many R&D models incorporate the idea that innovators cannot appropriate the full value of their innovations—[Nordhaus \(2002\)](#), [Popp \(2004\)](#) and [Gerlagh and Lise \(2005\)](#) make precise assumptions on this. But whereas in the broad innovation literature the finite lifetime of patents is a common reason for this feature (for an early contribution, see [Nordhaus 1969](#)), in the environmental economics literature, the time dimension of the appropriation problem is mostly neglected. If the appropriation gap would be a constant fraction of the social value (as assumed in these models), then a constant innovation subsidy would be sufficient to correct for this market failure. If, however, patents expire, innovations will be biased towards technologies that pay back within the patent's lifetime, while there is no incentive to develop and improve technologies whose value lies in the farther future. A generic R&D subsidy cannot correct for this timing dimension of the appropriation problem, and instead, a complementary climate policy may be required for its correction. We also refer to [Gerlagh et al. \(2008\)](#) where we use a related model to the one presented below, but in continuous time, and without research subsidies but with the lifetime of the patent endogenously determined.

This paper is organised in the following way. In Sect. 2 we develop a partial model for abatement, emissions and a greenhouse gas atmospheric stock. The model has discrete time steps, and technological change is driven by the [Romer \(1987\)](#) type of endogenous growth through increasing varieties, based on the 'love of variety' concept ([Dixit and Stiglitz 1977](#)).

We analyse optimal climate change policies in Sect. 3, starting with a first-best setting as in [Hartman and Kwon \(2005\)](#) and [Bramouille and Olson \(2005, cf Proposition 8\)](#). In the first best solution all policy instruments to correct for imperfections are available. Then we consider the second-best setting, where an R&D subsidy is not available, for which we analyse the development over time of efficient carbon taxes relative to Pigouvian taxes. In Sect. 4 we study the cost-effective policy, i.e., when there is a fixed restriction on the build up of the atmospheric concentration of greenhouse gases. As in [Hart \(2008\)](#) and [Greaker and Pade \(2008\)](#), our timing analysis specifically addresses transition paths where the abatement sector is small initially but rapidly increases in size, followed by a slower growth when the sector becomes mature. Different from [Goulder and Mathai \(2000\)](#), the timing analysis is not based on a comparison of multiple scenarios, e.g., one with and another one without endogenous technological change.⁵ Instead, we analyse the development over time of research subsidies and the gap between efficient carbon taxes and Pigouvian taxes in the first- and second-best

⁵ The comparison made by [Goulder and Mathai \(2000\)](#) is problematic in the sense that their ETC scenario assumes technological change in addition to the benchmark (no-ETC) scenario. The scenario with ETC, therefore, has a more optimistic path of falling abatement costs compared to the scenario without ETC. Thus, the

setting. The relative gap between the two taxes tells us something about the relative stringency of climate change policy compared to the social cost of pollution, and we are particularly interested in its development over time.

Our focus on the gap between efficient carbon and Pigouvian taxes puts our analysis in a broad strand of literature. Much of this literature focused on tax interaction effects (c.f. [Bovenberg and de Mooij 1994](#)) and it raised lively debates in policy circles when it explored the potential for so-called double dividends. In addition to tax interaction, reasons for a divergence between efficient carbon and Pigouvian taxes include trade effects ([Hoel 1996](#)), scale effects in production ([Liski 2002](#)), and, more recently, the processes underlying technological change. [Rosendahl \(2004\)](#) shows that in an LbD model, the carbon tax should be higher than a Pigouvian tax, with the largest gap for those countries and sectors that generate most of the learning. In a similar fashion, [Golombek and Hoel \(2005, Proposition 9\)](#) show that in a climate change treaty the optimal carbon price can exceed the Pigouvian level when abatement targets lead to innovation and international technology spillovers that are not internalised in domestic policies.⁶ Our paper studies the dynamics of this gap between efficient and Pigouvian carbon taxes, in relation to endogenous technological change.

Finally, in Sect. 5 we carry out some numerical calculations to further investigate the substance of the theoretical findings. Throughout the simulations, the model parameters are chosen to reflect the common climate change context. Sect. 6 concludes.

2 Model Set Up

We consider an economy where there are concerns for the environment due to stock pollution. The set up of the model is general, but the interpretation of the pollutant will be in terms of carbon dioxide emissions following from the combustion of fossil fuels. More generally, we assume a benchmark emission path and a demand for abatement of emissions because of environmental considerations.

2.1 The Abatement Sector

The model of research and development (R&D) is based on Romer's endogenous growth model ([Romer 1987, 1990](#); [Barro and Sala-i-Martin 1995](#)). The model has an infinite horizon with discrete time steps, $t = 1, \dots, \infty$. There is one representative abatement sector, which could either be interpreted as an alternative, emission-free resource sector (e.g., renewables) or as abatement of emissions (e.g., fossil fuels supplemented with carbon capturing and storage). There are H_t producers of abatement equipment at each point of time t , and an R&D sector producing new ideas or innovations. Technological progress takes the form of expansion in the number of abatement equipment varieties. The producers of the abatement equipment own patents and, therefore, receive monopoly profits. However, they have to buy the innovations from the R&D sector, where innovators are competitive and use research effort as an input. We assume that patents last for one period, and so innovations are public

Footnote 5 continued

comparison between the two scenarios is mainly driven by the difference in technology paths, and is largely independent of the source of technological change, be it endogenous or exogenous. Though our set up is not directly comparable with [Goulder and Mathai \(2000\)](#), our broader context is comparable as both study the timing of action.

⁶ The analysis by [Golombek and Hoel \(2005\)](#) is in a game-theoretic context, and the result depends on the instrument used to define the treaty (compare Proposition 9 and 10).

goods thereafter. Hence, there are positive spillovers to innovation from the previous-period stock of innovations (standing on shoulders). Also, we assume negative externalities from aggregate current research through fishing out of ideas. Thus, in this model there are three imperfections related to innovations; too little production of abatement equipment due to monopolistic competition, positive spillovers of the earlier period innovation stock on new innovations, and negative spillovers of total research effort on new innovations. Thus, the market outcome of innovations may exceed or fall short of the social optimal level.

Let E be emissions of the stock pollutant, Y is benchmark emissions without any climate change policies, while A is abatement. Thus, total emissions are as follows:⁷

$$E_t = Y_t - A_t \tag{1}$$

Production of abatement requires intermediate flow inputs Z_t , and the use of abatement equipment x_i for various varieties $i \in [0, H_t]$ where H_t is the number of equipment varieties. H_t can be interpreted as the state of knowledge.⁸

$$A_t = B Z_t^\alpha \left(\int_0^{H_t} x_{t,i}^\beta di \right)^\gamma, \tag{2}$$

B is a constant and $0 < \beta < 1, 0 < \alpha < 1, 0 < \gamma < 1$. Furthermore, we demand $\alpha + \beta\gamma \leq 1$, where a strict inequality implies that there is a fixed factor in production, e.g., due to site scarcity for renewables. The presence of a fixed factor implies that the value of output is strictly larger than the value of all variable inputs. In that case we can specify B as $B = cF^{1-\alpha-\beta\gamma}$, where F is the fixed factor and c is a constant, such that the total value of output is fully attributed to all inputs Z, x_i , and F .⁹

The different abatement equipments are neither direct substitutes nor direct complements to other specific equipments. That is, the marginal product of each abatement equipment is independent of the quantity of any particular equipment, but depends on the total input of all other equipment varieties together. Since all varieties have the same production costs and decreasing marginal product, in equilibrium the same quantity will be employed of each equipment. Thus, assuming that the equipment can be measured in a common physical unit, we can write $x_i = X/H$, where X is the aggregate input of abatement equipment. The production identity then becomes:

$$A_t = B Z_t^\alpha X_t^{\beta\gamma} H_t^{(1-\beta)\gamma}. \tag{3}$$

It is clear that while the abatement sector has (short-run) decreasing returns to scale for given technology H_t , $\alpha + \beta\gamma \leq 1$, there are possibly long-run increasing returns to scale when

⁷ The relation between emissions and benchmark emissions is specified as a linear function for convenience of notation. A more general function would give the same qualitative results. In the numerical simulations in Sect. 5, we use a CES aggregation.

⁸ Note that the productivity of abatement equipment does not diminish over time. This means that the benefit from a new innovation on abatement production is higher at the earlier stage of abatement as it contributes to the knowledge base for a longer period. This would be an argument for a longer lifetime of patents at the early stage of emission abatement, see Gerlagh et al. (2008). See also the discussion in Sect. 3 below on the optimal R&D subsidy.

⁹ We will see later that total expenditures on variable inputs for abatement make up a constant share $\alpha + \beta\gamma$ of the value of abatement.

$\alpha + \gamma > 1$, due to the endogenous nature of technology H_t .¹⁰ Now consider the case where abatement efforts have to increase over time continually to maintain a ceiling on the atmospheric stock of greenhouse gases jointly with an increasing overall economic activity. For $\alpha + \gamma < 1$, the abatement expenditures will have to increase more than proportionally with the abatement effort. For $\alpha + \gamma = 1$, the costs of abatement rise in proportion with abatement levels. For $\alpha + \gamma > 1$, the price of abatement decreases, and total expenditures increase less than the abatement effort.

Assume now that the public agent implements a carbon tax τ_t , or more generally an environmental policy that induces a market cost of emission, τ_t . From (1) we see that this translates into a market price for abatement A_t . The abatement producer’s optimisation problem is:

$$\text{Max } \tau_t A_t - Z_t - \int_0^{H_t} p_{t,i} x_{t,i} di, \tag{4}$$

subject to (2).

The price of Z is set to unity and the price of abatement equipment $x_{t,i}$ is equal to $p_{t,i}$. Thus, the abatement producer maximises the value of abatement minus the abatement costs.

The first order conditions of this maximisation problem determine the abatement producer’s demand for Z and x_i :

$$\begin{aligned} Z_t &= \alpha \tau_t A_t \tag{5} \\ x_{t,i} &= \left\{ \left[\gamma \beta \tau_t B Z_t^\alpha \left(\int_0^{H_t} x_{t,k}^\beta dk \right)^{\gamma-1} \right] / p_{t,i} \right\}^{1/1-\beta} \\ &= \left\{ \left[\gamma \beta \tau_t A_t \left(X_t^\beta H_t^{(1-\beta)} \right)^{-1} \right] / p_{t,i} \right\}^{1/1-\beta}. \tag{6} \end{aligned}$$

From (5) we see that the costs of Z should equal the share α of the production value, where α expresses the relative contribution of Z in production.

The demand for $x_{t,i}$ is given by (6). Alternatively, by rearranging (6) we can also express the demand for aggregated input of abatement equipment using $x_i = X/H$, and $p_{t,i} = p_t$:

$$p_t X_t = \beta \gamma \tau_t A_t. \tag{7}$$

Thus, the demand for abatement equipment is falling in the own price, but increasing in the carbon price.

2.2 Production of Abatement Equipment

The producers of abatement equipment own patents and therefore act as monopolists. Their costs of producing intermediates $x_{t,i}$ are set to unity, and they maximise profits (or the value of the patent), $\pi_{t,i}$, taking into account the falling demand curves for abatement equipment. For a patent valid for one period, we get the following maximisation problem:

$$\text{Max } \pi_{t,i} = x_{t,i} (p_{t,i} - 1), \tag{8}$$

¹⁰ An interesting case arises when $\gamma = 1 - \alpha$. There are decreasing returns to scale for a given technological level H_t , e.g., due to a fixed factor. This can be understood as the short-term feature of the model. At the same time, there are constant returns to scale for endogenous level of knowledge. The technology effect precisely balances the fixed factor effect.

subject to (6).

The first order condition from maximising (8) with respect to $p_{t,i}$ determines the price of the abatement equipment:

$$p_{t,i} = p = 1/\beta. \tag{9}$$

From (7) and (9) we find the market equilibrium for X :

$$X_t = \beta^2 \gamma \tau_t A_t. \tag{10}$$

As all varieties are identical ($x_i = X/H$), and prices are equal across varieties, see (9), the value of a patent is also equal for all innovations, i.e., $\pi_{t,i} = \pi_t$. Using this in addition to (8), (9), (10) and $x_i = X/H$, we find the value of all patents:

$$\pi_t H_t = (1 - \beta) \beta \gamma \tau_t A_t. \tag{11}$$

2.3 The Innovation Process

The producers of abatement equipment buy patents from innovators that operate in a competitive market.¹¹ Innovators develop new varieties according to the following production function:

$$h_{t,j} = r_{t,j} (H_{t-1}/R_t)^{1-\psi}, \tag{12}$$

where $r_{t,j}$ is the research effort of innovator j , $h_{t,j}$ is the number of varieties produced by this innovator, and we assume $0 < \psi < 1$. R_t denotes aggregated research efforts by all innovators.

As seen from the production function in (12), there is a positive externality through a spillover from the previous period knowledge stock through H_{t-1} , and a negative externality through fishing out of ideas, through current research R_t .¹² The former is typically referred to as ‘standing on the shoulders’. The latter mechanism captures the idea that when the number of researchers increases, more researchers will find the same new variety that is just on the frontier of current knowledge, but only one of the discoverers will be able to patent the new variety. Thus, for every researcher, the aggregate research effort enters negatively in his innovation production function. We also see that both externalities are higher the lower the value of ψ .

The innovators maximise profit with respect to research effort, where the price of the innovation equals the monopoly profit of equipment producers, or equivalently the value of the patent.

$$\text{Max } \pi_t h_{t,j} - r_{t,j}, \tag{13}$$

subject to (12).

¹¹ Alternatively we could assume that the innovators are producing the abatement equipments, such that they own the patents and get the monopoly rent. This would not change the arguments or conclusions of the analysis.

¹² Encaoua and Ulph (2004) distinguish between knowledge and technology information flows. *Knowledge flow* or knowledge diffusion is equal to ζH_{t-1} , which means that a fraction $0 < \zeta < 1$ of previous knowledge is public information at time t . The *technology flow* is the technology spillover according to which a technology can be imitated by others, such that a patent does not offer a perfect protection to its holder. In our model this would mean that χH_t will be private property of the patent holders, where $0 < \chi < 1$, while $(1 - \chi)H_t$ can be copied by others. In our model we assume that both ζ and χ are set to unity.

The price of research effort is set equal to one. First order conditions give that the unit cost of research (i.e., one) is equal to the value of the patent, π , multiplied by the productivity of r .

Due to the zero-profit condition, in equilibrium the value of all patents is equal to the value of all research effort:

$$\pi_t H_t = R_t. \tag{14}$$

Substitution of (14) in (11) and aggregation of (12) give the following two conditions for research effort and knowledge dynamics in the economy:

$$R_t = (1 - \beta) \beta \gamma \tau_t A_t \tag{15}$$

$$H_t = R_t^\psi H_{t-1}^{1-\psi}. \tag{16}$$

For any given carbon price policy path τ_t , the five equations (3), (5), (10), (15) and (16) define a market equilibrium through the variables A_t, Z_t, X_t, R_t, H_t .¹³

3 Efficient Policy Implementations

3.1 First-Best Policy

The social planner aims at minimising the present value of abatement costs plus the damage from the stock pollutant. This can for instance be interpreted as the damage from the concentration of carbon in the atmosphere, i.e., the carbon stock. The minimisation problem becomes (where $\delta < 1$ is the social discount factor):

$$\text{Min} \sum_1^\infty \delta^{t-1} [Z_t + R_t + X_t + D(S_t)], \tag{17}$$

subject to (1), (3), (16) and stock accumulation dynamics

$$S_t = (1 - \varepsilon) S_{t-1} + E_t. \tag{18}$$

The social abatement costs are the sum of the costs of Z, R and X , which all have unit cost equal to 1.

$D(S)$ is the damage cost function, where damage depends on the stock of emissions, S . We assume that $D(S_0) \geq 0, D'(S_t) > 0$ and $D''(S_t) > 0$, and that the stock depreciates by the rate $\varepsilon < 1$.

The first order conditions from this minimisation problem are:

$$Z_t = \alpha \theta_t A_t \tag{19}$$

$$X_t = \beta \gamma \theta_t A_t \tag{20}$$

$$R_t = \psi \eta_t H_t \tag{21}$$

$$\eta_t H_t = \delta (1 - \psi) \eta_{t+1} H_{t+1} + (1 - \beta) \gamma \theta_t A_t \tag{22}$$

$$\theta_t = D'(S_t) + \delta (1 - \varepsilon) \theta_{t+1}. \tag{23}$$

Note that $\theta_t - \lambda_t \geq 0$, where λ_t is the dual variable for Eq. 1, and, hence, the current value shadow price of emissions. θ_t is often referred to as the Pigouvian tax. Note also that

¹³ Strictly speaking, uniqueness of the equilibrium requires decreasing returns to scale within one period, that is, $\alpha + \beta \gamma + \psi \gamma (1 - \beta) < 1$.

θ_t is equal to the social price (or marginal value) of abatement in this model, as E_t and A_t are perfect substitutes, and since A_t has no effects on knowledge (as it would in an LbD model). $\eta_t \geq 0$ is the dual variable of Eq. 16 and, therefore, the current value shadow price of knowledge.

The first order conditions for Z and X defined by (19) and (20), are similar to the corresponding conditions for the market equilibrium given by (5) and (7), with the exception that market prices are replaced by the corresponding social prices.

As seen from (21), the value of research should equal the share ψ of the social value of knowledge. ψ expresses the relative contribution of R in producing knowledge. Eq. 22 shows that the shadow price of knowledge is in general positive, but equal to 0 if there is no abatement throughout the time horizon.

According to (23), the social cost of emissions at time t , θ_t , is the present value of the damages caused by one unit of emission emitted at time t . It follows from a comparison of (5) and (19) that in the first-best policy, θ_t is equal to the optimal emission tax τ_t at time t .

As there are three types of imperfections in the model; pollution, imperfect competition in the market for abatement equipment, and positive and negative externalities of research effort, we would need three policy instruments to implement the social optimum: an emission tax, τ_t , a subsidy on abatement equipment, $s_{x,t}$, and a subsidy/tax on research, $s_{r,t}$. We can then write the market conditions corresponding to (19), (20) and (21) as

$$Z_t = \alpha \tau_t A_t \tag{24}$$

$$(1 - s_{x,t}) p_t X_t = \beta \gamma \tau_t A_t \tag{25}$$

$$(1 - s_{r,t}) R_t = (p_t - 1) \beta \gamma \tau_t A_t / (1 - s_{x,t}) p_t. \tag{26}$$

First, Eq. 24 is equal to the market condition defined in (5). Second, replacing p_t in Eq. 7 with $(1 - s_{x,t}) p_t$, gives the demand for X_t expressed by (25). Finally, (26) is derived in the same way as Eq. 11 and 15, apart from that we use (25) instead of Eq. (10). The price innovators pay for r_t is now set to $(1 - s_{r,t})$ instead of unity.

Setting the carbon price equal to the Pigouvian tax, i.e., $\tau_t = \theta_t$, implements the optimal use of Z_t , see (19) and (24). To find the optimal subsidy rate on abatement equipment, $s_{x,t}$, we first replace θ_t for τ_t , which gives the following demand for X_t :

$$(1 - s_{x,t}) p_t X_t = \beta \gamma \theta_t A_t. \tag{27}$$

From (9) we know that $p = 1/\beta$. Thus, $s_{x,t} = 1 - \beta$ implements the optimal use of X , cf. (20). Finally, to find the optimal subsidy/tax on research, $s_{r,t}$, we insert $p = 1/\beta$ from (9), $\tau_t = \theta_t$ and $s_{x,t} = 1 - \beta$ in Eq. 26. The market outcome of R then changes to:

$$(1 - s_{r,t}) R_t = (1 - \beta) \gamma \theta_t A_t. \tag{28}$$

Inserting the first-best level of R from (21) gives after some calculation:

$$s_{r,t} = 1 - (1 - \beta) \gamma \theta_t A_t / \psi \eta_t H_t. \tag{29}$$

The optimal level of $s_{r,t}$ in Eq. 29 may be positive or negative. This is because research effort has both positive and negative external effects. The positive external effect is that current research contributes to future research, and this use of knowledge is not protected. The negative externality is the fishing out described below Eq. 12.

The development of the research subsidy/tax, $s_{r,t}$, will depend on the development of the ratio $\theta_t A_t / \eta_t H_t$, i.e., the social value of abatement relative to the social value of knowledge, see Eq. 29. From Eqs. 24–26 we see that the social value of abatement is proportional to the abatement expenditure (i.e., $Z_t + X_t + R_t$), as $\theta_t = \tau_t$. To see how this ratio develops over

time, it is useful to define the abatement expenditure growth factor as $\phi_t = \tau_{t+1} A_{t+1} / \tau_t A_t$. In a mature abatement sector, this growth factor is constant. For an infant industry, growth will exceed the matured growth level. When the sector is becoming mature, expenditure growth will gradually fall from its infant level to its mature level. We define the abatement sector to be *maturing* when $\phi_t \geq \phi_{t+1}$ for all $t \geq 0$. We can now answer the first research question: how does the possibility of technological improvement through R&D affect the timing of climate change instruments? The answer is that, where R&D may delay the abatement level as shown in [Goulder and Mathai \(2000\)](#), at the same time it requires the advance of the climate-change related research subsidies. That is, research subsidies will have to start at a high level and fall over time. Note that this is related to our assumption that the productivity of abatement equipment does not diminish over time. Thus, the benefit from a new innovation is higher at the earlier stage of emission abatement as it contributes to the knowledge base for a longer period. The following proposition answers our first research question.

Proposition 1 *Through a tax on emissions equal to the Pigouvian tax, $\tau_t = \theta_t$, a subsidy on abatement equipment equal to $s_{x,t} = 1 - \beta$, and a subsidy/tax on R&D effort equal to $s_{r,t} = 1 - (1 - \beta)\gamma\theta_t A_t / \psi \eta_t H_t$, the first best outcome can be implemented. For a maturing abatement sector, the efficient R&D subsidy/tax $s_{r,t}$ will fall over time.*

Proof The first part of the proposition has been shown above. To prove that the R&D subsidy will fall over time, we consider (29) and see that it suffices to prove that $\eta_t H_t / \tau_t A_t$ decreases over time. Notice that $\theta_t = \tau_t$. Writing out Eq. 22 for the entire horizon, we have

$$\eta_t H_t / \theta_t A_t = (1 - \beta)\gamma\{1 + \delta(1 - \psi)\phi_t + [\delta(1 - \psi)]^2 \phi_t \phi_{t+1} + \dots\}. \tag{30}$$

It is obvious that when ϕ_t is decreasing in t , then when we compare the equation for $\eta_t H_t / \theta_t A_t$ and $\eta_{t+1} H_{t+1} / \theta_{t+1} A_{t+1}$, in the latter equation, each of the terms on the right-hand side will be smaller, and thus, $\eta_{t+1} H_{t+1} / \theta_{t+1} A_{t+1} \leq \eta_t H_t / \theta_t A_t$. □

3.2 Second-Best Policy

Even if the social optimum in principle may be implemented using the appropriate number of policy instruments, it may be hard to target R&D at the firm level (as long as R&D effort is not completely undertaken in the public sector). For instance, R&D is not specified as a separate activity or sector in most national accounts. Consequently, it is difficult to use instruments such as a subsidy to producers of abatement equipment and a subsidy/tax on research effort. Based on this, we specify a second-best optimum, where the social planner has only one policy instrument available, namely the carbon price.

The second-best optimisation problem of the social planner is, therefore, the minimisation problem (17) subject to (1), (3), (16), and (18), but also subject to the market equilibrium for Z , R and X given by Eqs. 5, 10 and 15. The social planner now sets the value of τ_t that minimises social costs subject to the functioning of the atmospheric carbon stock, the technology stock, and the different markets.

We can solve this social optimisation problem by substitution. In combination with (5), Eqs. 10 and 15 give

$$X_t = (\beta^2 \gamma / \alpha) Z_t \tag{31}$$

$$R_t = ((1 - \beta) \beta \gamma / \alpha) Z_t. \tag{32}$$

Substitution of (31) and (32) in (17), (3), and (16) give

$$\text{Min} \sum_1^{\infty} \delta^{t-1} [wZ_t + D(S_t)], \tag{33}$$

subject to (1), (18), and

$$A_t = CZ_t^{\alpha+\beta\gamma} H_t^{(1-\beta)\gamma} \tag{34}$$

$$H_t = K Z_t^{\psi} H_{t-1}^{1-\psi}, \tag{35}$$

where $w = 1 + \beta\gamma/\alpha > 0$, $C = B(\beta^2\gamma/\alpha)^{\beta\gamma} > 0$ and $K = ((1 - \beta)\beta\gamma/\alpha)^{\psi} > 0$.

As before, let θ_t be the Pigouvian tax, so that $\lambda_t = -\theta_t \leq 0$ is the dual variable for Eq. 1. Let η_t be the dual variable for Eq. 35. The first order condition for Z_t and the optimal level of H_t are given by

$$wZ_t = (\alpha + \beta\gamma)\theta_t A_{t+\psi} \eta_t H_t \tag{36}$$

$$\eta_t H_t = \delta(1 - \psi)\eta_{t+1} H_{t+1} + (1 - \beta)\gamma\theta_t A_t. \tag{37}$$

In addition, Eq. 23 carries over from the first-best solution. While Eq. 37 is equal to the corresponding equation (22) in the first-best solution, the first order condition for Z is different due to the restrictions on the use of policy instruments (compare (36) with (19)).

From (5) and (36) and inserting for w , we derive

$$\tau_t/\theta_t = 1 + [\psi/(\alpha + \beta\gamma)] \eta_t H_t/\theta_t A_t \tag{38}$$

This formula calculates the efficient second-best carbon price relative to the Pigouvian tax on basis of the constant parameters $\alpha, \beta, \gamma, \psi$ and the ratio of the value of knowledge over the value of abatement, $\eta_t H_t/\theta_t A_t$. As we see from (38), $\tau_t/\theta_t > 1$, which means that the efficient carbon price will be higher than the Pigouvian tax. Notice that this result also holds when there are decreasing returns to scale, $\alpha + \gamma < 1$. The main mechanism leading to higher carbon taxes, compared to the Pigouvian level, is the monopolistic undersupply of abatement equipment.

Will τ_t/θ_t rise or fall over time? As seen from (38), this depends on the development in the ratio of the value of knowledge over the value of abatement, i.e., $\eta_t H_t/\theta_t A_t$. This means that the development in τ_t/θ_t follows a similar path as the development in the optimal subsidy/tax on research, see (29). Thus, without the possibility to target research effort, the difference between the efficient emission tax and the Pigouvian tax should mimic the development in the optimal research subsidy/tax. This answers the second research question. In the second best setting with constant R&D subsidies, the carbon tax should be accelerated compared to the Pigouvian tax.

Proposition 2 *In the second-best model, the efficient carbon price, τ_t , will always be higher than the Pigouvian tax, θ_t , as long as abatement is positive. For a maturing abatement sector, the relative difference between the efficient carbon price, τ_t , and the Pigouvian tax, θ_t , will fall over time.*

Proof From (5) and (36), we calculate a slight deviation from (38),

$$\theta_t/\tau_t = 1 - [\psi/(\alpha + \beta\gamma)] [\eta_t H_t/\tau_t A_t], \tag{39}$$

which is less than unity. It suffices to prove that $\eta_t H_t/\tau_t A_t$ decreases over time, which follows the same argument as the proof of Proposition 1. □

4 Cost Effective Policy

When pollutant damages $D(S)$ are highly uncertain, such as damages from global warming, an alternative policy might be to minimize the costs associated with a constraint on the build up of the pollutant, set by a ceiling, \bar{S} . Such a cost-effective policy is likely to induce a high growth in abatement expenditures before the ceiling is hit. The minimisation problem becomes:

$$\text{Min } \sum_1^{\infty} \delta^{t-1} [Z_t + R_t + X_t], \tag{40}$$

subject to (1), (3), (16), (18) and the stock restriction $S_t \leq \bar{S}$. We maintain the first order conditions (19), (20), (21), and (22), but (23) becomes

$$\theta_t = \delta (1 - \varepsilon) \theta_{t+1} + \mu_t, \tag{41}$$

where μ_t is the dual variable of the constraint $S_t \leq \bar{S}$. If the pollutant stock starts at very low level, $S_t \ll \bar{S}$, the social marginal costs θ_t grow at a factor $1/\delta(1 - \varepsilon)$. After the pollution stock ceiling is reached, the social marginal costs grow at a lower rate. Unless the initial knowledge stock is very high, this pattern for θ_t of a high growth rate followed by a levelling off (but not necessarily a continuous drop after the ceiling is reached) will result in a similar pattern for abatement levels A_t and knowledge levels H_t . The formal establishment of such a pattern is very tedious as the growth path for all variables depends on the initial knowledge stock. An obvious assumption would be to require that the economy starts at a balanced growth path, but one cannot assume such. For example, when the abatement sector has overall increasing returns to scale: $\alpha + \gamma > 1$, one can show that prices cannot go up on a balanced growth path with increasing abatement effort. Thus, the economy may not start at a balanced growth path, and we allow ourselves a relatively loose statement in the next proposition to describe the feature that abatement expenditures grow rapidly before the ceiling is hit, and grow less rapidly thereafter, but the growth rate of expenditures ϕ_t may not necessarily decrease monotonically.

Proposition 3 *Until the ceiling is reached, assume that the abatement sector is maturing and the growth in expenditures exceeds the growth at any time after the ceiling is reached. Then, in a first-best allocation, the cost-effective R&D subsidy/tax s_t will fall over time until the ceiling is reached. Similarly, in the second-best R&D model, the relative difference between the efficient carbon price, τ_t , and the Pigouvian tax, θ_t , will fall over time until the ceiling is reached.*

Proof The proof is very similar to that of Proposition 1. Let T be the time that the ceiling is reached, the assumption states that $\phi_t > \phi_v > \phi_w$ for all $t < v < T < w$. It is now easy to see that in Eq. 30, when we move from $t < T$ to $t + 1$, in each element at the RHS we replace ϕ_t by some ϕ_v or ϕ_w , and thus the RHS must drop. The same argument applies to the second-best model. □

The proposition generalizes Proposition 1 and 2, in the sense that it makes clear that in a cost-effective scenario, where initial knowledge is not too high, in the first phase of the climate change problem, before the ceiling is hit, the innovation externality is largest and requires correction through either research subsidy or higher carbon prices. The size of the correction decreases over time, at least until the ceiling is reached.

5 Simulations

In this section we want to supplement the theoretical findings by developing and simulating a numerical model that mimics a transition from a fossil fuel based to a carbon free energy system. The speed of transition is determined by technological progress, driven by policies and market forces. In particular, the numerical model gives insight into the magnitude and development over time of the relationship between the optimal carbon price and the Pigouvian tax in a situation where it is not possible to specifically subsidize abatement cost reducing research.

5.1 Calibration

We set out to calibrate a model that reproduces key characteristics of the climate change debate in a stylised manner. The model is consistent with the theoretical model set up in Sect. 2, except for Eq. 1. In the analytical model, it was assumed that abatement is a purely additional activity, decreasing emissions one-to-one. The assumption in the analytical model is convenient and common practice in theoretic models, but in the context of climate change policy, abatement may better be treated as the substitution of non-carbon energy sources for fossil fuels, and rather than assuming perfect substitution between the two, we assume a CES-aggregate of energy production.¹⁴ Equation 1 is thus replaced by:

$$Y = \left(E^{(\sigma-1)/\sigma} + A^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)}. \quad (42)$$

Y_t is here (exogenous) benchmark use of energy, not emissions as in Eq. 1. This CES-aggregate means that CO₂-free energy is an imperfect substitute to fossil fuels, so that the prices of fossil and CO₂-free energy may differ. Still, we assume that both E and A are measured in the same units. In energy system analysis, this would typically be in primary energy equivalents (EJ), but for convenience of our presentation, we present energy in Gigaton carbon equivalents, using the average carbon content of fossil fuels for conversion. An implication of the CES aggregation of energy is that we now also need to add the costs of the fossil fuel energy supply to the cost-minimization program (17), which becomes

$$\text{Min} \sum_1^{\infty} \delta^{t-1} [Z_t + R_t + X_t + D(S_t) + q_t E_t], \quad (43)$$

where q_t is the unit cost of fossil fuel energy.

In order to calibrate the model, we assume that the economy moves from one steady state in the base year 2000 to a new steady state in 2250. Furthermore, we put forward the following calibration requirements for the business as usual (BaU) scenario:

- (i) Fossil fuel production costs (i.e., the price of E) grow (exogenously) from €200 per ton carbon in 2000 to €600 in 2250. €200 per ton carbon corresponds approximately to the average international market price of fossil fuels in 2004 and 2005 (BP 2006). The rising unit costs over time reflect the exhaustion of easy-to-recover reserves.
- (ii) Global emissions of CO₂ (i.e., fossil fuel production) in the base year 2000 (E_0) are 6 Gigatons carbon per year.

¹⁴ For an elaborate discussion on this parameter, see Gerlagh and van der Zwaan (2004, pp. 45, 56). Note that with $\sigma = \infty$, Eq. 42 reduces to Eq. 1.

- (iii) CO₂-free energy amounts to 0.5% of fossil energy in the base year (A_0). This is the share of commercial non-hydro, non-bio renewables in global energy supply (see [IEA 2005](#)). Moreover, the annual growth in CO₂-free energy in 2000 is set to 4.5%, which is consistent with actual growth rates in the 1990's for those renewables (cf. [IEA 2002](#), p. 27).
- (iv) CO₂-free energy constitutes 50% of total energy use in 2250 in the BaU scenario.
- (v) In the BaU scenario, the marginal damages of CO₂ emissions (the equivalent of the Pigouvian tax on CO₂ emissions if it were levied) in 2000 are €100 per ton carbon, or €28 per ton CO₂. As a comparison, the price of allowances in the EU's Emission Trading Scheme has hovered between €20 and €30 per ton CO₂ since the start of Phase II in 2008. On the other hand, the [Stern Review \(2007\)](#) suggests that the *present* social cost of carbon is around \$85 per ton CO₂, if the world continues on the BaU path, and \$25–30 if the concentration of CO₂-equivalents stabilises between 450–550 ppm CO₂e (the future stock of carbon affects the present social cost of carbon because current emissions of CO₂ stay in the atmosphere for many decades).

In addition to the calibration requirements, the following assumptions are made. The length of the simulation periods, and thus the lifetime of patents, is set to ten years.¹⁵ Future costs and benefits are discounted at a rate of 5% per year, setting $\delta = 0.61$. This is a compromise between typical market rates and social discount rates used in e.g. [Stern Review \(2007\)](#). Concentration of CO₂ in the atmosphere above the pre-industrial level decays by 1% annually (i.e., 10% per period).¹⁶ The substitution parameter σ between E and A is set to 2, which implies that the price of A is 14 times higher than the price of E initially. The long-term returns to scale in CO₂-free energy ($\alpha + \gamma$) is 1.2. This assumption is loosely based on evidence from learning curves, which show increased output levels followed by decreasing costs for many alternative energy sources.

The exogenous variable q_t is determined by (i). Energy use Y_t in the first period is determined by (ii) and (iii). Its future path is based on the assumption that per capita energy use grows by 1% per year, whereas population grows by 1.2% initially, but levels off at around 11 billion people during the first century. Damage costs are a quadratic function of the stock of concentration (i.e., $D(S_t) = D_t \cdot S_t^2$). In addition, marginal damage costs grow linearly with population and with economic growth per capita (for which we take 2 per cent per year). These assumptions, together with (v) enable us to calculate the path for D_t . The assumptions about growth in population, economy and energy use seem to be in between the A1 and the A2 scenarios put forward by the IPCC's Special Report on Emission Scenarios ([IPCC 2000](#)).

Based on the other calibration requirements and assumptions above, we can calibrate the remaining model parameters α , γ and ψ as listed below in Table 1. The value of β is picked.

5.2 Scenarios

We run four alternative scenarios, see Table 2. All scenarios have the same stock levels in 2000, and climate change policy is introduced in 2010 in all scenarios except S_0 (the BaU scenario). S_1 and S_2 denote the first- and second-best policy scenarios, whereas S_3 denotes the cost-effective scenario outlined in Sect. 4. However, instead of assuming a concentration

¹⁵ Ten years may seem a bit short for the lifetime of patents, as patent length in the US is 17 years and in Europe 20 years. Note, however, that the main results regarding the ratio of efficient tax over Pigouvian tax (cf. Fig. 6) are quite similar when we e.g. double the length of the simulation periods.

¹⁶ This is of course a simplification of the carbon cycle, i.e., the interaction between CO₂ in the atmosphere and CO₂ in the land and in the ocean (see e.g. [IPCC 2007](#), Chap. 7.3). In particular, it may overestimate the decay of CO₂ when the concentration level gets higher.

Table 1 Calibrated and chosen parameters in the simulation model

Calibrated parameters		Chosen parameters	
α	0.69	β	0.30
γ	0.51	δ	0.61
ψ	0.14	ε	0.1
		σ	2

Table 2 Model scenarios

Scenarios	
S0	Business as Usual (BaU)
S1	First-best
S2	Second-best
S3	Cost-effective with same damage as in S2

ceiling, we apply the following constraint:

$$\sum_0^{\infty} \delta^t D(S_t) \leq \sum_0^{\infty} \delta^t D(S_t^*), \tag{44}$$

where S_t^* is the concentration level in the S2 solution. The purpose of introducing this scenario is to examine the timing of abatement within a first- and second-best model, where the discounted climate change damage costs are equal. That is, S3 is delivering the least cost emission trajectory with the same discounted damage costs as S2.

5.3 Numerical Results

Figure 1 shows the development of fossil (E_t) and CO₂-free (A_t) energy over the next two centuries, measured in Gigaton carbon per year (on a logarithmic scale) in the business as usual and the second-best policy. We only show policy scenario S2, as the policy scenarios S1, S2, and S3 almost coincide when using the logarithmic scale of Fig. 1. In the policy scenarios, we see from Fig. 1 that fossil energy reaches a top in the middle of this century,

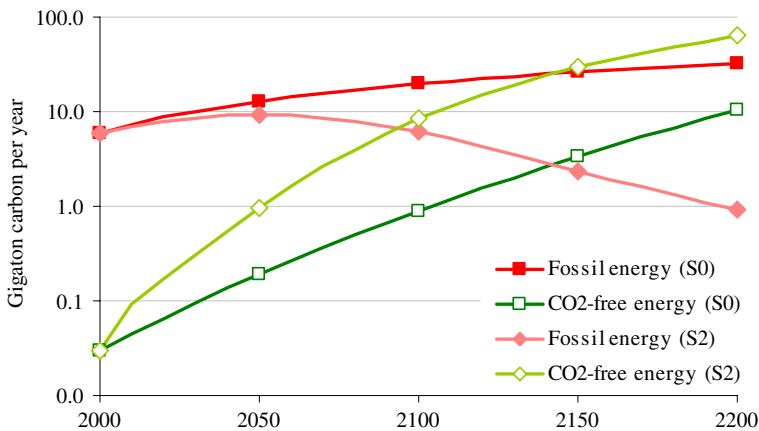


Fig. 1 Fossil and CO₂-free energy in the S0 and S2 scenarios

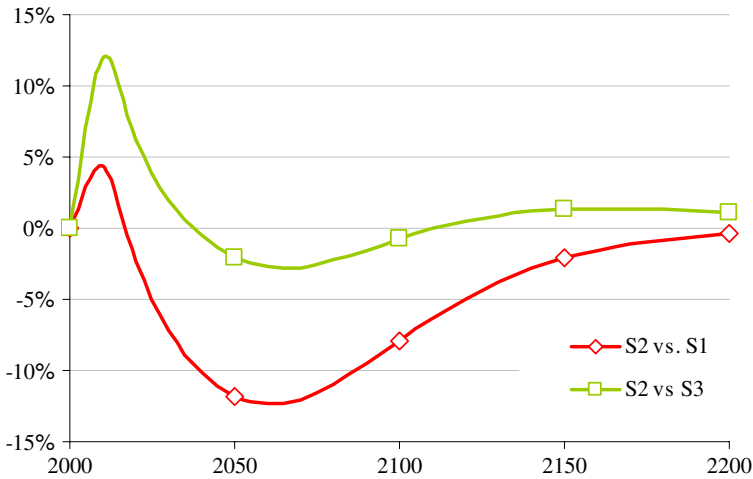


Fig. 2 CO₂ free energy in second-best versus first-best

and falls below CO₂-free energy just before 2100. Comparing the second-best scenario *S2* with *S1* and *S3* (see Fig. 2), we can see the implications of policy having abatement research subsidies available, or not. In general, the absence of a policy instrument raises the social costs of abatement, and thus lowers the aggregate abatement level (*S2* vs. *S1*). But, when there are no abatement research subsidies, efficient carbon taxes will be higher. Therefore, in the first periods when the level of technology is still similar in both scenarios, abatement levels are higher in the second-best policy scenario. The effect is more pronounced when we compare *S2* with *S3*. Making this comparison, the net present value of damages are the same, and the only difference between the scenarios is due to the timing of abatement. We thus see that the second-best policy scenario starts with high carbon taxes and consequently, with high abatement levels. The other way around, with all policy instruments available (*S3* vs. *S2*, the negative of the upper curve), R&D is shifted upfront, whereas abatement is delayed.

The timing issue is also visible in Fig. 3, which shows the annual growth rate in CO₂-free energy expenditures (i.e., growth in $Z_t + X_t$). We notice that in all scenarios the growth rate falls, that is, the abatement sector is maturing as defined above Proposition 1. The transition from an infant industry into a matured industry is most pronounced in the policy scenarios. Obviously, climate change policy increases abatement growth substantially over the first century, but eventually, the CO₂-free energy sector matures around the middle of the next century, as it takes over the energy market almost completely. From that time onwards, CO₂-free energy expenditures grow at the same rate as total energy use, i.e., by 1% per year. We further notice that growth rates in the scenarios *S1* and *S3* virtually coincide (in the figure, the *S1* curve is hidden behind the *S3* curve). When comparing these scenarios with the second-best scenario (*S2*), we find that expenditures grow slightly faster in the former scenarios throughout the simulation period (the *level* of expenditures starts at a higher level in *S2* though).

Although we apply only a simple one-box resource model, still it can produce qualitative insights in the concentration level of CO₂ in the atmosphere (S_t). The concentration peaks around 2100 in the policy scenarios at a stock level equivalent to about 475 ppmv (Fig. 4). Under the first-best policy, *S1*, more action is taken and thus the concentration level peaks

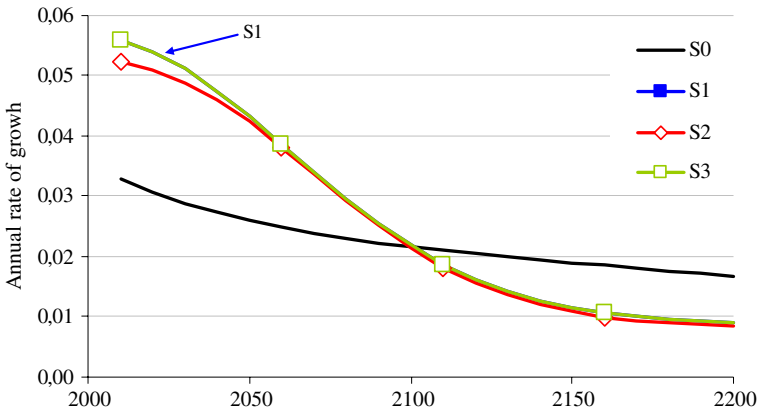


Fig. 3 Growth in CO₂-free energy expenditures in the different scenarios. The arrow points to scenario S1 that is behind scenario S3

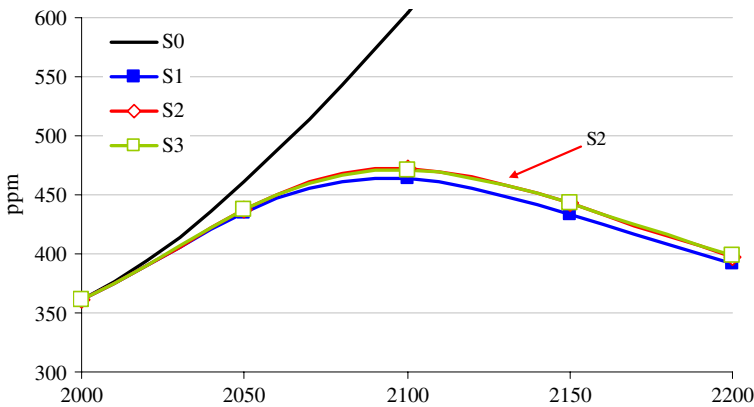


Fig. 4 Concentration level of CO₂ in the different scenarios. The arrow points to scenario S2 that is behind scenario S3.

at a slightly lower level than with a second-best policy S2. The two scenarios with equal net present value of damages, S2 and S3, are very similar.

In Figs. 5 and 6 we show how the Pigouvian tax (θ_t) and the efficient tax (τ_t) develop in the three policy scenarios. In the first-best scenario (S1), these two taxes are equal (cf. Proposition 1). In the second-best scenario (S2) they are generally not (cf. Eq.38), and in our numerical simulations the efficient tax is well above the Pigouvian tax, almost 100% in 2010, while the relative gap falls monotonically to about 20% in 2100 (Fig. 6, “S2 (Eff. versus Pig. tax)”). The lack of policy instruments to directly target R&D has thus very significant effects on the (second-best) tax level. This confirms Proposition 2, which states that the relative difference between the efficient and the Pigouvian tax will fall over time in the case with a maturing abatement sector (see Fig. 3).

The figures further show that the Pigouvian tax is higher in the second-best scenario (S2) than in the first-best scenario (S1), which reflects the higher CO₂ concentration level, and thus higher marginal climate change damages, in this scenario. Consequently, in the cost-effective scenario (S3), the efficient tax lies about 14% below the Pigouvian tax, as less

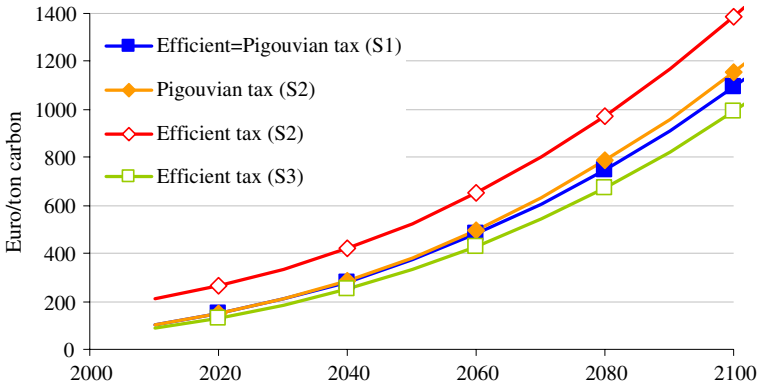


Fig. 5 Efficient tax and Pigouvian tax in the different scenarios

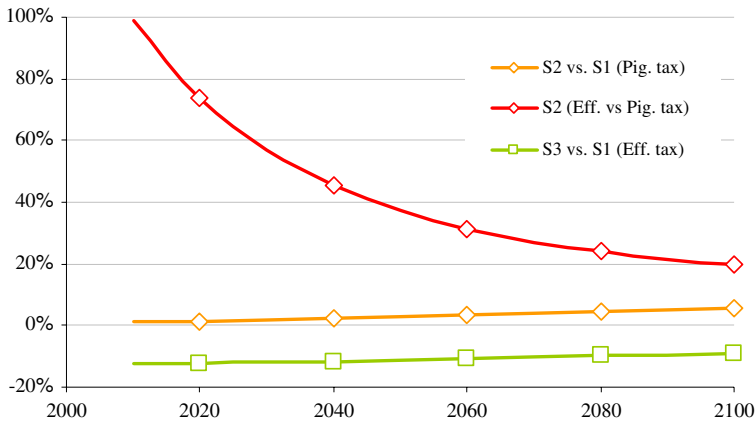


Fig. 6 Tax differences

abatement is required compared to the first-best (*S1*) (cost-benefit) scenario. Note that in the cost-effective scenario (*S3*), abatement levels are less than optimal (given the climate change damage function), as the objective is to minimise abatement costs for a fixed present value of future climate change damages (based on *S2*).

6 Conclusion

In the climate change literature a pressing question is whether currently it is sufficient to stimulate the development of clean technologies for future use (technology push), or alternatively, that we need to start emission abatement sooner rather than later. Some take the technology push perspective even one step further, and assume that the foresight of a future need for abatement is sufficient to lead private firms to develop clean technologies. Within this optimistic perspective, it is unwarranted to start with abatement activities too hastily, as these early abatement efforts are unnecessarily costly compared to the cheaper options that will become available in the future. In the literature on technology development and climate change, the proponents of delayed and early action have often been divided along the lines

of users of R&D models versus users of LbD models. This divergence in perspective arising from the two types of models may be overcome. First, the empirical literature suggests that both R&D and learning by doing play their own role in bringing down the costs of abatement (Söderholm and Klaassen 2007; Söderholm and Sundqvist 2006). Second, we find in an analytical framework that also in a pure R&D model, one can find reasons for upfront or delayed abatement efforts, but the difference in results is now based on the availability of policy instruments.

If the public authority can directly steer the development of energy-related technology, either through public energy-related R&D or through targeted private R&D, then it is efficient to spend much of the initial effort on this technological development. In both cases it is to be noted that in the phase of the emerging climate change problem, substantial public funds are to be directed to developing emission reducing technologies, either through public R&D or through high subsidies on private R&D (Proposition 1).

However, if the public authority cannot directly determine the development of an emission reducing technology, then efficiency considerations suggest that the clean technology should be extra stimulated through an increased demand for its produced goods. The technology pull policy should be relatively strong during the emerging phase of the climate change problem, when the abatement technologies still have to mature. The major feature responsible for this result is an assumed finite lifetime of patents. The numerical simulations suggest that this may translate into a significantly higher tax on CO₂ than in a first-best scenario.

As a final comment, we notice that the theoretical analysis we carried out has been fairly general, so that our findings may imply more generally that infant industries should be stimulated to a larger degree than mature industries. This topic may be worked out in future research.

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