All or nothing: Climate policy when assets can become stranded *

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Abstract

In this paper we develop a new perspective on the role of stranded assets for climate policy using a partial equilibrium model of the energy sector. Stranded assets are a consequence of the time-inconsistency of the second-best carbon tax when lobbying power or fiscal revenues influence the government's objective. As the second-best tax is not credible, we determine a third-best policy under rational expectations. The policy is an all-or-nothing outcome with either a zero carbon tax or a prohibitive carbon tax leading to zero fossil investments. Although stranded assets are crucial for the third-best policy to occur, they disappear again under that policy. Which polar outcome prevails depends upon the lobbying power of owners of fixed factors (land) and not on fiscal revenue considerations. When marginal damages are high, pollution under the third-best policy is lower than under the first-best or second-best carbon taxes.

Key words: climate policy, optimal control, political economy, public finance, credible policy, time inconsistency

JEL codes: H21, H23, D72, Q54, Q58

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1 Introduction

Achieving internationally agreed climate targets will require ambitious climate policies. While those policies are generally seen as welfare improving, internalizing external costs, they will also create losers that might have the political power to veto the necessary reforms (Arent, 2017; Sovacool et al., 2016; Trebilcock, 2014). Hence, in order to successfully implement climate policy, it is important for governments to consider aspects that are related to the political economy of reforms together with other factors such as the reforms' technical soundness and administrative feasibility (Rentschler and Bazilian, 2017; Sdralevich et al., 2014).

Analysing how climate policy can be implemented in the energy sector is particularly relevant. The energy sector is a major contributor to global greenhouse gas emissions primarily due to fossil fuel combustion. The IPCC (2014) estimated the global share of energy related emissions to be 65 per cent. Investments in fossil fuels, particularly coal, are the single largest source of carbon lock-in (Bertram et al., 2015; Davis et al., 2010), which increasingly endangers long term climate stabilization targets (Edenhofer et al., 2018). This trend is ongoing (Jackson et al., 2017) despite recent costs degressions into alternatives, notably renewable energy (Creutzig et al., 2017). One reason is that specific actors in the energy sector are particularly vulnerable to climate policy. These include workers (e.g. in the fossil fuel sectors), fossil fuel asset owners and industry and energy users that would suffer from potential energy price increases (Fay et al., 2015; Vogt-Schilb and Hallegatte, 2017). Some of those actors have been particularly powerful in terms of lobbying in the past (Kim et al., 2016; Dolphin et al., 2016).

As investments into fossil fuels continue to be undertaken - despite international commitments to limit global warming to two degree - an increasing literature has raised the issue of stranded assets (Caldecott, 2017). The term is used to describe various situations, including assets that are lost as a consequence of climate impacts, capital that is retired prematurely or is under-utilized as a consequence of climate policies, and fossil fuel resources that cannot be burned if a given climate target is to be reached, also referred to as unburnable carbon (McGlade and Ekins, 2015). Recent works have focused on stock market implications of climate impacts (Dietz et al., 2016) as well as the consistency of investment decisions with climate targets (Carbon Tracker Initiative, 2013, 2015).

In this emerging literature, assets are stranded due to an unanticipated shock, either in energy policy or in climate-change related damages. Investment decisions are, however, guided by expectations, which make it seem implausible to assume that climate policy or climate damages are neglected at all. Under a rational expectations framework, it is difficult to argue that stock market values of firms are mis-priced because of non-anticipated but expectable climate policies or climate impacts. It seems more plausible, that stranded assets occur when the rational expectation assumption is relaxed, e.g. by using a bounded rationality concept.

In this paper, we develop a new perspective on the role of stranded assets for climate policy: stranded assets are a consequence of time-inconsistency of the second-best carbon tax in a political economy model. The threat of stranded assets ensures that only a third-best policy is implemented. Under the third best policy, however, no stranded assets occur. The paradox of the stranded asset is that they are not observed in an economy with rational agents and time-consistent policies. Nevertheless, they crucially influence the choice of the tax level and are decisive for enabling or hindering the green transformation of the energy sector.

Time-inconsistency is a particular feature of dynamic problems, where the decision maker revises his/her decision over time (Helm et al., 2003). Kydland and Prescott (1980) were among the first to emphasize that time inconsistency is linked to expectations about the future. In particular, economic agents that form expectations about the future might be impacted by time-inconsistent optimal solutions, i.e. solutions that are optimal ex-ante, but that are not optimal ex-post. Fischer (1980) identifies two conditions for dynamic problems that lead to time inconsistency: (1) the government has a different objective function than the representative agent; or (2) the government cannot use the full set of policy instruments, in particular lump-sum taxes. While (1) is related to political economy aspects, i.e., lobbying of special interest groups, (2) is related to public finance aspects, i.e., the impossibility to rely on non-distortionary taxes to finance public expenditures due to broader welfare considerations and information asymmetries.

A substantial strand of literature has analyzed time inconsistency problems for environmental policy making. These works refer more or less explicitly to the two fundamental causes of time inconsistency outlined by Fischer (1980). Biglaiser et al. (1995) develop a dynamic differential game between firms and regulators focusing on emissions trading and emission taxes. They find that emission trading is time-inconsistent because the regulator will set a tighter cap after investments have been made (and abatement costs become lower due to investments into abatement). Time inconsistency will not occur for carbon taxes when damages are linear, as the optimal tax equals constant marginal damages – before as well as after investments have been made. Contrary to Biglaiser et al. (1995), Gersbach and Glazer (1999) find that carbon taxes can cause hold-up problems that are linked to time inconsistency. The model differs from Gersbach and Glazer (1999) in assuming a discontinuous abatement choice and oligopolistic markets. They also show that an emissions trading scheme with grandfathering can overcome the hold-up problem as firms who abate benefit from selling excess allowances.

The time-inconsistency in Marsiliani and Renstrom (2000) can be linked to the more general Fischer (1980) analysis as its cause is based on missing lump-sum taxes. As the government maximizes social welfare considering distributional aspects, a (time-consistent) first-best optimum could be achieved with household-specific lump-sum taxes. A similar mechanism for time inconsistency is at work in Abrego and Perroni (2002) who use a Utilitarian social welfare function. Schmitt (2014) develops a numeric dynamic growth model within an optimal taxation framework, in which time inconsistency arises due to missing lump-sum taxes. In the model of Ulph and Ulph (2013), time inconsistency evolves as the preferences of the government change over time. Recently, research focused also on second-best policies like renewable energy subsidies when efficient carbon pricing is politically not feasible (Kalkuhl et al., 2013). Rezai and Van der Ploeg (2017) show that second-best policies can also suffer from time-inconsistency and quantify the costs of imperfect commitment.

The paper proceeds as follows. In Sections 2–4, we develop a model for the transition of the energy system when the regulator's policy choice may be time-inconsistent and create stranded assets. We start with the social planner economy (Section 2) that defines the first-best optimum. The decentralized market economy is characterized in Section 3. We then endogenize the policy choice in Section 4 by considering a government objective function that includes public finance as well as political economy aspects in addition to the standard welfare components. When the government is able to commit, the optimal policy is a second-best optimum and serves as a reference case of the political-economy model (Section 4.1). Notably, the carbon tax under perfect commitment is influenced by the marginal costs of public funds as well as political power of landowners, while the political power of fossil or renewable energy firms is irrelevant. We then show in Section 4.2 that the political power of fossil or renewable energy firms is one reason for the carbon tax to be time-inconsistent. If governments cannot perfectly commit, they will deviate from the announced tax after investments have been made. Further causes of time inconsistency are lobbying power of landowners and fiscal policy effects. Time inconsistency causes stranded assets in either the fossil or renewable energy sector as the ex-post carbon tax is lower or higher than the announced ex-ante carbon tax, creating financial losses or excess revenues. As rational firms will anticipate the credibility of the government, the second-best policy is inconsistent. We determine the equilibrium policy under imperfect commitment in 4.3. Under rational expectations, the stranded asset problem dissolves as an equilibrium policy exists that is again time consistent - the government cannot "improve" the policy by deviating from what was announced. This third-best policy proves to be an all-or-nothing option consisting of two polar outcomes: Either carbon taxes are zero and business-as-usual emissions occur, or, carbon taxes are prohibitive, leading to zero fossil investments. Which equilibrium prevails depends on the political power of landowners, but not on fiscal policy aspects (although they all caused time inconsistency). In Section 4.4 we compare the third-best carbon tax under imperfect commitment presented in Section 4.3 with the second-best policy under perfect commitment discussed in Section 4.1 and the first-best Pigouvian tax. If marginal damages are high, pollution under the third-best tax is lower than under the second-best or first-best policy. Hence, imperfect commitment, time inconsistency and stranded assets do not necessarily need to be bad for the environment. We discuss major extensions of the model framework and possible alternative policy instruments in Section 5. Our findings are summarized and conclusion provided, together with implications for further research and climate policymaking, in Section 6.

2 Social Planner

This section develops the benchmark model that describes the optimality conditions in a first-best world, i.e. where only technological and environmental constraints are relevant.

2.1 Welfare and technology

The social planner maximizes welfare

$$W = PS + CS + \pi_N - D(E) \tag{1}$$

Producer surplus PS is given by the sum of profits from fossil energy firms $\pi_F = pY_F - rK_F - wE$ and renewable energy firms $\pi_R = pY_R - rK_R - qN$ with E carbon emissions, p the price of energy, Y_i and K_i output and capital in fossil (subscript F) or renewable (subscript R) sector, respectively, and $N = 1$ a fixed land endowment.[1] Introducing land creates decreasing returns to investment for the renewable energy sector, which reflects increasing scarcity of locations with high wind, solar or hydro power potential. Costs of capital r and carbon w are given (note that w only refers to the market price of fossil fuels, hence, extraction and fuel production costs). Consumer surplus CS is given defined by the inverse demand function $p(Y) = d^{-1}(Y)$ with

[1] We set $N = 1$ and determine the market clearing (zero profit) land price q to simplify the analysis without loss of generality. Alternatively, we could have assumed a given land price q and determine demand for land N endogenously. Both approaches are equivalent.

$Y = F_F + Y_R$ the total energy production:

$$CS = \int_0^Y d^{-1}(z)dz - p(Y)Y \tag{2}$$

As land N is a fixed factor, is it associated with a scarcity rent π_N. Damages $D(E)$ increase weakly convex in emissions E with $D(0) = 0$, $D'(E) > 0$ and $D''(E) \geq 0$.

For the fossil fuel sector we assume a Leontief production function where $Y_F = \min\{\gamma_F K_F, E\}$ as this allows excess fossil fuel capacity ($\gamma_F K_> E$) to be considered, which is related to stranded fossil investments. Renewable energy is produced with a Cobb-Douglas production function $Y_R = \gamma_R K_R^\alpha N^{1-\alpha}$ with $\alpha < 1$. We discuss the appropriateness of this modeling choice as well as the implications of considering more general production functions in Section 5.

Combining producer and consumer surplus as well as damages, welfare reads

$$W = \int_0^{Y_F+Y_R} d^{-1}(z)dz - wE - r(K_R + K_F) - D(E) \tag{3}$$

2.2 Welfare optimum

The social welfare optimum is determined by the first-order conditions $\frac{\partial W}{\partial K_F} = \frac{\partial W}{\partial K_R}$. Note that it is never optimal to build excess fossil capacity, thus $E = \gamma_F K_F$ and thus $Y_F = \gamma_F K_F$. The optimum is therefore determined by

$$\frac{\partial W}{\partial K_F} = 0 \Leftrightarrow p = \frac{r}{\gamma_F} + w + D'(\gamma_F K_F) \tag{4}$$

$$\frac{\partial W}{\partial K_R} = 0 \Leftrightarrow p = \frac{r}{\partial Y_R / \partial K_R} \tag{5}$$

$$p = d^{-1}(\gamma_F K_F + Y_R(K_R)) \tag{6}$$

Combining (4) and (5) and using in the following $Y_R'(K_R) = \partial Y_R / \partial K_R$ (as $N = 1$ is fixed) finally gives the reduced set of optimality conditions that fully characterizes the investment decision. Optimal values are denoted with *:

$$r/\gamma_F + w + D'(\gamma_F K_F^*) = \frac{r}{Y_R'(K_R^*)} \tag{7}$$

$$d^{-1}(\gamma_F K_F^* + Y_R(K_R^*)) = \frac{r}{Y_R'(K_R^*)} \tag{8}$$

with $E^* = \gamma_F K_F^*$.

Lemma 1. *(Corner solution) A corner solution of zero fossil energy production exists if and only if* $r/\gamma_F + w + D'(0) > \frac{r}{Y_R'(\hat{K}_R)}$ *with* $\hat{K}_R$ *the market-clearing renewable energy capacity if fossil energy production is zero (thus,* $\hat{K}_R$ *such that* $\frac{r}{Y_R'(\hat{K}_R)} = d^{-1}(Y_R(\hat{K}_R))$*).*

Proof. As $Y_R'(K_R) \to \infty$ if $K_R \to 0$, we will always have a strictly positive K_R. A corner solution in K_F occurs if the solution in K_F to (7–8) is negative. The Lemma follows then as $D''(K_F) \geq 0$ and $(d^{-1})'(K_F) < 0$. □

Lemma 1 says that it can be optimal to have zero fossil energy production if the social costs of producing the first unit of fossil energy (i.e. the LHS of (7)) are higher than the cost of producing renewable energy at a level $\hat{K}_R$ that clears the energy market. Note that the corner solution will always occur if the market costs of fossil energy production $r/\gamma_F + w$ or if damages from carbon emissions $D'(0)$ are sufficiently high. The existence of the corner solution is a basic implication of the linear production technology in the fossil sector. We chose a Leontief production function because it represents well the characteristics of fossil power plants: the production of final energy depends crucially on the energy that is contained in the fossil input fuel. Capital cannot substitute this fuel due to basic thermodynamic laws.[2] On the other hand, for the renewable sector K_R will be always strictly positive: $Y_R'(K_R)$ converges to infinity (and thus, the RHS of (7) converges to zero) if renewable energy capacity approaches zero.

3 Decentralized economy

In the decentralized economy, climate damages $D(\cdot)$ are an external effect and are not considered by firms. Therefore, a tax on emissions τ is included for fossil fuel firms. The tax is announced before investment decisions are made and remains unchanged after the investment decision. Hence, it is never optimal to build excess fossil capacity and $E = \gamma_F K_F$. The first order conditions in the decentralized economy with perfect commitment on carbon taxes are therefore analogue to the social planner model with an additional equation determining the price of the fixed factor land in the competitive equilibrium:

$$\frac{\partial \pi_F}{\partial K_F} = 0 \Leftrightarrow p = \frac{r}{\gamma_F} + w + \tau \tag{9}$$

$$\frac{\partial \pi_R}{\partial K_R} = 0 \Leftrightarrow p = \frac{r}{\partial Y_R / \partial K_R} \tag{10}$$

$$p = d^{-1}(\gamma_F K_F + Y_R(K_R)) \tag{11}$$

$$q = p \partial Y_R / \partial N \tag{12}$$

[2] Capital can increase the energy convergence efficiency and substitute for labor in the production process, but increases in convergence efficiency are rather limited.

The resulting market equilibrium values for investment are fully characterized by

$$r/\gamma_F + w + \tau = \frac{r}{Y_R'(K_R)} \tag{13}$$

$$d^{-1}(\gamma_F K_F + Y_R(K_R)) = \frac{r}{Y_R'(K_R)} \tag{14}$$

with $E = \gamma_F K_F$. It becomes obvious that the optimal social planner outcome will be achieved if the carbon tax is set at the Pigouvian level, equaling marginal damages at the social optimum: $\tau = D'(\gamma_F K_F^*)$. Further, with respect to corner solutions (zero fossil fuel production), the market outcome will show the same behavior as the social planner model.

4 The government as Stackelberg leader

We now introduce a government that maximizes a specific objective function. The starting point is the standard welfare measure consisting of consumer surplus, producer surplus and revenues. The standard welfare measure is then augmented by political contributions from lobbying groups – energy firms and land owners.[3] Thus, political economy aspects are included in a reduced form approach that is close to the political support function established by Hillman (1982) and Van Long and Vousden (1991) for analyzing trade policies. An advantage of this procedure is that the role of special interest groups in government policy can easily be captured without developing a policy equilibrium model like the common agency models used in Grossman and Helpman (1994) and Aidt (1998). While common agency models also require assumptions on why some groups have lower costs to organize, they model political contributions as outcome of a competition between various lobbying groups. As a more explicit modeling of the lobbying process is beyond the scope of this paper, we assume that lobbying is represented as a financial flow to the regulator that is proportional to the profits of a specific sector. This reflects the plausible assumptions that the regulator cares more about firms when their profits are large or when there is a lot at stake. Besides political economy aspects, the welfare function is augmented by public finance and political credibility costs. The objective function thus reads:

$$W^G = (1+\mu_P)PS + CS + (1+\mu_N)\pi_N + (1+\mu_G)G - D(E) - \psi(\tau, \tau_A) \tag{15}$$

[3] The consideration of rents from land owners is not just for formal closure of the model. In a recent paper, Haan and Simmler (2018) estimate that almost one fifth of the revenues from wind mills are capitalized in land rents.

where $G = \tau E$ are government revenues from carbon pricing, τ is the actual carbon tax (after the K_F and K_R have been chosen by firms) and τ_A is the announced carbon tax (before K_F and K_R have been chosen by firms). μ_P represents an additional weight for producer surplus that can be related to lobbying by firms. Likewise, μ_N may account for additional weight (lobbying power) of land owners; μ_G are one minus the marginal cost of public funds (MCFs) of the fiscal system. Hence, $\mu_G = 0$ indicates that MCFs are one and the government would be indifferent with respect to revenues from non-distortive taxes. If MCFs are larger than one (the usual case), $\mu_G > 0$ and the government places more value on revenues from carbon pricing as they can be used to reduce other distortionary taxes.

Finally, $\psi(\tau, \tau_A)$ represents political costs of changing an announced carbon price from τ_A to τ. $\psi(\tau, \tau_A) = 0$ if $\tau = \tau_A$ and $\psi(\tau, \tau_A) > 0$ if $\tau \neq \tau_A$. These costs allow a continuous scaling of the government's capability to commit to an announced policy. For perfect commitment, the costs of deviating are prohibitive, $\psi(\tau, \tau_A) \to \infty$ if τ, τ_A. $\psi(\tau, \tau_A) = 0$ implies no incentive to commit at all. The credibility costs will typically depend on the legal and institutional conditions, but will also depend on political and reputation factors. We assume a quadratic relationship, but allow for fixed costs if a new policy is introduced: $\psi(\tau, \tau_A) = \psi_\tau + \frac{\psi_2}{2}(\tau - \tau^A)^2$ with $\psi_\tau = 0$ if $\tau^A = 0$ but $\tau \neq 0$.[4]

The government maximizes W_G by choosing τ and τ_A subject to the constraints (13–14). Hence, the government is a Stackelberg leader maximizing W_G considering the profit maximization of firms that, in turn, take government's policy τ as given.

4.1 Optimal policy under perfect commitment

We first focus on the case in which the government can perfectly commit to the announced policy, i.e. where $\tau = \tau_A$. This policy optimum differs from the social planner optimum that only considers consumer preferences as well as technological and environmental constraints. The optimal policy of the political economy model is a second-best benchmark that serves as an important reference case for the subsequent analysis of time inconsistency. This second-best policy is not a hypothetical reference case: it could be achieved if governments could commit, i.e. if the legal system provided a way to make the costs of deviating from announced policies, ψ, prohibitive. As these costs are not a natural constant but are subject to institutional, legal or constitutional design options, political reforms may indeed provide ways to solve the commitment problem.

[4]We consider the fixed costs to be sufficiently small such that they do not change the cost benefit analysis of *introducing* a carbon tax at all. The case of zero announced carbon tax - but non-zero carbon tax ex-post – is discussed in Section 5.

The optimal policy under perfect commitment is given in the following proposition:

Proposition 1. *(Carbon tax under commitment) Assuming an interior solution (i.e. positive fossil capital stocks), the carbon tax under commitment that maximizes government's objective is strictly positive and*

$$\tau^c = \frac{\mu_G Y_F + \mu_N Y_R}{-(1+\mu_G)\frac{dE}{d\tau}} + \frac{D'(E)}{(1+\mu_G)} > 0 \tag{16}$$

with $\frac{dE}{d\tau} < 0$*. If a corner solution prevails, i.e. no fossil energy production occurs, a marginal change of* τ^c *has no impact on the government's objective.*

Proof. See appendix. □

The proposition allows for various special cases. First, the case of $\mu_G = \mu_N = 0$ replicates the social planner outcome where the tax equals the standard Pigouvian tax and $\tau^c = D'(E)$. Second, the political power of energy firms (μ_P) is irrelevant as they receive zero profits. The stronger the political power of land owners, the higher the carbon tax, as land owners benefit from higher land rents due to renewable energy production.

The role of the MCFs μ_G is ambiguous. Consider the case in which land owners do not have political excess power, i.e. $\mu_N = 0$. With $\eta_{E,\tau} := \frac{dE}{d\tau}\frac{\tau}{E} < 0$ the elasticity of emissions with respect to the carbon tax, the optimal carbon tax is

$$\tau^c = \frac{D'(E)\eta_{E,\tau}}{\eta_{E,\tau}(\mu_G+1)+\mu_G} \tag{17}$$

Holding marginal damages $D'(E)$ and the elasticity of emissions $\eta_{E,\tau}$ constant, the tax changes in the MCF (μ) according to

$$\frac{d\tau^c}{d\mu_G} = -\frac{D'(E)\eta_{E,\tau}(\eta_{E,\tau}+1)}{(\eta_{E,\tau}(\mu_G+1)+\mu_G)^2} \tag{18}$$

A higher MCF (μ_G) therefore leads to a higher carbon tax if and only if $-1 < \eta_{E,\tau} < 0$, i.e. if the response of emissions to the carbon tax is rather inelastic. If the response of emissions is highly elastic, i.e. $\eta_{E,\tau} < -1$, a higher carbon tax reduces actual tax revenues because of an over-proportional reduction of the tax base (emissions). Thus, public finance aspects and MCFs only lead to carbon taxes above the Pigouvian level if emissions are inelastic in carbon taxes, $-1 < \eta_{E,\tau} < 0$.

Corollary 1. *(Carbon taxes and MCFs) When costs of public funds matter* ($\mu_G > 0$)*, carbon taxes are above the Pigouvian level if fossil fuel energy is dominant and if optimal carbon taxes are low. If the fossil fuel energy sector is small or if the carbon tax sufficiently large, the optimal carbon tax is below the Pigouvian level.*

Proof. We need to identify the conditions when $\eta_{E,\tau} < -1$ (elastic case) or $\eta_{E,\tau} > -1$ (inelastic case). By definition, $\eta_{E,\tau} = \frac{dE}{d\tau}\frac{\tau}{E}$ with $\frac{dE}{d\tau} = d'(P) - \frac{\partial Y_R}{\partial K_R}\frac{dK_R}{d\tau}$. Substituting $\frac{dK_R}{d\tau}$ from the proof of Proposition 1 and considering that Y_R is Cobb-Douglas with capital income share α, we get

$$\eta_{E,\tau} = \left(\varepsilon_{Y,p}\frac{1}{\lambda_F} + \frac{\alpha}{\alpha - 1}\frac{1-\lambda_F}{\lambda_F}\right)\frac{\tau}{p}$$

with $\varepsilon_{Y,p} = d'(p)\frac{p}{Y}$ the price elasticity of energy demand and $\lambda_F = Y_F/Y$ the share of fossil energy in total energy production. If the share of fossil fuel energy is large, $\lambda_F \to 1$, $\eta_{E,\tau} \to \varepsilon_{Y,p}\frac{\tau}{p}$. The tax elasticity of emissions will be low if τ is sufficiently low compared to the energy price p. If the tax equals the energy price, the tax elasticity of emissions will be the same as the price elasticity of energy demand (reductions in emissions will only be driven by reductions in energy demand). On the contrary, if the share of fossil energy vanishes $\lambda_F \to 0$, then $\eta_{E,\tau} \to -\infty$ and emissions are highly elastic in the carbon tax. □

The corollary emphasizes that when introducing a small carbon tax, because marginal damages are initially low or because producing fossil energy has large cost advantages, the public finance aspect of carbon pricing is relatively more important than environmental damage internalization. The carbon tax will therefore be above the Pigouvian level. The higher the carbon tax and the smaller the fossil energy sector, however, the more will the costs of public funds reduce the carbon tax . This is intuitive as for a low share of fossil fuel energy, a higher carbon price will induce a relatively strong substitution of fossil fuels with renewable energy. As high carbon taxes deteriorate the tax base and reduce public revenues that are otherwise costly to raise, carbon taxes will then be lower than the Pigouvian level. We thus observe an environmental Laffer curve effect as a revenue-maximizing carbon tax rate exists that might be higher or lower than the Pigouvian tax rate.

Hence, under perfect government commitment, the optimal carbon tax can be higher or lower than the Pigouvian carbon tax, depending on the costs of public funds and the cost-benefit ratio of internalizing environmental damages. As a direct consequence of (16), lobbying power of land owners leads to higher carbon taxes. The lobbying power and profits of investors or energy firms are irrelevant in the perfect commitment case. There will also be no problem of stranded assets as profits are zero. As we elaborate in the next section, this changes if the government cannot commit to the announced policy.

4.2 Time inconsistency of the second-best policy under imperfect commitment

We now elaborate the conditions that make the previously determined carbon tax time-inconsistent. Time inconsistency arises when – after investments have been made and capital stocks K_F, K_R were determined – the regulator reverses its announced carbon tax τ_A and implements the tax τ. For this to happen, the credibility costs need to be small; the government can no longer credibly commit to the announced tax.

Consider the case in which the optimal tax under commitment implies a corner solution, i.e. zero fossil investments. As Lemma 1 also translates to the decentralized case, a corner solution with zero fossil capital stocks occurs if (and only if)

$$r/\gamma_F + w + \tau^A > \frac{r}{Y_R'(\hat{K}_R)} \tag{19}$$

with $\tau^A = \tau^c$ the announced carbon tax of the government after optimization (i.e. 16) and $\hat{K}_R$ the market-clearing zero-profit renewable energy capacity if fossil energy production is zero (thus, $\hat{K}_R$ such that $\frac{r}{Y_R'(\hat{K}_R)} = d^{-1}(Y_R(\hat{K}_R))$).

The corner solution is *time consistent* as a deviation of the carbon tax after investments have been undertaken neither effects carbon emissions, nor profits, consumer surplus, land rents nor government revenues because emissions are zero in any case. This result depends on the assumed Leontief production function and the perfect substitutability between fossil fuels and renewable energy. If the expected carbon price is too high, no capital is built and, thus, no emissions will occur later even if carbon taxes turn out to be lower.

For the case in which the announced and expected carbon tax does not satisfy (19), we derive response functions for emissions, profits and prices with respect to ex-post changes in carbon taxes with an expected carbon tax of $\tau^A = \tau^c$. These are substituted into the objective function of the government to determine the optimal deviation from the announced policy.

Lemma 2. *(Response in emissions) Assume no corner solution for fossil investments. If the ex-post carbon tax deviates from the announced (and expected) carbon tax $\tau^A = \tau^c$, emissions respond as follows:*

$$E(\tau, \tau^c) = \begin{cases} d(r/\gamma_F + w + \tau^c) - Y_R, & \textit{for } \tau < \underline{\tau}(\tau^c) := r/\gamma_F + \tau^c \\ d(w + \tau) - Y_R, & \textit{for } \underline{\tau}(\tau^c) \leq \tau \leq \bar{\tau}(\tau^c) = d^{-1}(Y_R(K_R)) - w \\ 0, & \textit{for } \tau > \bar{\tau}(\tau^c) \end{cases} \tag{20}$$

with $\underline{\tau}'(\tau^c) = 1 > 0$ *and* $\bar{\tau}'(\tau^c) < 0$. *In particular, for a marginal change in the carbon tax, emissions will not change from the ex-ante emissions if the tax is sufficiently small* $\tau < \underline{\tau}$ *or sufficiently large* $\tau > \bar{\tau}$*:*

$$\frac{dE(\tau,\tau^c)}{d\tau} = \begin{cases} 0, & \text{for } \tau < \underline{\tau}(\tau^c) \\ d'(w+\tau), & \text{for } \underline{\tau}(\tau^c) < \tau < \bar{\tau}(\tau^c) \\ 0, & \text{for } \tau > \bar{\tau}(\tau^c) \end{cases} \tag{21}$$

Proof. (a) $E(\tau,\tau^c)$ – case 1: Fossil firms will produce at their capacity limit if $d(w+\tau) \geq \gamma_F K_F + \gamma_R K_R$, i.e. if the total energy demand for the energy price at marginal fossil energy production costs exceeds total capacity. Equating (13) with (14) gives total capacity as a function of the announced carbon tax τ^c: $\gamma_F K_F + \gamma_R K_R = d(r/\gamma_F + w + \tau^c)$. Hence, the corner solution case holds if $\tau < r/\gamma_F + \tau^c$. Emissions in that case equal fossil capacity, i.e. $E = \gamma_F K_F = Y - Y_R$. Total energy production Y, in turn, is determined by the expected carbon tax τ^c and will just equal $d(p) = d(r/\gamma_F + w + \tau^c)$ due to (9).

(b) $E(\tau,\tau^c)$ – case 3: Fossil firms will not produce if marginal costs are higher than the market clearing energy price when only renewable energy is produced, i.e. if $w + \tau > d^{-1}(\gamma_R K_R)$. This condition is equivalent to $\tau > \bar{\tau}(\tau^c)$. Adding fossil energy production will only lower the energy price and cause additional losses to fossil energy firms as they produce at prices below marginal costs.

(c) $E(\tau,\tau^c)$ – case 2: Fossil energy firms produce at marginal costs and below capacity if case 1 or case 3 does not hold. Fossil energy production will be at a level to clear markets, thus $E = Y - Y_R(K_R)$. The optimality condition for fossil firms producing below capacity is $w + \tau = p = d^{-1}(E + Y_R(K_R))$, which gives the emissions in case 2.

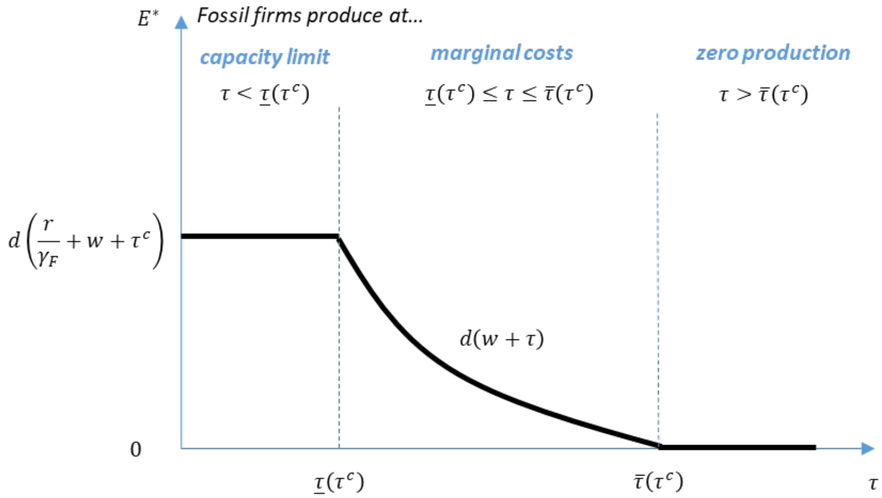
(d) $\underline{\tau}'(\tau^c) = 1 > 0$ follows directly.

(e) From (13) and $Y''(K_R) < 0$ follows $dK_R/d\tau > 0$ and $dY_R/d\tau > 0$. As further $d'(\cdot) < 0$, we obtain $\bar{\tau}'(\tau^c) < 0$.

(f) Eq. 21 is straight-forward. □

The important implication of Lemma 2 is that a marginal change in the carbon tax after investments have been undertaken may have no effect on emissions at all. Even if the ex-post tax was increased by an amount smaller than r/γ_F, there would be no impact on emissions as the fossil energy sector would still produce at capacity. Only if the ex-post tax were to become too large and require fossil firms to produce where marginal costs (including carbon tax) equal final energy prices, would higher taxes reduce emissions further. If carbon taxes are higher than a second critical threshold, $\bar{\tau}$, fossil energy production becomes zero and additional increases in carbon taxes have no

Figure 1: Emissions as a function of ex-post carbon tax τ.



effect. Figure 1 illustrates this behavior among the three possible regimes graphically.

With the emission response function from Lemma 2 and using equilibrium conditions of the decentralized equilibrium under the carbon tax τ^c from (16), we can analyze how a marginal change in the ex-post tax affects government's objective, depending on the three regimes of the ex-post tax.

Proposition 2. *Assume no corner solution for fossil investments. If the ex-post carbon tax deviates from the announced (and expected) carbon tax τ^c, then the government's objective changes with the change in the ex-post tax τ according to*

$$\frac{dW^G}{d\tau} = (1+\mu_P)\begin{Bmatrix} -\gamma_F K_F \\ Y_R \\ 0 \end{Bmatrix} + \begin{Bmatrix} 0 \\ -Y \\ 0 \end{Bmatrix} + (1+\mu_G)\begin{Bmatrix} \gamma_F K_F \\ \tau d'(w+\tau) + E \\ 0 \end{Bmatrix}$$

$$- \begin{Bmatrix} 0 \\ D'(E)d'(w+\tau) \\ 0 \end{Bmatrix} - \psi_2(\tau - \tau^A) \tag{22}$$

$$= \begin{Bmatrix} (\mu_G - \mu_P)Y_F \\ \mu_P Y_R + \mu_G Y_F + [(1+\mu_G)\tau - D'(E)]d'(w+\tau) \\ 0 \end{Bmatrix} - \psi_2(\tau - \tau^A) \tag{23}$$

where the brackets indicate the cases $\tau < \underline{\tau}$ (upper element), $\underline{\tau} < \tau < \bar{\tau}$ (middle element) and $\tau > \bar{\tau}$ (bottom element) with the definitions of $\underline{\tau}$ and $\bar{\tau}$ from Lemma 2.

Proof. We need to show 22 and use (15). The proof is straightforward by substituting (21) in profit functions, in consumer surplus, in government revenues and in environmental damages. Rearranging and simplifying gives the result. □

The government will choose the optimal τ that maximizes W^G. As the government announced the carbon tax τ^c before firms' investment decisions, it is natural to start with an ex-post tax near τ^c and to analyze whether a deviation from τ^c increases or decreases the government's objective. Hence, we focus first on the case in which $\tau < \underline{\tau}$. In the first regime (R1) with $\tau < \underline{\tau}$, $\frac{dW^G}{d\tau}$ becomes zero if

$$\tau^{R1} = \tau^{\#}_{\tau<\underline{\tau}} = \frac{(\mu_G - \mu_P)\gamma_F K_F}{\psi_2} + \tau^A \tag{24}$$

with $\psi_2 \geq 0$ denoting the marginal costs of revising the announced carbon tax. In the first-best case with no political economy and public finance aspects and all $\mu_i = 0$, there is no time inconsistency problem and the optimal ex-post tax equals the announced tax.

If the political costs are very high, $\psi_2 \to \infty$, the ex-post tax converges to the announced tax τ_A as the first term becomes zero. The government would like to decrease the announced carbon tax ex-post whenever $\mu_G < \mu_P$.[5] The intuition is that if $\mu_G < \mu_P$, the producer surplus has a higher weight in the government's objective than revenue raising. As only profits for fossil firms change with the carbon tax but emissions, damages, renewable energy firms' and landowners' profits as well as consumer surplus remain constant (as long as we are in the $\tau < \underline{\tau}$ regime), the government reduces carbon taxes. If $\mu_G = \mu_P$, the government has no incentive to deviate from the announced tax. On the contrary, if $\mu_G > \mu_P$, the revenue raising motive becomes stronger and the ex-post tax will be higher than the announced tax. If the ex-post tax becomes sufficiently large such that $\tau^{\#}_{\tau<\underline{\tau}} > \underline{\tau}$, the second regime in (22) would apply.

When $\underline{\tau} < \tau < \bar{\tau}$ and the second regime (R2) holds, $\frac{dW^G}{d\tau}$ becomes zero if

$$\tau^{R2} = \tau^{\#}_{\underline{\tau}<\tau<\bar{\tau}} = \frac{\mu_P Y_R + \mu_G Y_F - D'(E)d'(w+\tau) + \psi_2 \tau^A}{\psi_2 - (1+\mu_G)d'(w+\tau)} \tag{25}$$

Again, in the non-political economy world where all $\mu_i = 0$, the optimal ex-post tax equals the announced tax and there is no time inconsistency. For the general case, the role of ψ_2 is similar to the carbon tax in the first regime: if political costs are very high and $\psi_2 \to \infty$, the ex-post tax converges the announced tax as $\lim_{\psi_2 \to \infty} = \tau^A$.

For a deeper analysis of the optimal ex-post tax in the second regime, we focus now on the case in which political costs are irrelevant. We expect the incentive to deviate strongly from the announced tax. For $\psi_2 = 0$, the optimal ex-post tax is:

$$\tau^{\#}_{\underline{\tau}<\tau<\bar{\tau};\psi_2=0} = \frac{D'(E)}{1+\mu_G} + \frac{\mu_P Y_R + \mu_G Y_F}{-(1+\mu_G)d'(w+\tau)} \tag{26}$$

[5] In the case in which the political costs of revising the carbon tax are zero, $\psi_2 = 0$, the optimal ex-post carbon tax would converge to minus infinity if $\mu_G < \mu_P$.

The expression is similar to the optimal tax under perfect commitment (16) but has some notable differences. While in the perfect commitment case, political power of land owners μ_N tends to increase carbon taxes, it is now the political power of (renewable) energy firms μ_P that increases carbon taxes. The reason for this is that profits of land owners do not change with the carbon price as renewable energy is deployed and, thus, land prices are determined under the announced carbon tax τ^c. Note that profits of fossil firms become irrelevant as they are negative in regime two and do not change with a marginal change in carbon taxes. Hence, while political power in regime 1 tends to benefit fossil firms through lower carbon taxes, political power benefits renewable firms through higher carbon taxes in regime 2. Finally, the role of carbon taxes for raising public revenues changes quantitatively. As $\frac{dE}{d\tau} = d'(p) + \frac{\alpha}{\alpha-1}\frac{Y_R}{p} < d'(p)$, we have for $d'(p) \approx d'(w+\tau)$ that the denominator in the RHS of (16) is, in absolute terms, larger than the corresponding denominator of (26). Therefore, public finance aspects through $\mu_G > 0$ play out more strongly for the optimal ex-post tax than for the ex-ante tax under perfect commitment. The intuition behind this finding is that under perfect commitment, emissions respond rather elasticly in carbon taxes because the tax reduces energy demand and also triggers substitution by higher investments in renewable energy. Therefore, public-finance motivated increases in carbon taxes above the Pigouvian level are rather moderate. For the ex-post optimum, the carbon tax only triggers reductions in energy demand as the amount of renewable energy production is fixed. As the response of emissions in carbon taxes is less elastic, a government seeking for public revenues will use a higher carbon tax.

We can therefore conclude that for regime 2, without policy costs of changing the announced carbon tax, the carbon tax will be higher than the carbon tax under perfect commitment when $\mu_P \geq \mu_N$. The latter condition should easily be met in practice as energy firms are usually much more concentrated than land owners and might therefore excise higher political influence (but equal influence will be sufficient, too). The higher the political costs of changing an announced carbon tax, ψ_2, the smaller will be the deviation from the announced tax. If, however, the increase of $\tau^{\#}_{\underline{\tau}<\tau<\bar{\tau};\psi_2=0}$ above τ^c is not sufficiently high and $\tau^{\#}_{\underline{\tau}<\tau<\bar{\tau}} < \underline{\tau} = \tau^c + r/\gamma_F$, then the optimality conditions of regime 1 hold.

Note that in regime 3 ($\tau > \bar{\tau}$), producer surplus, consumer surplus, damages and tax revenues do not depend on the carbon tax as emissions are always zero. Due to reputation costs, a local optimum exists when $\tau = \tau^A$. As this is lower than $\bar{\tau}$, a corner solution will prevail:

$$\tau^{R3} = \tau^{\#}_{\tau>\bar{\tau}} = \bar{\tau} \tag{27}$$

Corollary 2. *(Optimal ex-post tax) The optimal ex-post carbon tax $\tau^{\#}$ is either $\tau^{R1}, \underline{\tau}, \tau^{R2}$*

or $\bar{\tau}$, depending on the prevailing case specified in Tab. 1.

Proof. As $E(\tau)$ is continuous in τ and W is continuous composition of functions that are continuous in E, W is again continuous in τ. □

Lemma 3. *(Increase of ex-post tax) The optimal ex-post carbon tax $\tau^{\#}$ is higher than the ex-ante tax τ^A if $\mu_G > \mu_P$. If $\mu_G < \mu_P$ the optimal ex-post carbon tax is higher than the ex-ante tax if argmax $\{W(\tau^{R1}), W(\tau^{R2})\}$ or argmax $\{W(\tau^{R1}), W(\bar{\tau})\}$.*

Proof. This follows directly from Corollary 2. □

Lemma 3 identifies the conditions that lead to larger or smaller ex-post carbon taxes. As illustrated in Tab. 2 in the Appendix, μ_G is typically larger than 0.5 and is sometimes even larger than one. Hence, substantial lobbying power would be required for lowering the ex-post carbon tax. Lobbying power is further constrained above: μ_P should not exceed one as firms would not willingly pay policymakers more than they receive in excess profits.

A direct consequence of the previous Propositions is that time inconsistency can only occur when at least μ_P or μ_G differs from zero, i.e. when public finance or political economy aspects of energy firms are relevant.

Corollary 3. *The carbon tax is time consistent if $\mu_P = \mu_G = 0$. Political power of land owners, μ_N, is irrelevant for time inconsistency.*

Proof. From Proposition 1 follows that $\tau^c = D'(E)$ is the optimal carbon tax under commitment if $\mu_P = \mu_G = 0$. Substituting this in $\frac{dW^G}{d\tau} = 0$ from Proposition 2 gives $\tau = \tau^c$ as the optimal ex-post carbon tax. Furthermore, ex-post taxes are independent from μ_N. □

4.3 Equilibrium with rational expectations

If the government cannot commit to an announced carbon tax, it has an incentive to deviate from the announced tax. The announced tax is therefore no longer credible. Rational firms anticipate the deviation by the government after investments have been made and adjust their capital stocks accordingly. Thus, τ^c from (16) cannot be an equilibrium. As the optimal ex-post tax is a function of both capital stocks, $\tau^{\#} = \phi(K_F, K_R)$ an equilibrium is determined by substituting τ in (13) by $\tau^{\#} = \phi(K_F, K_R)$. Thus, the rational expectations equilibrium is defined by

$$r/\gamma_F + w + \phi(K_F, K_R) = \frac{r}{Y_R'(K_R)} \tag{28}$$

$$d^{-1}(\gamma_F K_F + Y_R(K_R)) = \frac{r}{Y_R'(K_R)} \tag{29}$$

Table 1: Choice of optimal ex-post carbon tax $\tau^{\#}$.

Carbon tax of regime 2	Carbon tax of regime 1	
	$\tau^{R1} < \underline{\tau}$	$\tau^{R1} \geq \underline{\tau}$
$\tau^{R2} < \underline{\tau}$	τ^{R1}	$\underline{\tau}$
$\underline{\tau} \leq \tau^{R2} \leq \bar{\tau}$	argmax $\{W(\tau^{R1}), W(\tau^{R2})\}$	τ^{R2}
$\tau^{R2} > \bar{\tau}$	argmax $\{W(\tau^{R1}), W(\bar{\tau})\}$	$\bar{\tau}$

In equilibrium, the ex-post and ex-ante tax will be the same, $\tau^{\#} = \tau^{A}$. Hence, we can disregard the role of the credibility costs ψ for determining the equilibrium tax under imperfect commitment.[6]

Proposition 3. *(Equilibrium tax under imperfect commitment) If firms are rational and anticipate the behavior of the government, there are only two equilibrium taxes possible: Either carbon taxes are set to zero (lowest possible value) or they are set prohibitively high at $\tau \geq \tau^{\star} := d^{-1}(Y_R(\hat{K}_R)) - w$ with $\hat{K}_R$ from Lemma 1 where no fossil investments, and thus, emissions occur.*

Proof. Case (1) zero carbon taxes – lobbing power of fossil firms dominates: If lobbying power is sufficiently large ($\mu_P > \mu_G$), $\tau^{R1} = 0$ is a local optimum. For this optimum, the government reduces the ex-post tax to zero (lower bound). For adjusted investments under an anticipated zero tax, however, $\tau^{R1} = 0$ remains a local optimum. Hence, $\tau^{R1} = 0$ is also an equilibrium tax under imperfect commitment.

Case (2) prohibitive carbon tax – public finance dominates: If lobbying power is sufficiently small ($\mu_P < \mu_G$), $\tau^{R1} = \underline{\tau} = d^{-1}(Y) - w$ is a local optimum. If such a tax is anticipated, substituting $\phi(K_F, K_R) = d^{-1}(\gamma_F K_F + Y_R(K_R)) - w$ into (28) implies with (29) $r/\gamma_F = 0$, which is a contradiction. Thus, there is no interior solution possible. A corner solution holds with zero fossil investments where $\tau^{R1} = \underline{\tau} = d^{-1}(Y_R) - w$.[7] If fossil investments are zero, the regulator becomes indifferent to the change in carbon tax - unless the tax becomes too low, in which case an interior solution is again induced. Hence, any carbon tax $\tau > d^{-1}(Y_R(\hat{K}_R)) - w - r/\gamma_F$ will be optimal. This line of argumentation also holds for all other locally optimal ex-post taxes τ^{R2} and τ^{R3} as they are larger than $\underline{\tau}$ and therefore cause a corner solution. □

Because fossil investments are irreversible and can be taxed without efficiency losses, the government will always tax them at least at $\underline{\tau}$ if it sufficiently values public revenues. This explains how stranded assets can emerge under climate policy. As the threat of stranded fossil fuel assets is anticipated by fossil investors and as it is never optimal for them to invest into fossil resources if the tax will be $\underline{\tau}$, they invest nothing at all. On the contrary, if fossil lobbying power is sufficiently large, investors in renewable energy fear that their assets may become stranded. As the announced carbon tax will be decreased to zero in equilibrium, renewable energy asset owners cannot recover investment costs. Anticipating this, they only invest into renewables as they would under a business-as-usual (no carbon pricing) policy.

[6] Alternatively, we could assume that credibility costs are rather low for the government and can be neglected.

[7] As $d^{-1}(Y_R) - w$ is larger than $d^{-1}(Y_R) - w - r/\gamma_F$ the necessary condition for a corner solution from Lemma 1 is met as well.

The proposition gives some remarkable insights. First, there is only a bang-bang time consistent equilibrium outcome possible that implies either a business-as-usual policy or the most stringent form of climate policy one can imagine (effectively a complete ban of fossil investments). Second, if the government needs revenues from carbon pricing, its incentive to increase the tax ex-post prevents any revenue raising. This is because the equilibrium tax will be excessively high that no emissions occur – and thus no revenues are generated from carbon pricing. Third, when the prohibitive carbon tax is the equilibrium outcome, the government has to impose a carbon tax $\tau = \underline{\tau}$ although the tax ex-post is unnecessary as no emissions occur (due to zero fossil investments). Forth, while the prohibitive carbon tax is always a time-consistent equilibrium, the zero-carbon tax is only a time-consistent equilibrium if $\mu_P > \mu_G$, i.e. if lobbying power of energy firms is larger than the fiscal revenue benefits.

Proposition 3 suggests that the policy problem for the regulator becomes one of comparing business-as-usual with the corner solution of zero fossil fuel emissions (and investments) and choosing the policy that creates the highest pay-offs for the government.

Corollary 4. *(Choice of equilibrium tax) (i) If lobbying power of energy firms is sufficiently small, $\mu_P < \mu_G$, only the prohibitive carbon tax will be an equilibrium outcome. (ii) If $\mu_P > \mu_G$, the government will choose fossil phase-out over no climate policy if and only if*

$$CS_{\tau=0} + (1+\mu_N)q_{\tau=0} - D(E_{\tau=0}) < CS_{\tau=\tau^\star} + (1+\mu_N)q_{\tau=tau^\star} \tag{30}$$

In particular, the policy choice is independent from public finance aspects or lobbying power of land owners and fossil energy firms.

Proof. A rational government will only choose a (time-consistent) equilibrium tax. Case (i) follows directly from the proof of Proposition 3. For case (ii), only two equilibrium taxes exist, $\tau = 0$ and $\tau = \tau^\star$ according to Proposition 3.[8] The government chooses then the policy that gives higher government welfare W_G as defined in (15). As both taxes are equilibrium taxes (and are not revised), producer surplus is zero in both cases. Government revenues are zero as are the tax or the tax base (emissions). The simplified condition then immediately follows as $D(0) = 0$. Note further that when case (ii) holds, the tax choice is independent of μ_P and μ_G. □

This corollary gives another remarkable result: While Corollary 3 implies that lobbying power by fossil or renewable firms or public finance aspects causes time in-

[8] Technically, the second policy also includes all taxes higher than $\tau^\star$. In order to avoid unnecessary clutter in proofs, we subsume the full set of excessively high taxes under that case as the outcome of higher taxes is equivalent to $\tau = \tau^\star$.

consistency, these aspects are irrelevant for the final choice of the equilibrium carbon tax of the government when two equilibria exist. The reason is that for the equilibrium taxes, profits of fossil and renewable firms are zero anyway and so no tax revenues arise. Profits occur in these two sectors only when deviating from an announced tax. Profits in one sector, however, necessarily result in stranded assets in the other sector.

The choice of the equilibrium tax turns out to be rather simple. It is a comparison of consumer surplus, damages and land rents under business-as-usual vs. under a fossil energy ban. Hence, lobbying power of environmentalists, consumers and landowners matter for the final policy outcome, while public finance aspects and lobbying of firms (investors) reduce the policy space to a binary decision problem.

4.4 Time inconsistency and the environment

Under imperfect commitment, the optimal second-best carbon tax from Section 4.1 becomes time-inconsistent and the carbon tax can therefore not be an equilibrium outcome. Under rational expectations, a time-consistent bang-bang environmental policy will prevail where all or no emissions are reduced (third-best policy). In the following, we analyze the environmental implications of the commitment problem.

Consider a linear approximation of the environmental damage function, thus, $D(E) \approx \delta E$ with δ the constant marginal damages.[9] Let $\tilde{E}$ be the emissions if the carbon tax is zero. From Proposition 1 , it follows that the second-best tax under commitment will always be positive and, thus, emissions will never exceed $\tilde{E}$. If marginal costs of public funds are zero and there is no lobbying power by rent owners, the carbon tax in the political economy is the standard Pigouvian tax and achieves a first-best emission outcome. In the first-best case, the tax will be zero when marginal damages are zero, $\delta \to 0$. In the presence of lobbying power or fiscal considerations, the tax will be higher and emissions will be lower than $\tilde{E}$. As a first-order effect, $\frac{dE}{d\delta} \leq 0$ because $\frac{dE}{d\tau} \leq 0$ from Proposition 1 and, with (16), $\frac{\partial \tau^c}{\partial \delta} = 1$. Hence, the first-order approximation of the emissions curve is downward sloping in δ. This behavior is illustrated in Fig. 2. The solid black line represents the first-best outcome, equivalent to the Pigouvian tax when $\mu_G = \mu_N = 0$. The solid grey lines illustrate the second-best tax with land owners' lobbying power ($\mu_N > 0$) or public revenue considerations ($\mu_G > 0$). Due to changes in δ, however, the second-best tax changes and therefore also the left term in (16) changes, creating second-order effects. As shown in Corollary 1, the second-best tax is higher (lower) than the Pigouvian tax if E is rather low (high). Under this second-order effect, the emission curve under perfect commitment might therefore be locally upward-sloping as indicated by the dotted line in Fig. 2. As δ becomes large

[9] We use this linearization to capture the magnitude of the environmental damages in one single parameter, δ.

enough, the right term in (16) increases without bound and a corner solution with zero emissions will eventually hold due to (19). In sum, for the first-best and second-best tax, we have $0 \leq E \leq \tilde{E}$ for $\delta \to 0$ and $E \to 0$ for $\delta \to \infty$.

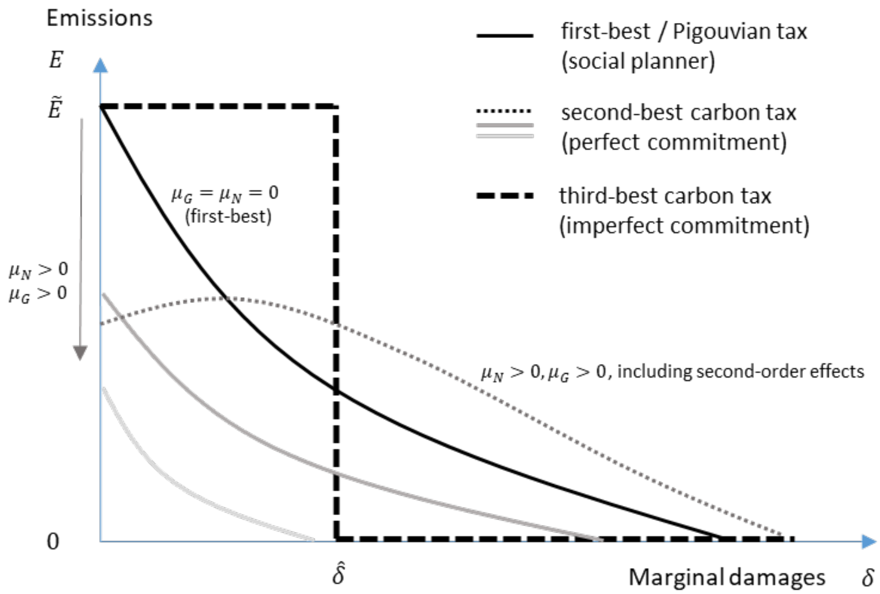
From (30) in Corollary (4), it follows that the emissions under the third-best policy without commitment will be $\tilde{E}$ if δ is sufficiently small and two equilibria exist. Let $\hat{\delta}$ be the critical value where the equilibrium policy switches from zero taxes to prohibitive taxes and, hence, emissions from $\tilde{E}$ to zero. This is illustrated by the dashed line in Fig. 2. When lobbying power of land owners is sufficiently large, $\hat{\delta}$ may become negative and the equilibrium carbon tax will be prohibitive for any positive marginal damages. If only one equilibrium exists, we have always zero emissions. From these considerations follows:

Corollary 5. *(i) When marginal environmental damages are high, the time-consistent third-best policy is characterized by lower or equal emissions than the first-best and second-best policies. (ii) When marginal environmental damages and lobbying power of landowners are low and lobbying power of energy firms is sufficiently high that the zero-tax equilibrium exists, the third-best policy will cause higher emissions than the first-best and second-best policies.*

The corollary says that the commitment problem does not need to be bad for the environment. In particular, if marginal damages are high, the time-consistent third-best policy will be more stringent as it become more likely that a zero-emission outcome prevails. On the contrary, imperfect commitment weakens environmental policy if the environmental externality is small, if landowners have little political power and energy firms large political power. In that case, a business-as-usual emissions outcome becomes more likely, which would imply higher emissions than the optimal tax under commitment.

Studying the welfare implications of imperfect commitment is less straightforward. Taking the social planner's objective as a welfare function disregards all political economy and fiscal revenue aspects. The second-best and third-best policy will therefore always involve welfare losses. It is, however, not obvious whether the welfare losses of the third-best policy are greater than those of the second best policy. Fig. 2 illustrates various cases in which carbon emissions under the third-best policy are, in absolute terms, closer to the first-best outcome than the emissions under the second-best policy (i.e. when damages are small, or when damages are large and the second-best policy is below the Pigouvian level due to fiscal revenue effects). These cases could indicate situations in which the third-best policy might actually be welfare-improving compared to the second-best policy.

Figure 2: Emissions and marginal damages δ under perfect and imperfect commitment.



Note. For the third-best policy, $\mu_P > \mu_G$ is assumed as otherwise only the prohibitive tax with zero emissions prevails.

5 Discussion

In this section, we discuss some of the key model assumptions about production technologies as well as possible implications of considering alternative policies to carbon pricing.

5.1 Dynamics with more general production functions

A critical assumption of our model is the Leontief production function for fossil energy. We justify this functional form by the characteristics of fossil power plants. Final energy generation depends directly on the energy that is contained in a specific fossil fuel (e.g., specific sub-categories of coal, such as lignite, sub-butimous coal etc. or natural gas). Capital in turn cannot (directly) substitute fuel due to basic thermodynamic limits. One could argue, though, that capital could increase the energy convergence efficiency and hence could substitute for labor in the production process. There are, however, only limited possibilities to increase the carbon efficiency in fossil energy production. Additional investments as well as technological progress in the past have only slowly increased conversion rates. For example, investment costs of ultra-supercritical plants (with an expected efficiency rate of 39%) compared to less efficient super critical plants (with an expected efficiency of 36 %) are expected to increase by 16% (WCA, 2016). Gas power plants are usually more efficient (with efficiency levels higher than 50 %, (EIA, 2016)), but fuel costs are considered to be significantly higher in most areas. Comprehensive assessments on future mitigation scenarios see some mitigation potential by shifting from coal to gas in the power sector (Clarke et al., 2014). Most mitigation, however, comes from shifting towards non-fossil technologies, such as renewable energy technologies (Clarke et al., 2014). While carbon capture and storage could be considered as a way to reduce emissions close to zero by simultaneously using fossil energy, it is in our model conceptually equal to a renewable energy technology. While for renewables we assume decreasing marginal productivity due to increasing scarcity of the best production sites (e.g., the windiest locations), for CCS increasing scarcities in underground storage sites could be considered as the reason why marginal productivity of capital decreases with expanding production, see Kalkuhl et al. (2015). For fossil fuels, the choice of the Leontief production function is hence adequate when abatement in that technology can only be achieved through reductions in output production. It therefore seems to be a plausible approximation in the fossil power sector without CCS.

Nevertheless, we illustrate how a more general production function in the fossil energy sector would affect the dynamics discussed in this paper. For a typical neoclassical production function – ruling out Leontief for the moment – the first order condition in the fossil energy sector in the decentralized economy (9) had to be replaced by two conditions, one for investments $\frac{\partial \pi_F}{\partial K_F} = 0 \Leftrightarrow p = \frac{r}{\partial Y_F / \partial K_F}$ and one for emissions $\frac{\partial \pi_F}{\partial E} = 0 \Leftrightarrow p = \frac{w+\tau}{\partial Y_F / \partial E}$. The derivation of the optimal carbon tax corresponding to (16) is more tedious, but is also straight-forward. There will be a substantial change in time-inconsistency dynamics, however. With the Leontief production function, three different cases need to be considered; with a non-Leontief neoclassical production function, only a modification of the middle case in (21) holds. In particular, the response function needs to be multiplied by an additional term $\psi(E, \tau^c)$. Instead of the three cases in (21) we obtain just (see appendix for derivation): $\frac{dE(\tau,\tau^c)}{d\tau} = d'(\cdot)\psi(E,\tau^c)$ with $\psi(E,\tau^c) = \left[\left(\frac{\partial Y_F}{\partial E}\right)^2 + \varepsilon_{Y,p} Y \frac{\partial^2 Y_F}{\partial E^2}\right]^{-1}$ Without the different cases to consider, one would then put the response function into the welfare function and calculate the optimal response as well as the equilibrium policy under rational expectations. The suggestive outcome would be that the ex-post tax will be higher or lower depending on whether the public finance effect or the lobbying power of fossil firms is stronger. We would further expect an interior solution of the equilibrium tax to evolve as the response function is smoothly differentiable. In summary, using a non-Leontief production function would increase the complexity in the formal expressions substantially, but would not add new dynamics. The key feature of the Leontief production function is to allow different regimes to hold – one in which carbon taxes reduce emissions by reducing fossil energy production and one in which carbon taxes affect public revenues and profits but not emissions and energy production. This feature makes the Leontief technology interesting from a political-economy perspective.

The choice of the Cobb-Douglas production function for renewable energy can easily be relaxed by using any other homothetic production function in land and capital. For the key propositions, we used only the homothetic property. The Cobb-Douglas specifications, however, allow one to refer to the constant land income share $1 - \alpha$ in the renewable sector, which is relevant for the public finance motive of carbon taxes. With a more general homothetic production function, α has to be replaced by a non-constant and more complex expression, which would make interpretation of the carbon tax under public finance aspects less intuitive, though the results would not be altered.

5.2 Alternative policy instruments to carbon taxes

Given our results, it is not immediately obvious how policy can avoid the problem of time inconsistency. Any policy that achieves the optimal allocation of *investments* in fossil and renewable energy is subject to a new or modified carbon tax after investments have been made. A tax on fossil investments, for example, can reduce fossil capacity to the socially optimal level. After investments are sunk, however, the regulator can introduce a carbon tax to raise public revenues (or a carbon subsidy to benefit fossil energy firms). As rational investors anticipate this, they will adjust their investments.

There may, however, be a compelling argument that changing the level of a tax ex-post comes at lower political and institutional costs than introducing a completely new tax. The main reason is the complex legislation process that includes public hearings and debate as well as necessary impact assessment by the regulator. If introducing a new instrument ex-post is indeed considerably more costly than changing the level of a tax, investment taxes may become more favourable. The optimal investment tax on fossil energy investments is then effectively an upfront tax on carbon emissions that will be released when fossil firms operate at full capacity. As firms always operate at full capacity when a policy is credible, the optimal investment tax is just $\varsigma^* = \gamma_F \tau^*$ with γ_F indicating the life-time carbon emissions per dollar invested in fossil capacity and τ^* indicating the optimal carbon tax (which is given in (16) when governments can commit).

The regulator could further increase credibility in announced policies by increasing the costs of deviating from the announced policy, ψ_2. Examples include a constitutional state of carbon pricing (and its level) or delegation to an independent institution like a central bank (Brunner et al., 2012). This, however, might come with the costs of reduced flexibility or democratic legitimacy.

6 Conclusion

In this paper, we have developed a stylized model of the power sector with (non-polluting) renewable and (polluting) fossil firms. In this model, stranded assets result from the government strategically deviating from a previously announced (climate) policy. Both renewable and fossil energy related assets can become stranded, depending whether actual carbon prices are higher or lower than previously announced. Stranded assets are therefore a consequence of a time-inconsistent policy. In contrast to existing literature, we endogenize stranded assets in the optimization of the governments' objective function. Hence, we do not have to assume ad-hoc changes in climate policy as is typically done for analyzing stranded assets (Carbon Tracker Initiative, 2013).

In a dynamic policy setting, this cannot be expected to be a stable outcome as rational firms will anticipate the government's deviation. When the government in turn anticipates the firms' response, a rational expectations equilibrium emerges in which no agent has an incentive to deviate. This leads to a paradox situation: the problem of stranded assets disappears again as the equilibrium policy is time-consistent. In this case, we show that only two equilibrium third-best policies are conceivable: one in which no carbon tax is applied (business-as-usual) and one in which the carbon tax is prohibitively high, i.e. where no fossil energy is used. Thus, climate policy is torn between extreme policy cases – all or nothing.[10] Moreover, note that imperfect commitment that makes the second-best policy time-inconsistent does not necessarily need to be bad for the environment. The equilibrium tax without commitment will cause lower pollution than the optimal policy under commitment if marginal damages are sufficiently large.

Our research emphasizes that stranded assets in reproducible capital of energy firms as well as commitment problems by governments may not be the key problem for effective climate policy. Also, the lobbying power of energy firms is irrelevant under the perfect commitment policy and under imperfect commitment whenever a bipolar third-best policy equilibria exist. Rather, the lobbying power of land owners – owners of non-reproducible capital –, environmentalists and consumers (paying higher energy prices) are decisive for policy choice.

Although lobbying of fossil fuel asset owners, as well as public finance aspects, make the second-best carbon tax time-inconsistent, both issues are irrelevant for the choice of the equilibrium carbon tax. It is only determined by consumer surplus, land rents and climate damages and is only affected by the lobbying power of landowners. Moreover, note that imperfect commitment that makes the second-best policy time-inconsistent does not necessarily need to be bad for the environment. The equilibrium tax without

[10] Note that this outcome prevails even if the social planner initially chose an intermediate climate policy.

commitment will cause lower pollution than the optimal policy under commitment if marginal damages are sufficiently large.

Although a large strand of literature emphasized the role of fossil resource rents (Sinn, 2008; Edenhofer and Kalkuhl, 2011; Harstad, 2012; Kalkuhl and Brecha, 2013), it is the political power of landowners that might become increasingly relevant for climate policy to be successful. Recent research emphasizes the large demand for land by some mitigation and negative emissions technologies, such as bioenergy with carbon capture and storage (Smith et al., 2016). But, non-bioenergy related technologies such as wind and solar power also require land and may substantially impact land prices (Haan and Simmler, 2018). The role of land rents and lobbying power by landowners (notably farmers) in the context of climate policy has hardly been analyzed. Interestingly, in contrast to fossil fuel owners, they might support mitigation policy, as farmers can experience high climate damages (Schlenker and Roberts, 2009). Hence, farmers and (agricultural) landowners might not only become the driving political lobbying force in favor of ambitious climate policy; they could also determine which policy equilibrium will be chosen.

A Marginal costs of public funds

Table 2: Marginal costs of public funds (MCFs)

Country	Barrios et al. (2013)	Kleven and Kreiner (2003)
	Labor taxes	All taxes incl. benefits
Denmark	2.31	1.68
Finland	1.61	1.98
France	2.41	1.57
Germany	1.96	2.12
Hungary	1.53	–
Italy	1.68	1.38
Poland	1.63	–
Spain	1.79	1.34
Sweden	2.06	1.74
United Kingdom	1.81	1.37
United States	–	1.15

B Proofs

B.1 Proof of proposition 1

Because of homothetic production functions and no changes in the announced carbon tax, no excess capacity is builtd and profits in both sectors are zero for any choice of the carbon tax (thus, producer surplus does not change and $\frac{dPS}{d\tau} = 0$). The total derivative of W^G after τ is

$$\frac{dW^G}{d\tau} = \frac{dCS}{d\tau} + (1+\mu_G)\frac{dG}{d\tau} - \frac{dD(E)}{d\tau} + (1+\mu_N)\frac{dq}{d\tau} \tag{31}$$

The change in consumer surplus due to the tax is $\frac{dCS}{d\tau} = \frac{dY}{d\tau}p - \left(\frac{dp}{d\tau}Y + \frac{dY}{d\tau}p\right) = -\frac{dp}{d\tau}Y$. The change in government revenue is $\frac{dG}{d\tau} = E + \tau\frac{dE}{d\tau}$ and damages change according to $\frac{dD(E)}{d\tau} = D'(E)\frac{dE}{d\tau}$. Finally, changes in land rent, using (12), are

$$\frac{dq}{d\tau} = \frac{dp}{d\tau}\frac{\partial Y_R}{\partial N} + p\frac{d(\partial Y_R/\partial N)}{d\tau} = \frac{dp}{d\tau}\frac{\partial Y_R}{\partial N} + p\frac{\partial Y_R^2}{\partial N \partial K_R}\frac{dK_R}{d\tau}$$

Totally differentiating (10) after τ gives

$$\frac{dK_R}{d\tau} = \frac{-\frac{dp}{d\tau}\partial Y_R/\partial K_R}{p\partial^2 Y_R/\partial K_R^2}$$

with $\frac{dK_R}{d\tau} < 0$. Substituting this into $\frac{dq}{d\tau}$ and using further that $-\frac{\partial^2 Y_R/\partial K_R \partial N}{\partial^2 Y_R/\partial K_R^2} = \frac{K_R}{N}$ (because Y_R is homothetic), we finally get

$$\frac{dq}{d\tau} = \frac{dp}{d\tau}\left(\frac{\partial Y_R}{\partial N} + \frac{\partial Y_R}{\partial K_R}K_R\right) = \frac{dp}{d\tau}Y_R$$

Hence, we obtain for $\frac{dW^G}{d\tau}$ (using further that $Y = Y_F + Y_R = E + Y_R$ and that $\frac{dp}{d\tau} = 1$ due to (9) if no corner solution prevails)

$$\frac{dW^G}{d\tau} = \mu_G Y_F + \big((1+\mu_G)\tau - D'(E)\big)\frac{dE}{d\tau} + \mu_N Y_R$$

Setting this equal to zero gives the final result. Note further that using (14), $\frac{dE}{d\tau} = d'(p) - \frac{dY_R}{d\tau} = d'(p) - \frac{\partial Y_R}{\partial K_R}\frac{dK_R}{d\tau} < 0$.

If a corner solution with zero fossil energy production and $K_F = 0$ occurs, $\frac{dp}{d\tau} = \frac{dE}{d\tau} = 0$ and, thus, $\frac{dW^G}{d\tau} = 0$.

B.2 Emission response function under non-Leontief technology

The first order conditions for a general neoclassical production function in the fossil energy sector read:

$$\frac{\partial \pi_F}{\partial K_F} = 0 \Leftrightarrow p = \frac{r}{\partial Y_F / \partial K_F} \tag{32}$$

$$\frac{\partial \pi_F}{\partial E} = 0 \Leftrightarrow p = \frac{w + \tau}{\partial Y_F / \partial E} \tag{33}$$

$$\frac{\partial \pi_R}{\partial K_R} = 0 \Leftrightarrow p = \frac{r}{\partial Y_R / \partial K_R} \tag{34}$$

We need to assess how emissions respond to a change in the ex-post tax, when investments haved already been made and capital stocks K_F, K_R are fixed. Totally differentiating (33) after τ gives:

$$1 = \frac{dp}{d\tau}\frac{\partial Y_F}{\partial E} + p\frac{\partial^2 Y_F}{\partial E^2}\frac{dE}{d\tau} \tag{35}$$

with $p = d^{-1}(Y_F + Y_R)$, $\frac{dp}{d\tau} = \frac{1}{d'(\cdot)}\frac{\partial Y_F}{\partial E}\frac{dE}{d\tau} = p'(\cdot)\frac{\partial Y_F}{\partial E}\frac{dE}{d\tau}$ follows:

$$1 = \left[\frac{1}{d'(\cdot)}\left(\frac{\partial Y_F}{\partial E}\right)^2 + d^{-1}(\cdot)\frac{\partial^2 Y_F}{\partial E^2}\right]\frac{dE}{d\tau} \tag{36}$$

Note that the announceds carbon tax τ^C determines capital stocks K_F, K_R in the first stage and the expression in the RHS of (36) depends in general on E. Hence, (36) is equivalent to

$$d'(\cdot) = \psi^{-1}(E, \tau^C)\frac{dE}{d\tau} \tag{37}$$

with $\psi^{-1}(E, \tau^C) = \left(\frac{\partial Y_F}{\partial E}\right)^2 + d^{-1}(\cdot)d'(\cdot)\frac{\partial^2 Y_F}{\partial E^2} = \left(\frac{\partial Y_F}{\partial E}\right)^2 + \varepsilon_{Y,p} Y \frac{\partial^2 Y_F}{\partial E^2}$. We therefore obtain $\frac{dE}{d\tau} = d'(\cdot)\psi(E, \tau^C)$.

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