Optimal commitment under uncertainty: adjustment rules for climate policy

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Abstract

This paper analyses the optimal type and degree of commitment to a future climate policy when damage costs from climate change are uncertain. Taking uncertainty into account, it is shown within the framework of a sequential game between firms and a regulator that commitment to an emission abatement target fails to achieve the first best optimal outcome. Though commitment to a future policy reduces the risk of time-inconsistency, it imposes costs in the form of reduced flexibility to respond to new information. If, however, the regulator commits to an adjustment rule that sets the abatement level contingent on the realization of the uncertain parameter, the first best optimal outcome can be obtained.

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1 Introduction

Emissions of greenhouse gases contribute to climate change. Regulators, by putting a price on such emissions, can encourage firms to invest in the development and deployment of technologies that reduce emissions and thereby climate change. Firms may, however, doubt the stability of that policy over time if the regulator is perceived to have an *ex-post* incentive to renege on a policy that was optimal *ex-ante*; a phenomenon known as 'time-inconsistency' (Kydland and Prescott 1977, Helm et al. 2003). A lack of confidence in the future stability of a policy reduces the effectiveness of that policy today. The perceived risk of policy change increases the cost of achieving any given level of emissions abatement.

The question of how to make climate policy more stable and credible figures prominently in discussions surrounding the reform of the EU emission trading scheme (EU ETS) (Grosjean et al., submitted). Following the sharp drop of prices for emission permits from about 30 Euros in January 2008 to less than 5 Euros in December 2013 several adjustments have been proposed such as reducing the number of emission permits and other interventions (European Commission 2012). All proposals imply a trade-off, often unmentioned and unresolved, that is fundamental for the design of long-term policies: while on the one hand policy makers aim to establish credible carbon price signals to investors and innovators, they also seek flexibility in order to be able to react to unforeseen developments in the market, politics, and science (Brunner et al. 2012).

One important source of uncertainty that policy makers seek to address in climate policy concerns the cost of climate change which is a composite of many uncertain parameters including climate sensitivity, regional impacts, and economic growth. Consider for instance climate sensitivity: a doubling of the concentration of greenhouse gases in the atmosphere would likely increase the global mean surface temperature between 1.5°C and 4°C according to the Intergovernmental Panel on Climate Change (IPCC 2013). This range is fairly broad and newer evidence suggests that it is too low (Shiogama and Ogura 2014). Uncertainty over climate sensitivity is amplified by uncertainties on how a changing climate translates into actual impacts (such as draughts, sea-level rise or tropical storms) and lack of knowledge how societies can adapt to them (Malik and Smith 2012). For this reason, new knowledge on any of the above and other parameters could in the future make it desirable to opt for either more or less stringent emission reduction targets than what seems optimal from the current perspective. How can the trade-off between flexibility and commitment in climate policy be mitigated? The central insight conveyed by our analysis is that policy makers can reconcile this trade-off by committing to a transparent rule that allows readjusting the abatement target conditional on new information.

The remainder of this paper proceeds as follows: Section 2 sketches the theoretical background behind time-inconsisteny in climate policy. Section 3 presents a deterministic Stackelberg game to demonstrate how (i) time-inconsistency emerges if firms move first, and (ii) the social optimum can be obtained if the regulator can commit to a certain policy level. We then introduce a term into the regulator's objective function that punishes deviations from announced policies to generalize the polar cases of full commitment and no commitment and include settings with intermediate commitment. Section 4 derives the optimal level of commitment under uncertainty and shows that the first best outcome can only be achieved if the regulator commits to an adjustment rule that sets the abatement level contingent on the realization of climate change damage costs. Section 5 discusses policy design options of commitment devices and adjustment rules. Section 6 concludes.

2 Motivation and theoretical background

It is well recognized in the literature that in a dynamic setting, multiple objectives of which not all are directly addressed by specific policy instruments can give rise to time-inconsistency (Helm et al. 2003). For example, when designing and implementing climate policies, policy makers also tend to take into account industry competitiveness, effects on tax revenues, and distributional issues. Changes in these dimensions can make it desirable to deviate from previously announced emission reduction targets. For instance, Canada's withdrawal from the Kyoto protocol in 2011, and Japan's recent refusal to participate in its extension beyond the commitment period that ended in 2012 point to important incentives to deviate from previously announced targets though there is no consensus on the exact reasoning behind these government decisions. The same can be stated for the case of Australia, for which the new government appointed in mid-2013 announced a repeal of the carbon-tax introduced by its predecessor in 2012 (Guardian 2013).

In the context of climate policy, it has frequently been observed that the development and adoption of innovative low-carbon technologies by the private sector may be impeded by time-inconsistency: in order to provide incentives for firms to undertake irreversible investments in R&D, the regulator has to guarantee a relatively high future carbon price (Miliman and Prince 1989, Nordhaus 2011). Once these investments are undertaken, however, the socially optimal *ex post* carbon price set by the regulator is too low for firms to recoup their investment (Kennedy and Laplante 2000; Requate and Unold 2003; Montgomery and Smith 2005). As firms anticipate this policy change, the regulator's guarantee is not credible and under-investment results.

Previous literature has pointed out that a regulator's best response to the problem of time-inconsistency is to credibly commit to the *ex-ante* optimal policy level (e.g. Biglaiser et al. 1995; Gersbach and Glazer 1999; Helm et al. 2004). This literature tends to assume a deterministic settings in which there is no uncertainty over modelled parameters. In these settings, the regulator typically pursues two policy targets – the firm's technology choice and abatement effort – with a single policy instrument. With credible commitment to the ex-ante optimal policy level, firms' incentives to influence the regulator's *ex-post* choice are removed and the first best outcome is achieved (Kennedy and Laplante 2000; Ulph and Ulph 2013). Obtaining the first-best outcome rests on the assumption that no market failures or behavioral barriers other than the emissions externality exist (Staub-Kaminski et al., forthcoming) or, if they do exist, they get addressed by optimal policy instruments (e.g. R&D subsidies to internalize technology spill-overs, see Jaffe et al. 2005).

Previous literature has also looked at how the type of policy instrument can matter for optimality in settings of time-inconsistency. As has been pointed out by Ulph and Ulph (2013), the first-best optimal outcome can be obtained with committing to a quantity target but not with commitment to a certain tax level. With a carbon tax, the regulator would instead need to commit to implement the tax that achieves the ex ante optimal emission level (without responding to firms' actions), which translates in a menu of tax levels contingent on firms' investment behavior. For the purpose of this paper, we analyze the case in which the regulator commits to a certain level of emission abatement. This could be achieved either via a quantity instrument, or a menu of conditional carbon taxes as in Ulph and Ulph (2013). We show that if one acknowledges the presence of uncertainty regarding the costs of climate change damages, full commitment to an abatement target – identified as optimal in a deterministic setting – leads to suboptimal outcomes. As uncertainty is pervasive in climate change policy decisions (Kunreuther et al. 2013), devising a mechanism that combines credible incentives with policy flexibility may prove useful.

By expanding the stylized dichotomy between 'full commitment' and 'no commitment' frequently adopted in the literature, we show that in a setting in which the regulator commits to a policy level, an intermediate degree of commitment is optimal under uncertainty (as it is then desirable to retain some policy flexibility in order to respond to new information). We then demonstrate that if the resolution of uncertainty can be observed *ex-post* and the regulator can commit to a state-contingent rule that determines the amount of emission abatement as a function of climate change damage costs the first best outcome can be obtained.

In this paper we employ a Stackelberg framework, in which the regulator first announces its emission target and then firms decide on investment and abatement once uncertainty is resolved. This modeling framework captures some essential features of real-world issues. First, in order to send credible signals to the private sector, policy makers announce long-term abatement targets which are only altered on rare occasions. Second, uncertainty is – at least partially – resolved by new information that becomes available only after the policy target has been set. Third, firms decide on their investments based on expectations on the future policy enacted by the regulator. We use benefits of climate change mitigation – which to date is one of the most important unknowns regarding the formulation of climate policies – as an illustration of an uncertain parameter.

3 Full, no, and intermediate commitment in a deterministic setting

One example for time-inconsistency is when a regulator announces a future climate policy *ex ante* but faces an incentive to change the policy after the regulated entities have taken their investment decisions. Consider a regulator who decides about the aggregate level of emissions abatement e (the climate policy) to be provided by firms that can lower their abatement costs by investing in technology t at R&D costs $\vartheta(t)$, with $\vartheta_t(t) > 0$.[1] Let $b(e)$ and $c(e,t)$ denote the (social) benefits and (firms') costs of *e*, respectively, with $b_e(e) > 0$, $c_e(e,t) > 0$, and $c_t(e,t) < 0$. For an interior solution, we also assume $b_{ee}(e) \leq 0$, $c_{ee}(e,t) \geq 0$, $c_{et}(e,t) \leq 0$. Throughout this paper, we assume that all parameters determining the firms' as well as the regulator's decisions are public knowledge[2].

The first-best optimal solution is obtained maximizing the following social welfare function:

$$W = b(e) - c(e,t) - \vartheta(t) \tag{1}$$

Calculating the derivatives yields the following first-order conditions for the optimal values of *e* and *t*:

(i) $b_e(e^{opt}) = c_e(e^{opt}, t^{opt})$, and (2)

(ii) $c_t(e^{opt}, t^{opt}) + \vartheta_t(t^{opt}) = 0$. (3)

Let us consider a three stage game à la Stackelberg. First, the regulator announces its abatement target *e*. Second, firms invest in emission saving technologies. In the final stage of the game, the regulator implements a policy to achieve the socially optimal level of abatement *e*. This formulation captures essential properties of long-term climate policy.

<u>Lemma 1</u>: *If the regulator can commit to e, the socially optimal outcome can be obtained.*

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[1] Subscripts denote partial derivatives.

[2] There exists a gap in the literature because the problem of time-inconsistency under asymmetric information has – with the notable exception of Boyer and Laffont (1999) – hitherto not been analyzed.

<u>Proof</u>: In the decentralized solution, firms choose their level of technology *t* to minimize their total costs $c(e,t)+\theta(t)$. If the regulator is able to commit to its choice of *e*, it opts for e^{opt} in the final stage, firms choose technology t^{opt}, and the optimal outcome is obtained. □

<u>*Lemma 2*</u>*: If the regulator is unable to commit to the announced level of* e*, the firms choose technology level* t *which is below the social optimum as compared to the case with credible commitment. The same holds for the regulator's choice of* e.

<u>Proof</u>: If the commitment is not credible, firms anticipate the regulator's reaction when deciding their level of technology. In this case, the regulator's first-order condition in the final and decisive period, taking the firms choice of technology t^f as given, becomes:

$$b_e(e^{reg}) = c_e(e^{reg}, t^f). \tag{4}$$

This condition implicitly defines the regulator's reaction function to firms' choice of technology. It can easily be verified that $\frac{de^{reg}}{dt^f} > 0$, i.e. the regulator responds to firms' choice of a lower level of technology by adopting a less ambitious emissions abatement target. The firms' technology choice is determined by their cost minimization problem, taking into account the regulator's reaction function:

$$\min_t [c(e,t) + \vartheta(t)] \Rightarrow$$

$$c_e(e^{reg}, t^f)\frac{de^{reg}}{dt^f} + c_t(e^{reg}, t^f) + \vartheta_t(t^f) = 0. \tag{5}$$

As the first term is positive, $c_t(e^{reg}, t^f) + \vartheta_t(t^f) < 0$. This means that the social cost of supplying *e* is not at a minimum, as would be required by the optimality condition $c_t(e,t) + \vartheta_t(t) = 0$, but could be further decreased by increasing *t*. However, given the regulator's reaction function, such an increase in t would also raise the total level of emissions abatement e that firms are required to provide. □

As firms anticipate that lower marginal costs due to technological innovation will prompt the regulator to adopt more stringent policy, they choose a level of technology below the social optimum. In our model, this 'ratchet effect' (Weitzman, 1980), which is due to the regulator's flexibility to react to firms' choice of t, results in a time-inconsistent choice of the abatement target e.[3] However, this problem can be overcome if the regulator has a means to credibly commit to its future actions. A commitment is only credible if the cost of breaking it exceeds the potential gains from deviation (Schelling, 1960). The regulator hence only has an incentive to adhere to a prior commitment if deviation results in a punishment that is sufficiently large. Such punishments, which are discussed in more detail in Section 5, can e.g. include bad press and loss of reputation, a lower likelihood of being re-elected, or actual financial costs. If the punishment depends on the magnitude of the deviation from the announced policy, the regulator's optimal *ex-post* policy is determined by its *ex-ante* commitment and the severity of the punishment. For the case in which the punishment for an infinitesimally small deviation from the announced policy approaches infinity, the regulator never has an incentive to deviate from the announced policy and full commitment is obtained.

Lemma 3: The cases of 'full commitment' and 'no commitment' as well as all intermediate cases can be modeled by introducing a punishment function Θ into the regulator's objective function. Punishment of deviations from an announced policy then acts as a commitment device.

Proof: Let the regulator's objective function be

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[3] Note that by modeling one representative firm, we implicitly assume that firms are able to coordinate their actions. If a single firm's action has no influence on the regulator's reaction, the problem of time-inconsistency does not arise in our framework. Thus the formulation chosen here can be expected to be suitable for monopolistic markets such as power generation in many countries.

$$W = b(e) - c(e,t) - \vartheta(t) - \Theta(\left|e - e^{opt}\right|) \text{ with } \Theta' > 0 . \tag{6}$$

Obviously, the case of no commitment is obtained for $\Theta(e) = 0$. Furthermore, it can be easily verified that $\frac{de^{reg}}{dt^{f}} \rightarrow 0$ for $\Theta(e \neq e^{opt}) \rightarrow \infty$, yielding the full commitment setup. Between these polar cases lies a continuum of setups in which the regulator is punished for deviations from the pre-announced policy. □

With perfect foresight, it is clear that perfect regulatory commitment is the most desirable option from a social perspective (under the assumptions of our model). However, in presence of uncertainties with regard to benefits and costs of emissions abatement, some flexibility to deviate from prior announcements in order to react to unforeseen events can prove advantageous. Therefore, as we show in the next section, there is a trade-off between providing stable incentives for investments in emissions abatement on the one hand and retaining the flexibility to accommodate new information on the other.

4 Commitment under uncertainty

We outline a simple analytical model with linear benefits, quadratic abatement costs that decrease linearly in technology *t*, and a quadratic R&D investment cost function to acquire technology level *t,* characterized by the parameter *k*. We analyze the impacts of additive uncertainty in the slope of the benefit function[4], characterized by its expected value *b* and the realization of a random shock ε. With mean value 0 and a finite standard

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[4] In climate policy, the largest sources of uncertainty relate to the damage costs of climate change (IPCC 2007). At the same time, uncertainties regarding mitigation costs and costs of technology development undeniably play important roles, too.

deviation σ.[5] We assume that the magnitude of the regulator's punishment Θ for deviating from an announced target is characterized by the non-negative parameter θ and quadratic in the difference between the announcement e^* and the actually implemented level $e^{'}$. This formulation of a commitment device can be understood in terms of the reputational costs associated to violating a pledge à la Barro and Gordon (1983), or political costs in terms of renegotiating legislation (Brunner et al. 2012). Monetary costs can be introduced in an emission trading system by means of put options that obligate the regulator to buy back permits at a pre-defined price in the future (Ismer and Neuhoff 2009). In Section 5, design options of commitment devices are discussed in more detail.

The model is hence fully specified by the following set of equations:

$$\begin{aligned}
&b(e) = (b+\varepsilon)e';\ E(\varepsilon) = 0;\ Var(\varepsilon) = \sigma^2;\ \ \sigma^2 < \infty \\
&c(e) = \frac{1}{2}ce'^2 - te' \\
&\vartheta(t) = \frac{1}{2}kt^2 \\
&\Theta(e^{'}, e^*) = \frac{1}{2}\theta(e^{'} - e^*)^2 .
\end{aligned} \tag{7}$$

We require all parameters *b*, *c*, *k* and θ as well as the choice variable *t* to be non-negative. The social welfare function is given by:

$$W = (b+\varepsilon)e' - \frac{1}{2}ce'^2 + te' - \frac{1}{2}kt^2 - \frac{1}{2}\theta(e^{'} - e^*)^2 \tag{8}$$

Again, the game proceeds in three stages: In the first stage, the regulator (R) announces the target e^* which it aims to implement in the final stage. In the second stage, the

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[5] See Weitzman (2009) on limitations of expected utility theory for distributions with an infinite standard deviation.

uncertainty regarding benefits is resolved and firms (F) choose their level of technology *t*.[6] In the third stage, the regulator decides on the level of emissions abatement that is actually implemented ($e^{'}$), given the realization of the new information ε regarding benefits as well as firms' choice of *t*, and firms supply $e^{'}$ at the corresponding cost function (Figure 1).

[Figure 1 about here]

The decentralized nature of the strategic interaction between the regulator and the regulated firms requires both players to form expectations of future scenarios (which are determined by the other player's action, and, for the regulator, the possible realization of the shock). To solve the problem, we apply backward induction from the third to the second and finally to the first stage.

The Third Stage

In the third stage, the regulator chooses $e^{'}$, the level of emissions abatement to be performed by the firms, taking as given technology *t*, the realization of the shock ε, as well as e^{*} (its own announcement of the first stage). Its maximization problem then yields:

$$e' = \arg\max_{e'}[W] = \arg\max_{e'}\left[(b+\varepsilon)e' - \frac{1}{2}ce'^2 + te' - \frac{1}{2}kt^2 - \frac{1}{2}\theta(e^{'}-e^{*})^2\right] \Rightarrow$$

$$e' = \frac{(b+\varepsilon)+t+\theta e^{*}}{c+\theta}. \tag{9}$$

The level of emissions abatement that the regulator requires firms to supply is the higher (i) the larger actual benefits, i.e. $(b+\varepsilon)$, (ii) the higher the firms' level of

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[6] Hence, firms do not face uncertainty when deciding on their technology level.

technology *t*, (iii) the more ambitious the announced target e^*, and (iv) the lower abatement costs, characterized by *c*.

The Second Stage

In the second stage, firms take the regulator's announced policy e^* as given from the first stage and anticipate how the former will react in the third stage to their second stage choice of *t* and the shock ε. Firms observe the shock ε occurring to the benefit function and decide which level of technology to employ in order minimize their total costs:

$$t' = \arg\min_{t} \frac{1}{2} c e'(\varepsilon, t, e^*)^2 - t e'(\varepsilon, t, e^*) + \frac{1}{2} k t^2 \ . \tag{10}$$

As firms are able to solve the regulator's decision problem in the third stage, inserting e' in Eq.(10) results in the following solution for the firms' technology choice *t'*:

$$t' = \frac{\theta(b+\varepsilon) + \theta^2 e^*}{k(c+\theta)^2 - c - 2\theta} \ . \tag{11}$$

In order to ensure that *t'>0*, let us assume that the condition $k > \frac{c+2\theta}{(c+\theta)^2}$ holds.[7] Then, *t'* increases with (i) actual benefits $(b+\varepsilon)$, (ii) the regulator's announced policy e^*, and (iii) the strength of the regulator's commitment to its announced target (θ), as all parameters cause firms to anticipate that stricter requirements will be put into place by the regulator in stage three.

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[7] Otherwise, firms would have an incentive to choose a negative level of technology that raises their costs, in order to prompt the regulator to choose a laxer abatement target.

The First Stage

In order to be able to decide which target e^* to announce before knowing the actual realization of ε, the regulator has to form expectations about social welfare under all possible outcomes. Plugging the expressions for $e^{'}$ and $t^{'}$ into the welfare function and rearranging terms results in:

$$W = \frac{[\theta e^* + b + \varepsilon]^2[(k(c+\theta)-1)^2(c+\theta) - k\theta^2] - \theta[k(c+\theta)^2 - c - 2\theta]^2 e^{*2}}{2[k(c+\theta)^2 - c - 2\theta]^2} \ . \qquad (12)$$

Taking expectations then yields:

$$W^e = \frac{[\theta^2 e^{*2} + b^2 + 2b\theta e^* + \sigma^2][(k(c+\theta)-1)^2(c+\theta) - k\theta^2] - \theta[k(c+\theta)^2 - c - 2\theta]^2 e^{*2}}{2[k(c+\theta)^2 - c - 2\theta]^2}. \qquad (13)$$

Maximizing this expression with respect to e^* gives us the regulator's optimal choice of e^*, as a function of the underlying parameters:

$$e^* = \frac{b[(k(c+\theta)-1)^2(c+\theta) - k\theta^2]}{[k(c+\theta)^2 - c - 2\theta]^2 - \theta[(k(c+\theta)-1)^2(c+\theta) - k\theta^2]}. \qquad (14)$$

Welfare

Inserting e^* into the expression for expected welfare and rearranging terms yields:

$$W^e = \frac{b^2[(k(c+\theta)-1)^2(c+\theta) - k\theta^2]}{2[k(c+\theta)^2 - c - 2\theta]^2 - 2\theta[(k(c+\theta)-1)^2(c+\theta) - k\theta^2]} + \frac{\sigma^2[(k(c+\theta)-1)^2(c+\theta) - k\theta^2]}{2[k(c+\theta)^2 - c - 2\theta]^2}. \qquad (15)$$

<u>Proposition 1</u>: *With uncertainty and commitment to a pre-announced policy* e^*, *neither the case of full nor the case of no commitment yields the optimal result. Rather, in this setting an intermediate value of* θ *(i.e.* $0 < \theta < \infty$*) provides the socially optimal mix of commitment and flexibility.*

<u>Proof</u>: Calculating the derivative of expected welfare with respect to θ and evaluating the expression at the extreme values $\theta = 0$ and $\theta \to \infty$ shows that $\left.\frac{\partial W^e}{\partial \theta}\right|_{\theta=0} > 0$ and $\left.\frac{\partial W^e}{\partial \theta}\right|_{\theta\to\infty} < 0$. □

From a social welfare point of view, it is desirable to choose the value of θ such that it maximizes expected welfare. As maximizing the above expression for expected welfare would require solving polynomials in fourth order of θ, for which no analytical formulas exist, it is in general not possible to state the maximum in analytical terms. However, it is convenient to employ numerical methods[8] to calculate the values of θ that maximize W^e for different sets of parameters. The result of this exercise is shown in Figure 2, which plots the optimal value of θ as a function of b^2/σ^2. This set of graphs[9] suggests that the optimal level of commitment (i) increases as expected benefits *b* increase and uncertainty *σ* decreases, and (ii) decreases with higher abatement costs – characterized by *c* – as well as technology costs *k*. This finding is in line with intuition: the optimal level of commitment is the higher the higher the benefits of mitigation relative to costs, and the lower uncertainty over benefits. One can expect that this relationship holds for a broad class of models, independent of the specific functional form adopted for costs and benefits.

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[8] We used Matlab's bounded minimization routine fminbnd.

[9] Note that the optimal ϑ is always strictly positive.

[Figure 2 about here]

First best solution

As shown by the example in Section 2, the first best outcome can be obtained by simultaneously choosing *e* and *t* after observing the realization of ε, such that the first-order conditions $b_e(e^{opt}) = c_e(e^{opt}, t^{opt})$ and $c_t(e^{opt}, t^{opt}) + \vartheta_t(t^{opt}) = 0$ are fulfilled. This would result in the following policy:

$$\begin{aligned} t^{opt} &= \frac{b+\varepsilon}{kc-1} \\ e^{opt} &= \frac{k(b+\varepsilon)}{kc-1} \end{aligned} \tag{16}$$

Plugging these expressions in the social welfare function and taking expectations yields:

$$W^{e,fb} = \frac{(b^2+\sigma^2)}{2(kc-1)} \tag{17}$$

<u>Proposition 2</u>: *With uncertainty, the expected welfare of committing to a pre-announced policy e^* is strictly inferior to the first best optimum, regardless of the level of commitment θ.*

<u>Proof</u>: Comparing expressions for welfare in the commitment under uncertainty case (Eq.(15)) and the first best case (Eq.(17)) reveals that the two expressions differ, i.e. . $W^e \neq W^{e,fb}$. As the first best optimum of Eq.(17) corresponds to the optimal choice of *e′* and *t* (which maximizes expected welfare), Eq.(15) has to lie strictly below the level of expected welfare implied by Eq.(17). Hence, Eq.(15) constitutes a second best but not a first best optimum, i.e. it is only optimal under the precondition that the regulator's choice is restricted to committing to a specific abatement level. □

Commitment to an adjustment rule

Under uncertainty, there is no a-priori commitment to a specific e^* that yields the first-best optimal outcome. However, instead of making a commitment to a pre-announced policy the regulator could commit to an adjustment rule that sets e^* contingent on the realization of ε.

<u>Proposition 3</u>: *The first-best optimal outcome can be achieved if the regulator commits to an adjustment rule which implements a certain level of* e *contingent on the realization of the shock* ε*.*

<u>Proof</u>: As we have shown in Eq.(16), the first best outcome implies $e^{opt} = \frac{k(b+\varepsilon)}{kc-1}$ and $t^{opt} = \frac{b+\varepsilon}{kc-1}$. By announcing the policy $e^* = \frac{kb}{kc-1}$ and committing to an adjustment rule that includes a punishment term of the form $\Theta(e^{'}-e^*) = \frac{\theta}{2}(e^{'}-e^* - \frac{k\varepsilon}{kc-1})^2;\ \theta \to \infty$, the regulator will always adjust its a priori choice of e^* such that the first best level of $e^{'}$ identified in Eq.(16) will be chosen. This commitment strategy deprives firms of their incentive to implement a lower level of technology in order to influence the regulator's choice of $e^{'}$. As can easily be verified from firms' cost minimization problem, their cost-minimization problem then results in choosing the first best level of technology t^{opt}. □

Hence, commitment to a rule that adjusts the policy dependent on the realization of the uncertain variable can be both time-consistent and ex post optimal. At first glance, this finding may appear to be in line with Ulph and Ulph (2013) who show that regulators should commit to a menu of taxes contingent on the firm's investment instead of committing to a certain tax level. However, their reason for proposing an adjustable tax is to discourage strategic behavior by firms. By contrast, our adjustment rule aims at addressing the natural system uncertainty by adjusting the optimal abatement level. Its purpose lies in providing the regulator with flexibility if the best estimate of climate change damage costs varies due to new scientific insights. It thereby goes beyond the deterrence of strategic under-investment by firms toward improving policy resilience under natural system uncertainty. Ulph and Ulph (2013) also show that technology subsidies that remove firms' incentives to under-invest with the aim to influence the regulator to implement a less stringent abatement target can act as a substitute for a commitment device, i.e. it can achieve the socially optimal outcome. This line of reasoning also applies to our setting. In fact, if the subsidy is implemented after the stochastic shock is resolved, our model is equivalent to Ulph and Ulph (2013).

Practical implementation of an adjustment rule crucially rests on the assumption that the shock is publicly observable. While new information on the physical impacts can clearly be regarded as common knowledge, their economic valuation would require an agreed method to monetize damage costs. For this reason, putting an adjustment rule into practice is expected to be more challenging than stylized model above suggests.

Note that the uncertainty surrounding marginal abatement costs or R&D costs of new technologies – a case not investigated here – also derives from significant information asymmetries between firms and government. The existence of such 'strategic' uncertainty diminishes the value of adjustment rules in the context of time-inconsistency because the contingent variable can be influenced by firm behavior.

5 Implementing adjustment rules

The punishment term introduced above incurs costs on the government if it decides to deviate from the emission target that results from the adjustment rule. Costs can accrue in various forms: time, bad press, the need to seek cross-partisan consensus, losing votes, admonition from courts, financial expenditures etc.. Devices that incur such costs do not put an absolute limit on government flexibility. Rather, they provide governments with an incentive to adhere to the announced policy rule by decreasing the gains from deviation. Brunner et al. (2012) identify three broader types of commitment devices two of which seem appropriate to implement an adjustment rule for climate policy: legislation and delegation.

First, legislation provides the legal foundation for the abatement target, the adjustment rule and a transparent governance structure for implementing and updating the policy. Commitment by means of constitutional law presents a high hurdle to policy change because constitutional amendments often require qualified majorities. Instead of changing legal provisions, the incumbent could also decide to ignore laws and regulations. Plausibly, the main motivation for government to avoid non-compliance with the law is public scrutiny. If a governing majority anticipates that the political costs of pursuing a certain course of action will be a loss of public support, then taking this route is less attractive. Hence, climate laws could be designed such as to encourage public scrutiny. This could e.g. be achieved by earmarking revenues from emissions trading to be invested in public infrastructure or recycled back to consumers via annual lump-sum payouts (note that the economic efficiency of earmarking revenues is contested).

Second, delegating authority to an organization with a time horizon beyond the current legislative period may help to insulate interests dedicated to emissions abatement from day-to-day politics. The climate law may hence establish an independent institution that monitors and advises the government on climate policy. The merit of establishing an independent watchdog lies in forcing government to publically justify its own actions on a regular basis (Lazarus 2009). The law may also delegate the authority to set policy on government’s behalf to an independent carbon agency (Helm et al. 2003). Independent agencies which are more insulated from political pressures tend to have stronger incentives to build up and retain reputation over longer time horizons than their political principals (Barro and Gordon 1983). Using legislation and delegation in combination may therefore allow the government to credibly commit to a future climate policy by (i) legally enshrining the adjustment rule and (ii) delegating its implementation to an independent carbon agency. The agency retains the flexibility to react to new developments but it does so within the bounds of the adjustment rule. However, delegation may be opposed by all those who think that climate policies should remain within democratically accountable institutions. In addition, electoral competition could provide an incentive for a political party to avoid delegating responsibility for environmental policy in order to remain relevant for voters.

Some first examples of adjustment rules for climate policy are emerging in Europe. In the UK, the parliament defined long-term abatement targets in statutory law and delegated monitoring duties to a government independent advisory body. Adjustments to abatement targets follow a formal procedure where the advisory body observes developments in the economy, climate science, and international negotiations, and eventually recommends the parliament to adjust abatement targets. At EU level, the emissions cap in the European Union Emissions Trading Scheme (EU ETS) follows a linear reduction trajectory of -1.74% annually since 2013. Directive 2009/29/EC specifies that the reduction factor shall be reviewed and perhaps adjusted after 2020, leaving thereby open for what reasons, in which direction, and to what extent it may change. Even before 2020, the abatement target may be tightened if, amongst others, "*more advanced developing countries*" contribute "*adequately*" to global abatement efforts (Art. 28; Directive 2009/29/EC). Such vaguely formulated conditions under which policies are modified may be necessary to capture the multitude of potential outcomes. However, they may also offer loopholes for opportunistic policy change (Dixit, 1996) which undermines the time-consistency of policies rather than providing flexibility to react to unexpected developments. Hence, there is scope to improve institutional design by using adjustment rules that clearly state the conditions under which policy change is likely.

These considerations are also relevant for the recent debate on how to reform the EU ETS in face of the stark decline of permit prices witnessed recently. For instance, the automatic stabilizers suggested by Battles et al. (2013), which closely follows the spirit of a 'Taylor rule' designed to regulate money supply, is a direct expression of a rule-based approach as discussed above. Further, the proposed price floors and ceilings, which require the regulator to alter the supply of emission permits conditional on their market price (Burtraw et al. 2009) can be regarded as a particular form of an adjustment rule. Finally, approaches that hinge on discretion, such as the Independent Carbon Market Authority (Trotignon and de Perthuis 2013), or a Carbon Market Efficiency Board (Manson 2009) do not follow an explicitly stated rule. Yet, in order to establish a reputation for credibility, their behavior has to be consistent with some clearly identifiable explanatory variables. For central banks, empirical evidence suggests that their actions – even though they can exert discretion over the money supply – is well described by a Taylor rule (Whitesell, 2011). Hence, even an institutional setting relying on discretion might help to approximate the rule-based framework outlined above.[10]

6 Conclusions

How can regulators provide dynamically efficient incentives for emissions abatement when benefits of climate change mitigation are uncertain? In a setting in which all relevant parameters are known with certainty, a regulator can achieve the first-best optimal outcome by committing to the ex-ante optimal emission target. However, under uncertainty, new information may be revealed after the regulator's policy is put in place. Uncertainty makes flexibility very valuable. Full commitment to an ex-ante optimal target – which has been identified by previous literature as a remedy to time-inconsistency – leads to suboptimal results under uncertainty. We demonstrate that

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[10] Perhaps the main advantage of such discretionary approaches is that they do not require spelling out all contingencies (Grosjean et al. submitted).

under uncertainty, the first-best optimal outcome can still be achieved by means of a transparent rule that allows adjustments of the policy level conditional on new information. Commitment to such an adjustment rule can be established by means of legislating a climate law that specifies the rule and adjustment procedures and delegates implementation tasks to a politically independent agency. Legislation of transparent procedures is particularly important because of the difficulty to impartially evaluate and respond to new information on critical parameters such as climate sensitivity and climate change damage costs.

While we have presented an argument in favor of adjustment-rule-based policy within a stylized model that focuses on the uncertainty over climate change damage costs, the underlying intuition appears to be relevant to a broader set of applications. In cases in which there is uncertainty with regard to a parameter relevant to decision making that can be observed ex-post, using adjustment rules as a basis of policy can help to mitigate the trade-offs between commitment and flexibility. Such parameters could include not only climate change damage costs but also other important values such as climate sensitivity, sea level rise, economic growth, or even the emissions of other states. Given the many uncertain factors and the need to encourage long-term thinking and investment, adjustment rules could turn out to be an essential ingredient of prudent climate policy.

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Appendix: Figures

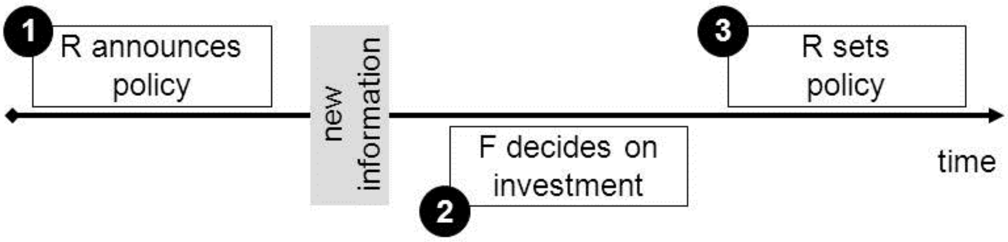

Figure 1: Emissions game between regulator (R) and firm (F) under uncertainty

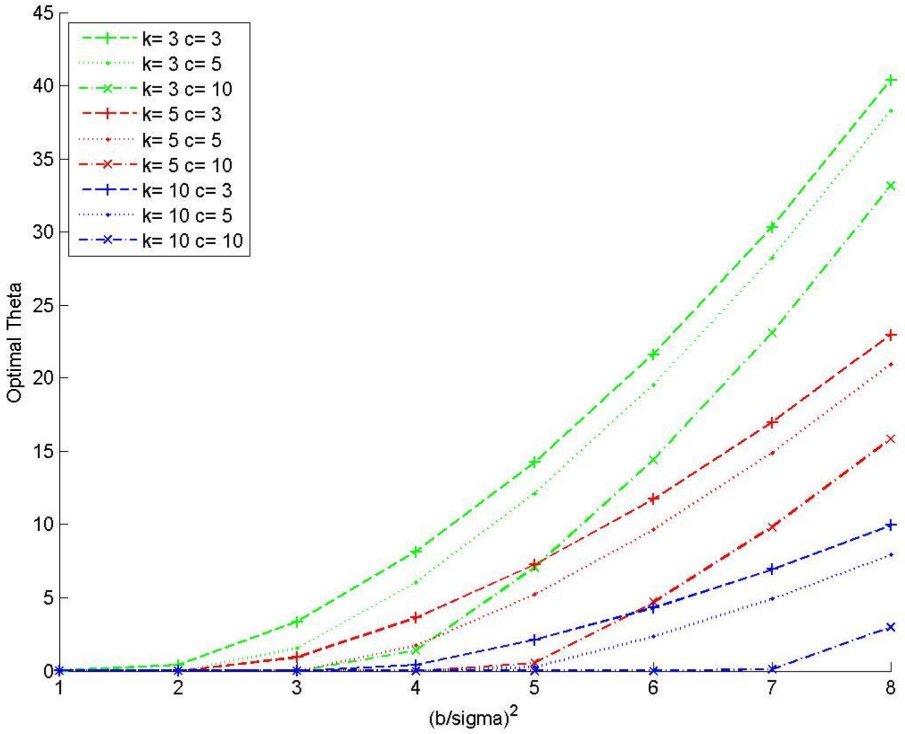

Figure 2: Optimal level of commitment for different values of the parameters *k* and *c*