# Special Interest Climate Policy

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**Abstract**

Can firms capitalize on social objectives? We scrutinize a mechanism for firms' private interests in climate externalities: In a dynamic common agency model, the private interest in internalizing externalities arises endogenously from interaction between income growth, social costs, and rents in dirty and clean productions. The mechanism shows how subsidies to socially harmful actions turn to externality prices and special interests can implement energy transition faster than socially optimal.

**Keywords:** Climate change, rents, organized special interests, dynamic games

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# 1 Introduction

Can special interests representing corporate profits internalize such grand externalities as climate change? While the common concern is that "*firms [are] spending millions lobbying to block climate change policies*",[1] evidence points to a more nuanced picture where diverse interests lead to some firms lobbying for and others against climate policies (Kim, Urpelainen, & Yang, 2014). In fact, it is not uncommon that firms spending millions to undermine policies turn later to policy advocates. Private interests are pushing for policies that are socially beneficial but, clearly, privately costly.[2]

While arguments for broader than profit objectives for firms are not in short supply (e.g., Hart & Zingales, 2017), it is not obvious how social objectives can turn to market value. Yet, policy-makers concerned with externalities may become a source of market value to firms that end up "internalizing" externalities. Evidence informs us that shareholders value "investments in influence" (Hill, Kelly, Lockhart, & Van Ness, 2013) and that, more specifically, returns to lobbying in the energy sector can be very high (Kang, 2016) — there is no *a priori* reason to rule out lobbying returns arising from the social desirability of the private activity as a source of market value for firms.

To explain why, when, and how private and social interests become aligned, we develop a dynamic common agency model with two main elements. First, the agent making policy decisions today is representative in all aspects but income: Special interests distort the income of the agent in office but otherwise the decision-maker internalizes all current and future market and non-market impacts of policies, as the agent experiences these herself as the future representative agent with normal income.

Second, principals from industries compete to influence the agent's decisions but, at the same time, rents in production cannot be competed away. Sunk past investment in power plants can lead to rent protection as free-entry investments in a declining industry is not possible (Baldwin & Robert-Nicoud, 2007). Simultaneously, new rents are created, e.g., for renewable energy sources located in the best sites. The energy sector is famous for its leverage in policy making, and rent destruction and creation seem likely drivers of the influence.[3]

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[1] Guardian, 26/09/2019.

[2] It is common for energy giants to announce bold stroke plans to reduce dependence on fossil fuels and use more renewable energy. One often-cited case is Duke Energy: "*Duke Leaves Coal Group Over Anti-Climate Bill Stance*". BusinessGreen, 3 September 2009. See also https://www.c2es.org/our-work/belc/, and https://www.euractiv.com/topics/magritte-group/

[3] See Kalkuhl, Steckel, and Edenhofer (2020) for a quantitative illustration of the quantitative rele-

We find dynamics that is new to menu auctions (Bernheim & Whinston, 1986) and the common agency applications: The principals' interests in the agent's actions changes endogenously on the equilibrium path, giving rise to "private interest in social objectives". In applied terms, subsidies to socially harmful production (i.e., fossil fuels) turn to externality taxes together with subsidies to green solutions as the relative returns from influencing these policies evolve with agent's wealth. It is thus the growth of income together with externalities that drive the decline of fossils and demand for renewables as a pollution-free solution.

The income-driven change in the private interests feeds back to drive the respective rise and fall of clean and dirty industries. This two-way dynamics is the main result of the paper, contrasting the one-way explanations for policy persistence; that is, why is it that policies protecting industries tend to persist without a clear efficiency justification (Brainard & Verdier, 1997; Coate & Morris, 1999; Baldwin & Robert-Nicoud, 2007; Kerr, Lincoln, & Mishra, 2014). The novelty of our mechanism arises purely from the dynamics of stakes that industries have in the economy. A declining industry, all else equal, captures an increasing share of the total value added as net rents (market rents minus contributions), until the industry collapses. Towards the end, the industry does not care about the future stakes in the economy and will thus distort more. In our specific application, a balancing act comes from the growing renewable energy industry that has a reason to look forward. In fact, in our quantitative illustration, by focusing on the green rents, the industry ends up buying a faster than socially optimal implementation of climate policies.

With no intention to explain cross-country variation in policies, we note however that the sum of total global fossil-fuel subsidies was at least three times larger than the renewable energy subsidies in 2014, low or middle income countries handing relatively greater subsidies to fossil fuels (IEA, 2016). According to Coady et al. (2015) subsidies are a staggering 13-18 % of GDP in a set of major emerging economies but the advanced country average is about 2.5 %. In addition to direct producer and consumer subsidies, lower income regions tend to leave out the externality costs arising from energy consumption to a greater extent, suggesting that income levels are associated with willingness to include externality payments in taxes.

Our climate-specific contribution is to extend the work-horse climate-economy model by Golosov, Hassler, Krusell, and Tsyvinski (2014) to cover the dynamics of special-interest influence. By restricting attention to a parametric class for preferences and

vance of land-use related rents in comparison to fossil-fuel rents.

technologies, this model has proven extremely useful in analytical works seeking to maintain the fundamentals of comprehensive climate-economy models.[4] We focus on Markov Perfect Equilibria, following Bergemann and Välimäki (2003)[5], and identify a new class of Markov strategies, called homogeneous strategies, that preserve the structure essential for the applied work building on Golosov et al. (2014). We can prove the existence and uniqueness of the homogeneous MPE, and can sharply characterize how measures of rents, income, and climate impacts shape the policy implementation. For example, it is not necessary to solve equilibrium strategies explicitly to predict the share of value-added taken by industries over time.

Conceptually, this paper differs from the core of applied common agency papers in that we have a joint inclusion of (i) non-transferable utility between the agent and principal (as in Dixit, Grossman, and Helpman (1997)) and (ii) a political relationship that is dynamic. These properties produce the endogenously changing private interest in externalities which we have not seen in the literature, including those with environmental focus (Aidt, 1998; Damania, 2001; Fredriksson & Svensson, 2003; Fredriksson, Vollebergh, & Dijkgraaf, 2004).

## 2 The allocation problem

There are two energy types, fossil fuel $i = D$ (dirty) and renewables $i = C$ (clean). Time is discrete and extends to infinity, $t \in \{..., 0, 1, 2, ..\}$. Let

$$h_t = \{..., E_{D,t-3}, E_{D,t-2}, E_{D,t-1}\}$$

be the history of fossil-fuel use at time $t$, assumed to impact the aggregate gross output through the total factor productivity in the economy:

$$\Omega(h_t)F_t(E_{D,t}, E_{C,t}, L_t) \tag{1}$$

where $F_t(E_{D,t}, E_{C,t}, L_t)$ is a constant-returns-to-scale output function depending on energy inputs and labor, $L_t$, which is supplied exogenously, and

$$\Omega(h_t) = \exp(-\sum_{n=1}^{\infty} \theta_n E_{D,t-n}), \tag{2}$$

[4]These include: the long delay between emissions and impacts (Gerlagh & Liski, 2017); the role of income in externality pricing; learning of climate impacts (Traeger, 2015; Gerlagh & Liski, 2016).

[5]However, the dynamic extension provided by these authors applies only to the transferable utility case.

where the sequence of weights $(\theta_n)_{n\geq 1}$ is taken as given. The "impulse-response" from the history can be micro-founded, which we illustrate shortly (Gerlagh & Liski, 2017); this link between past input choices and current total factor productivity (TFP) is main dynamic feature of the model. By this assumption, climate change is at the heart of the production technology (as in Golosov et al., 2014), although direct utility losses could be equally relevant.[6]

The aggregate net output, gross output minus energy production costs, is

$$Y_t = \Omega(h_t)\Big(L_t f_t(\frac{\sum_i E_{i,t}}{L_t}) - \sum_i c_i(E_{i,t})\Big) \tag{3}$$

where $c_{i,t} = \Omega(h_t)c_i$ is the cost function for energy production in sector $i$, and for convenience of notation we use $\sum_i$ for $\sum_{i=D,C}$. We note that, although the gross output has constant returns to scale, the net output $Y_t$ fails to do so as long as the energy cost is strictly convex, which is assumed throughout this paper. The rents in the energy sector will arise from this property.

We assume a representative consumer at each $t$, enjoying consumption utility $U(C_t) = \ln(C_t)$ at $t$. The consumer cares about the welfare of consumer $t+1$, giving it weight $0 < \beta < 1$, which, for a sequence of consumption $(C_n)_{n\geq t}$, leads to a dynastic representation of welfare

$$W_t = \ln(C_t) + \beta W_{t+1} \tag{4}$$

where $W_t$ is the value of the consumption program. The consumer's budget constraint is simply $C_t = Y_t$.

The socially optimal allocation maximizes the welfare of the representative consumer over time where the welfare is defined through a sequence of consumption utilities, $(U_t)_{t=0}^{\infty}$. The next lemma describes the dependence of the social optimum on history $h_t$.

**Lemma 1** *Utility and welfare in the social optimal allocation satisfy*

$$\begin{aligned} U_t^{SO}(h_t) &= \overline{U}_t^{SO} - \sum\nolimits_{n=1}^{\infty} \theta_n E_{D,t-n} \\ W_t^{SO}(h_t) &= \overline{W}_t^{SO} - \sum\nolimits_{n=1}^{\infty} \sum\nolimits_{i=0}^{\infty} \beta^i \theta_{n+i} E_{D,t-n} \end{aligned}$$

*where the first terms on the right-hand side denote a value sequence $(\overline{U}_t^{SO}, \overline{W}_t^{SO})$ that is dependent on current and future technology but independent of history $h_t$, and the second terms depend on history through the weights $\theta_n$ given by the climate-economy description.*

[6]This formalization, together with the time-structure of impacts, can replicate the outcomes of the detailed climate-economy model outputs quite well; see van den Bijgaart, Gerlagh, and Liski (2016).

The result thus separates the utility and welfare sequences into those arising from exogenous growth sources (i.e., technology) and those that capture the burden of past emissions. To see how the result arises and what it means, consider planner at $t$ choosing the optimal energy mix, when both energy sectors $i = D, C$ are active, to satisfy:

$$U'(Y_t)\frac{\partial Y_t}{\partial E_{i,t}} = -\beta \frac{\partial W_{t+1}}{\partial E_{i,t}}. \tag{5}$$

The right-hand side is the social cost of the energy use $E_{i,t}$ which for clean energy $i = C$ is zero but, for $i = D$, Lemma 1 implies:

$$-\frac{\partial W_{t+1}}{\partial E_{D,t}} = \sum\nolimits_{i=1}^{\infty} \beta^{i-1}\theta_i \equiv \Theta.$$

The social cost is thus a constant but it can still capture a rich time-structure of impacts, attributable to the delays and interactions in the climate system. Gerlagh and Liski (2017, Theorem 1), develop damage time structure $(\theta_n)_{n>0}$ based on a system of carbon and heat reservoirs in the climate system where flows between reservoirs are linear in stocks (Joos et al., 2013). Our quantitative analysis builds on this representation to calibrate the social costs.

The left-hand side of (5) is the utility-weighted marginal value of energy use today. Given the log utility, we may rewrite for dirty energy

$$\frac{\partial Y_t}{\partial E_{D,t}} = \beta \Theta Y_t,$$

giving the monetary externality price that the planner would like to implement on the use of $E_{D,t}$. As in Golosov et al. (2017) and Gerlagh and Liski (2018a, 2018b), the externality price depends on the income level, capturing the idea that the willingness to pay for pollution reductions depends on income.

To explicate the mechanisms that we want to capture and quantify by this formalization, an illustration might help. Consider

$$F_t(E_{D,t}, E_{C,t}, L_t) = A_t\big(A_{D,t}E_{D,t} + A_{C,t}E_{C,t}\big)^{\gamma_t} L_t^{1-\gamma_t} \text{ and } c_i(E_{i,t}) = \delta_{i,t}E_{i,t}^{\frac{1+\sigma}{\sigma}}$$

for $i = D, C$ where output function $F_t$ allows flexible changes in productivity drivers $(A_t, A_{D,t}, A_{E,t})$ and also in factor shares $\gamma_t$. Energy cost assumes constant elasticity form at time $t$, with $\sigma > 0$, and time-dependent cost shifter $\delta_{i,t}$. Appropriate choices for the time-changing parameters allow avoiding unrealistically deep early reductions of emissions, if such are incentivized by policies; parameter choices can approximate the energy sector capital adjustment delays (Hassler et al., 2012). Fossil energy is formalized as a reproducible good, but this assumption is not critical as long as the economy does not find it optimal to consume all fossil-fuel resources, due to climate damages (see also Golosov et al., 2014). Energy production is subject to diminishing returns, resulting in, for example, land rents in renewable energy production (Fischer and Newell, 2008).

In social optimum, the above functional forms imply

$$\frac{1}{F_t - \sum_i c_{i,t}} \times \Big( \underbrace{\gamma_t A_{D,t} \frac{F_t}{\sum_i E_{i,t}}}_{\substack{\text{marg prod of energy} \\ \text{in gross output}}} - \underbrace{\frac{1+\sigma}{\sigma} \frac{c_i(E_{i,t})}{E_{i,t}}}_{\text{marg prod costs of fuel}} \Big) = \mathbf{I}(i)\beta\Theta$$

where indicator $\mathbf{I}(i) = 1$ is iff $i = D$ (the future social cost arises only for the dirty energy). The current marginal utility-weighted gain from increasing $E_{i,t}$ is balanced against the future welfare loss. Because climate change is a TFP shock in our formulation, $\Omega(h_t)$ impacts income level multiplicatively but the marginal utility of that income inversely and so drops out from the planner's trade-off at any given $t$. Still, the history impacts the welfare level which will importantly shape the contributions made by the interest groups in the common agency game analyzed just below. Given the parametric class, the optimal energy mix sequence $(E_{i,t})_{t=0}^{\infty}$ for $i = D, C$ can be found through a sequence of choices solving the trade-off just outlined, defining period-by-period the history-independent part of the utility $\overline{U}_t^{SO}$.

## 2.1 Competitive equilibrium.

Given an allocation sequence $(E_{D,t}, E_{C,t})$, we can interpret it as an equilibrium outcome in which the agent's policy instruments are taxes $\tau_t = (\tau_{D,t}, \tau_{C,t})$ which, as instruments applied at the industry level, are perhaps more natural than energy output quotas. Decentralization also gives a microstructure for rents and links them to the policy distortions below.

**Final goods.** Taking unit taxes $\tau_{D,t}$ and $\tau_{C,t}$ (subsidies if negative) as given for now, consider a final good sector, where the representative firm has access to the production technology and decides on the use of the two energy inputs, with profits

$$\Pi_{Y,t} = \Omega(h_t) L_t f_t\Big(\frac{E_{D,t} + E_{C,t}}{L_t}\Big) - \sum_i (\tau_{i,t} + \mu_{i,t}) E_{i,t} - w_t L_t \quad (6)$$

where $\mu_{i,t}$ is the market price of the specific energy type, $w_t$ is the market wage, and $L_t$ denotes labor input. Since $L_t f_t(\cdot)$ is a constant-returns-to-scale technology, final-goods sector competitive profits are zero, $\Pi_{Y,t} = 0$.

In the competitive equilibrium, energy prices plus taxes equal marginal product of energy,

$$\Omega(h_t)f_t'(e_t) = \tau_{i,t} + \mu_{i,t}, \tag{7}$$

and wages equal marginal productivity of labour,

$$w_t = \Omega(h_t)[f_t(e_t) - f_t'(e_t)e_t], \tag{8}$$

where $e_t = \sum_i E_{i,t}/L_t$ is energy intensity.

**Energy supply.** In the energy sectors $i = D, C$, profits from energy input choices in period $t$ are

$$\Pi_{i,t} = \mu_{i,t}E_{i,t} - \Omega_t c_{i,t}(E_{i,t}) \tag{9}$$

where cost $c_{i,t}(E_{i,t})$ is assumed to define constant-elasticity energy supply,

$$\sigma = \frac{\partial E_{i,t}}{\partial \mu_{i,t}} \frac{\mu_{i,t}}{E_{i,t}} > 0, \tag{10}$$

which allows us to work with tractable expressions for rents. We have no prior if it is sector $i = D$ or $i = C$ that should have larger $\sigma$, and so we settle on symmetric $\sigma$ for the sectors; with symmetric $\sigma$, other parameters that are potentially time-varying can still differ between the sectors. Rents and costs make up constant fractions of the value of the resource-specific energy output:

$$\Pi_{i,t} = \frac{1}{\sigma + 1}\mu_{i,t}E_{i,t} \tag{11}$$

$$\Omega_t c_{i,t} = \frac{\sigma}{\sigma + 1}\mu_{i,t}E_{i,t}. \tag{12}$$

**Households** Households consume the aggregate net output, gross output of the final goods sector minus energy production costs. Its value equals factor compensations plus taxes and rents in the energy sector,

$$Y_t = \Omega(h_t)\Big(L_t f_t(\frac{\sum_i E_{i,t}}{L_t}) - \sum_i c_i(E_{i,t})\Big) \tag{13}$$

$$= w_t L_t + \sum_i \Pi_{i,t} + \Gamma_t \tag{14}$$

$$= C_t \tag{15}$$

where $\Gamma_t = \sum_i \tau_{i,t}E_{i,t}$ denotes taxes collected, $c_{i,t} = \Omega(h_t)c_i$.

The Ramsey rule for households sets the discount factor for future values through the marginal rate of substitution between period $t$ and $t+1$:

$$r_{t+1} \equiv \frac{\partial W_t/\partial C_t}{\partial W_t/\partial C_{t+1}} = \frac{Y_{t+1}}{\beta Y_t}. \tag{16}$$

This defines the implicit gross return in the economy, $R_{t+1} \equiv \frac{1}{r_{t+1}}$. In the market interpretation of the allocation, the price of consumption can be recovered from consumers trading payoffs with different maturities (see, for example, Cochrane 2000).

As our baseline economy does not feature capital and firms maximize profits within periods, we do not need the discount factor for the equilibrium definition. Yet when firms engage in strategic lobbying they will assess the implications of current actions on the net present value of their assets. We come back to the discount factor below.

But first, we can define the competitive equilibrium, for given tax policies.

**Definition 1** *Given policies $\tau_t = (\tau_{D,t}, \tau_{C,t})$, for $t = 1, 2, ...$ , competitive equilibrium at $t$ is an allocation $(Y_t, C_t, E_{D,t}, E_{C,t})$, supported by prices $(\mu_{D,t}, \mu_{C,t}, w_t)$, with output defined through (1) − (2), where firms maximize profits $(\Pi_{D,t}, \Pi_{C,t})$, with (7) − (8), (11) − (12), holding, and households consume output, (13)-(15).*

Given the convex production set, we immediately see:

**Proposition 1** *Given a policy sequence $(\tau_t)_{t=0}^{\infty}$, the competitive equilibrium is recursively dynamic, uniquely determined by history and current policies. Competitive equilibrium allocations $Y_t^* = Y_t^*(\tau_t, h_t)$ and $E_{i,t}^* = E_{i,t}^*(\tau_t, h_t)$ for output/consumption and energy uses recursively solve the program $(t = 1, 2, ...)$*

$$\max_{E_{D,t}, E_{C,t}} Y_t - \tau_{D,t} E_{D,t} - \tau_{C,t} E_{C,t} \tag{17}$$

*subject to the production constraints (1) and (2).*

# 3 The policy game

**Policy maker.** The policy maker is in office for one period and shares the preferences of the representative consumer but has a different income due to contributions from the energy sector. Let $T_t = \sum_i T_{i,t}$ be the aggregate transfer from the industries. The consumption of the policy maker is $G_t = Y_t + \zeta T_t$, where $0 < \zeta < 1$ is the multiplier transforming each contributed euro to an aggregate income equivalent, in the eyes of the policy maker. Alternatively, $\zeta$ can measure the broadness of polity, or the size of the policy making population with whom transfer revenues are to be shared, or the cost-wedge between transfer donor and recipient. In Bernheim and Whinston (1986), second application, $\zeta$ would be economic influence.

The welfare of the decision maker in power in period $t$ is then

$$\ln\Big(Y_t + \zeta T_t\Big) + \beta W_{t+1} \tag{18}$$

where the policy maker's post-office welfare coincides with that of the representative consumer. That is, he becomes a citizen or, in the dynastic interpretation, cares about the welfare of the children who are not policy makers, while understanding the equilibrium choices of those in power in the future. The equilibrium mechanism we are interested in is fundamentally of general-equilibrium nature and therefore income is transferable but not utility (as in Dixit et al. (1997)). By accepting transfers today the policy maker has to compromise future welfare gains from efficiency, so the policy game is dynamic (as in Bergemann and Välimäki (2003)).

**Organized special interest.** We assume that there are $K_i > 1$ firms in each sector $i = D, C$. For an implementation of the policy game outcome in competitive markets, we assume that $K_i$ is large and, for convenience of exposition, we assume a representative firm in each energy sector $i = C, D$. However, equilibrium outcome of the policy game will maximize the value of grand coalition of firms (to be explicitly defined), and this property will be independent of whether firms are small, heterogenous, or perhaps active in both sectors.

The representative firm in each energy sector $i = C, D$ offers a transfer menu $T_{i,t}$ to the policy maker, depending on the policies implemented; we frequently use the aggregate transfer, $T_t = \sum_i T_{i,t}$, in the analysis. The policy maker decides on the energy mix $E_t = (E_{D,t}, E_{C,t})$; these can be implement through taxes and subsidies in the decentralized economy.

The organized special intrest is willing to offer transfers since energy production commands rents that are strictly increasing in both sectors if respective $E_{i,t}$ increases above the socially optimal energy use. As in Hillman (1982), we think of rents that arise from specific factors rather than from non-competitive profits (as, for example, in the Stigler-Petzman model of regulation). Write $\Pi_{i,t}(E_t, h_t)$ for the reduced rents that depend on the current energy mix and history and, for the moment, take the rent function as given; its microfoundations will be given in the Section on the decentralized economy.[7] For any given $(\Pi_{i,n}, T_{i,n})_{n\geq t}$, the net present value profits for each firm type $i = D, C$ is

$$V_{i,t} = \Pi_{i,t} - T_{i,t} + R_{t+1}V_{i,t+1} \tag{19}$$

where the discount factor $R_{t+1}$ is determined by the Ramsey rule (16). The principals are sophisticated, that is, a firm offering a transfer to the agent in power, foresees how the current actions influence the future values through the equilibrium strategies. Climate change, through productivity impacts on the aggregate economy, will also affect future rents and thus the value of the firm; this general equilibrium feature is part of our policy game.

**Strategies.** In each period $t$ starting with history $h_t$, the timing is the following:

1. Industries $i = D, C$ offer reward schedules $T_{i,t} = T_{i,t}(E_t, h_t)$;
2. The policy maker selects the energy mix, $E_t = (E_{D,t}, E_{C,t})$.

For given transfer schedules, the policy gives $E_{i,t}$ for industry $i$; it can be thought of as an output quota. Equivalently, when the policy is to use a sector-wide tax (or subsidy) on $E_{i,t}$, firms cannot lobby for firm-by-firm taxes.

The conduct of policies may come from the past, for example, "noblesse oblige" may be important for those in power, but we focus on Markov strategies in this paper. They condition on history only because $h_t$ impacts the economy through productivity $\Omega(h_t)$, not because of strategic links to past actions. Formally, strategies are reward functions $\big(T_{i,n}(E_n, h_n)\big)_{n\geq t}$ and policy selections $\big(E_n(T_n(\cdot), h_n)\big)_{n\geq t}$, following Bergemann and Välimäki (2003). The first step towards the definition of Markov perfect equilibrium is the agent's best response:

**Definition 2** *For $E_t^*(\cdot)$ to be a best response of the policy maker, then for all $h_t$ and schedules $T_t(\cdot)$, policy $E_t^*(T_t(\cdot), h_t)$ is a solution to*

$$\max_{E_t} \Big\{ \ln\big(Y_t(E_t, h_t) + \zeta T_t(E_t, h_t)\big) + \beta W_{t+1}^*(h_{t+1}) \Big\},$$

*where $h_{t+1}$ is the continuation state induced by $(E_t, h_t)$.*

[7] We write $E_t$ for the pair $(E_{D,t}, E_{C,t})$.

In choosing the reward function, any given principal is constrained by the agent's option to ignore that particular principal, and this is essential in determining how much surplus must be left to the agent (as in Bernheim and Whinston (1986) and later applications). Principals in an industry lobby for a policy that affects all firms in the industry similarly, so a firm could consider not contributing and enjoying the industry-wide benefits from other firms' rewards to the agent. But if the agent stops paying attention to one firm in industry $i$, it does so for all firms in that industry and there will be no policy distortion (policies are not tailored firm by firm). This makes each principal pivotal in equilibrium, helping the principals in the industry to solve their coordination problem. The policy-maker cannot extract more surplus than achievable from following today's efficient actions, with the future continuation play given by equilibrium strategies. This one-shot deviation gives welfare, that we denote by $W_t^{**}$, setting a lower bound to the equilibrium welfare, denoted as $W_t^*$. Thus, in equilibrium, the policy maker is indifferent between the outcome with no transfers and one-shot optimal policies, and the equilibrium outcome: the firms do not have to leave any excess surplus to the policy maker above the uncompensated benchmark. Expanding, the indifference $W_t^* = W_t^{**}$ implies

$$\ln(Y_t^* + \zeta T_t^*) + \beta W_{t+1}^*(h_{t+1}^*) = \ln Y_t^{**} + \beta W_{t+1}^*(h_{t+1}^{**}) \tag{20}$$

where $Y_t^{**}$ and $h_{t+1}^{**}$ are current output and the continuation state induced by $(E_t^{**}, h_t^*)$ that implement the one-period social optimal deviation from the equilibrium.

The reward schedules that achieve these strong implications for the agent must be optimal for each principal:

**Definition 3** *An optimal reward function $T_{i,t}^*(E_t^*, h_t)$ maximizes profits for all $h_t$. It solves*

$$\max_{\widehat{T}_{i,t}(\cdot)} \Pi_{i,t}(\cdot) - \widehat{T}_{i,t}(\widehat{E}_t, h_t) + \widehat{R}_{t+1} V_{i,t+1}^*(\widehat{h}_{t+1}).$$

*where $\widehat{E}_t = E_t^*(\widehat{T}_t, h_t)$ is the best response to $\widehat{T}_t(\cdot)$, and $(\widehat{h}_{t+1}, \widehat{r}_{t+1})$ is the continuation state induced by $(\widehat{E}_t, h_t)$.*

The concept of a truthful equilibrium requires that changes in the principal's profits are locally fully transferred to the agent. A local condition for a truthful equilibrium transfer schedule is that

$$T_{i,t}(E_t, h_t) = \Pi_{i,t}(E_t, h_t) + R_{t+1} V_{i,t+1}^*(h_{t+1}) - V_{i,t}^*(h_t). \tag{21}$$

where $V_{i,t}^*$ denotes the equilibrium value of the firm. From (21), the Markov assumption thus means that the net payoff $V_{i,t}(h_t)$ becomes locally independent of transfers: changes in policies and transfers at any given $t$ have offsetting impacts in flow net profits so that firm's total level of profits remains constant.

**Definition 4** *(truthful Markov Perfect Equilibrium): Reward strategies* $\left(T^*_{i,n}(\mathbf{E}_n, h_n)\right)_{n\geq t}$ *and policy selections* $\left(\mathbf{E}^*_n(T_n(\cdot), h_n)\right)_{n\geq t}$ *constitute a Markov Perfect Equilibrium (MPE), supported by value functions* $W^*_t(h_t), V^*_{i,t}(h_t)$*, if they satisfy Definitions 2-3. A truthful MPE also satisfies (21).*

Our agent does not have a quasi-linear utility, as is typical in common agency games (also in Bergemann and Välimäki (2003)). However, as shown in the proof of the Theorem below, Definition 3 still implies the stated indifference between the equilibrium action and one-shot efficiency for the agent; see also Dixit et al. (1997) for the static case with non-transferable utility.

The set of Markov equilibria can still be large without further refinements. We want to focus on a class of strategies that embeds the first-best choices so that we are not making a strategic commitment to stay away from efficiency. More explicitly, recall that (interior) first-best solves

$$U'(Y_t)\frac{\partial Y_t}{\partial E_{i,t}} = \beta\frac{\partial W_{t+1}}{\partial E_{i,t}}$$

where the left-hand side measures the intensity of current climate policy in utils, and the right-hand side measures the future externality, also in welfare units. In social optimum, the right-hand side is independent of history, as we saw in Lemma 1. We define a class of Markov Perfect equilibria that copy this property. The formal definition characterizes the reward function; the implied equilibrium properties are then derived in subsequent sections.

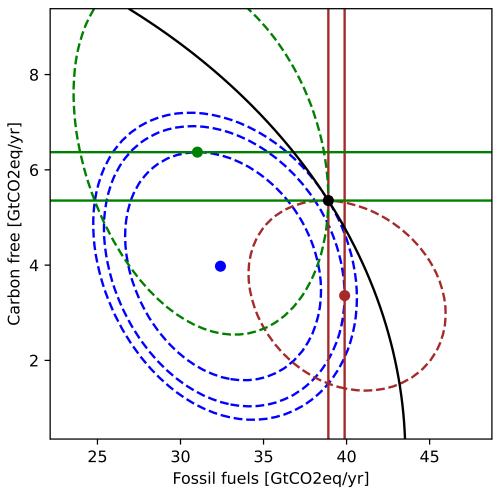
**Definition 5** *A Markov Perfect Equilibrium (Def 4) is called linearly homogeneous in total factor productivity* $\Omega(h_n)$*, if reward strategies can be written in intensive form:* $T^*_n(E_n, h_n) = \Omega(h_n)T^*_n(\frac{E_n}{\Omega(h_n)})$.

Homogenous transfers are proportional to TFP, $T_t \sim \Omega(h_t)$. Intuitively, for any two histories $h_t, h'_t$, such transfers compensate the agent for the income difference between the one-shot social optimal policy and the equilibrium, while this difference in income scales with TFP. Later, we will see that the equilibrium tax, denoted by $\tau_{i,t}$, implementing a homogeneous MPE is also proportional to TFP, $\tau_{i,t} \sim \Omega(h_t)$.

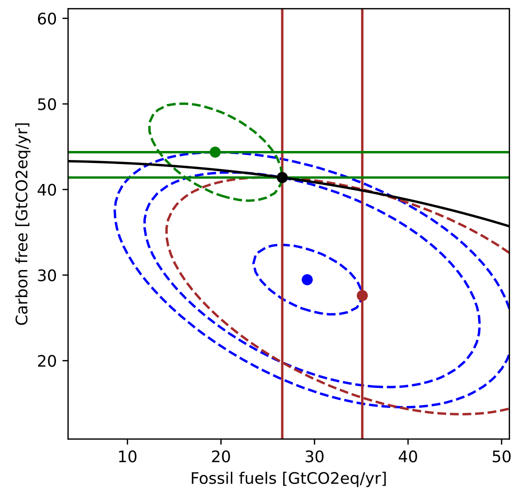
## 3.1 Equilibrium

Above we formally define the MPE equilibrium and its properties. Before we further establish its properties, we provide some intuitive graphs to present the mechanisms at work. The following graphs detail the incentives, based on parameters derived in the quantitative exercise, Section 4. Both graphs show fossil fuel and carbon-free energy use on the x- and y-axis, respectively, measured in $CO_2$ equivalents. Iso-Welfare lines are colored blue (4), with the dot representing the social optimum. The fossil fuel interests are colored red-brown. Profits for the fossil fuel sector increases with increasing fossil fuel use, that is, to the right. The vertical red-brown lines represents constant profits. When the fossil fuel sector transfers part of its rents to the policy maker, fossil fuel profits increase and overall welfare decreases. The red-brown dot marks the allocation where, for the planner, marginal social costs of subsidizing fossil fuels (shifting along the iso-welfare lines) equals marginal gains from transfers (shifting along the profits line). Similarly, the green dot presents the allocation when only the carbon-free energy producers transfer part of their rents to the policy maker. When both fossil fuel and carbon-free energy producers pay transfers, we arrive at the equilibrium presented through the black dot.

Note that there are 3 equivalent routes to describe the equilibrium. The first avenue starts with the planner who receives transfers from the fossil fuel industry, and in response moves the allocation from the blue to the red-brown dot. The red-brown ellipse represents indifference allocations for the policy maker, given the transfer schedule from the fossil fuels sector. The carbon-free energy supplier then offers a transfer schedule to increases the use of carbon-free energy, and in response the planner moves the allocation from the red-brown dot to the black dot. The second route starts with the planner considering the carbon-free transfers, moving the allocation from the blue to the green dot, so that the green ellipse represents the indifference allocations for the policy maker, given the transfers from the carbon-free sector. Then the fossil-fuel energy supplier pays a transfer to increase the use of fossil fuels, moving from the green to the black dot. The third avenue considers the route where the planner immediately takes into consideration both transfers, with the black line the iso-profit line for the joint energy sector. Note that for all three routes the reward strategies are the same truthful transfer functions, unique up to a constant, and all routes result in the same equilibrium allocation. Interestingly, the right panel shows a case where the fossil fuel industry sees a declining output in the MPE compared to the social optimum without transfers, and yet the fossil fuel sector pays a positive transfer to prevent the allocation from moving to the equilibrium where




(a) 2020




(b) 2060

Figure 1: Both panels show iso-interest lines for benevolent planner (blue), for fossil fuel industry (red), for renewable energy industry (green), for both industries jointly (black), in all cases ellipses present iso-welfare for the planner inclusive transfers (18), while straight lines present iso-profits for the industry. Dots present planner's maxima; the black dot denotes the MPE equilibrium. See main text for further clarification.

the renewables sector cuts out an even larger share of the fossil fuels (green dot). As the chart shows, also for this context, the same equilibrium allocation (black dot) results independently of whether the two energy sectors offer their reward separately, either synchronously or sequentially, or jointly.

Homogeneity as such puts a sharply characterizable structure on equilibrium payoffs, even without truthfulness. We document first the implications of homogeneity, and then build on these and truthfulness to obtain existence, uniqueness, and the full characterization of the MPE. A property of any homogeneous MPE is that the utility and welfare have a similar representation as in the first best:

**Lemma 2** *In any homogeneous MPE, utility and welfare must satisfy*

$$U_t^{MPE}(h_t) = \overline{U}_t^{MPE} - \sum\nolimits_{n=1}^{\infty} \theta_n E_{D,t-n}$$
$$W_t^{MPE}(h_t) = \overline{W}_t^{MPE} - \sum\nolimits_{n=1}^{\infty} \sum\nolimits_{i=0}^{\infty} \beta^i \theta_{n+i} E_{D,t-n}$$

*where the first terms on the right-hand side denote a value sequence* $(\overline{U}_t^{MPE}, \overline{W}_t^{MPE})$ *that* *is independent of history $h_t$, and the second terms depend on history through the weights $\theta_n$ given by the climate-economy description.*

In such an equilibrium the agent chooses $E_{i,t} > 0$ so that

$$U'(G_t)\Big(\frac{\partial Y_t}{\partial E_{i,t}} + \frac{\partial T_t}{\partial E_{i,t}}\Big) = \beta \frac{\partial W^{MPE}_{t+1}}{\partial E_{i,t}}$$

where the left-hand side is independent of $h_t$ because the marginal utility of income depends inversely in $\Omega(h_t)$ and both income and transfers vary proportionally in it. Thus, due to homogeneity of transfers, changes in marginal utilities cancel out the income effect coming from historical actions, exactly as in the first best outcome. In addition, the welfare cost of marginal emissions is the same in any homogeneous MPE as in the first-best,

$$\frac{\partial W^{MPE}_{t+1}}{\partial E_{D,t}} = \sum\nolimits_{i=1}^{\infty} \beta^{i-1}\theta_i = \Theta.$$

It follows that the policy maker chooses precisely the first-best policy if no transfers are made, $T_t = 0$. Now, we observe that, in equilibrium, the policy maker solves the trade-off between the utility gain of marginally increasing income $G_t$ and future social cos of emissions at each $t$, needing to know only the time-changing fundamentals such as sector-specific productivities and labor supply. Then, the equilibrium trade-off fixes the time-sequence of the energy mix, $(E_n)_{n=t}^{\infty}$, and thereby also output before multiplication by TFP: $(Y_t/\Omega(h_t))_{n=t}^{\infty} = (F_n - \sum_{i\in D,C} c_{i,n})_{n=t}^{\infty}$. This way the total output can be decomposed into time-dependent parts detailed above, and the history-dependent part $\Omega(h_t)$. The same decomposition carries over to rents $\Pi_t$ because, by being total factor productivity, $\Omega(h_t)$ has uniform multiplicative impact on productivities across sectors of the economy. From these observations, we obtain:

**Lemma 3** *In any homogeneous MPE, rents at $t$ are proportional to TFP, $\Pi_t \sim \Omega(h_t)$, and the total value of firms is*

$$V_t = \Pi_t - T_t + \beta\Xi_{t+1}Y_t, \tag{22}$$

*where $\beta\Xi_{t+1} = \sum_{n=1}^{\infty} \beta^n \xi_{t+n}$ and sequence $\xi_t$ is independent of history.*

Sequence $\xi_t$ captures the periodic net rents $\Pi_t - T_t$ as fraction of the total output. It may seem surprising that, in expression (22), the future firm value $\beta\Xi_{t+1}Y_t$ is impacted only by the current climate change through $\Omega(h_t)$ but not by future climate change. However, in equilibrium, future discount factors $(R_n)_{n>t}$ capture the future productivities and, thereby, precisely adjust to offset the impact of lower productivity on the firm values. This strong property depends on the parametric class but the main point is that firms pay attention to the total output: maximizing the industry value is equivalent to maximizing the weighted sum of the current rent, net of contributions, and output.

We supplement homogeneity of strategies by the requirement that principals' strategies are truthful, and then transfers from (21) can be written as

$$T_t(E_t, h_t) = \Pi_t(E_t, h_t) + \beta \Xi_{t+1} Y_t(E_t, h_t) - V_t^*(h_t), \tag{23}$$

which states that transfers increase with profits and gross output, while the last term $V_t^*(h_t)$ is a constant the value of which equals cumulative rents in Markov equilibrium. With this the policy maker's problem, as presented in Definition 2, can re-expressed to obtain the main tool for the policy analysis:

**Theorem 1** *The truthful homogeneous equilibrium is unique, recursively defined through output and energy use functions $Y_t^*(h_t)$ and $E_{i,t}^*(h_t)$ and $h_{t+1} = (E_{D,t}, h_t)$, solving the dynamic program:*

$$\max_{E_{D,t}, E_{C,t}} U\Big((1 + \zeta\beta\Xi_{t+1})Y_t(E_t, h_t) + \zeta \sum_{i \in C,D} \big(\Pi_{i,t}(E_t, h_t) - V_{i,t}^*(h_t)\big)\Big) + \beta W_{t+1}^*(E_{D,t}, h_t) \tag{24}$$

The proof in the Appendix shows that the equilibrium exists, using a fixed-point argument. In a subtle way (24) is not a straight planning program since policies simultaneously generate the agent's welfare function and the firms' values; $V_{i,t}^*(h_t)$ is from the planner's perspective a constant, and could be written as $V_{i,t}^*(h_t) = \overline{v}_{i,t}^* \Omega(h_t)$ for a given sequence of weights $\overline{v}_{i,t}^*$. The equilibrium path solves (24) and simultaneously generates consistent values for $V_{i,t}^*$.

From the Theorem, in each sector, the equilibrium energy use $E_{i,t} > 0$ solves

$$U'(G_t)\Big((1 + \zeta\beta\Xi_{t+1})\frac{\partial Y_t^*}{\partial E_{i,t}^*} + \zeta \frac{\partial \Pi_{i,t}}{\partial E_{i,t}}\Big) + \frac{\partial W_{t+1}^*}{\partial E_{i,t}} = 0 \tag{25}$$

where the weights on the income of the representative consumer, $Y_t^*$, and periodic profits are now explicit. The trade-off of the policy maker is the same as discussed above but re-expressed. Income $G_t$ can be tied to the policy actions explicitly by using the indifference in (20): the equilibrium compensation to the agent depends on the current action relative to the alternative, that is, one-shot efficient action. Let $Y_t$ be output in the equilibrium we consider, and let $Y_t^S(h_t^S)$ be equilibrium output for some alternative policy rule or scenario $S$, which depends on the scenario-specific history. It is convenient to write $\overline{Y}_t^S(h_t)$, or shorthand $\overline{Y}_t^S$, if that alternative scenario or policy has the same history as the equilibrium under consideration. This enables us to write the policy maker's compensation required for distorting policies away from the efficient ones.

**Lemma 4** *In any homogeneous MPE, the policy maker at period $t$ is exactly compensated for the social costs of the one-shot increase in emissions:*

$$g_t Y_t \equiv G_t = Y_t + \zeta T_t = \overline{Y}_t^{SO} \exp(\beta\Theta(E_{D,t}^* - E_{D,t}^{**})). \tag{26}$$

*where sequence $g_t$ is independent of history, $\overline{Y}_t^{SO}$ is the socially optimal output given history $h_t$.*

The beauty of the Lemma is that it allows us to obtain the income of the policy maker at any given history: both the equilibrium and deviation energy uses ($E_{D,t}^*$ and $E_{D,t}^{**}$, resp.) are time-dependent only, defining the "inflation factor $g_t$" to be applied to obtain the over-consumption of the decision maker. Now, given log utility, and the link between the aggregate $Y_t$ and $G_t$, we can express the policy maker's basic trade-off in (25) as:

$$(1 + \zeta\beta\Xi_{t+1})\frac{\partial Y_t^*}{\partial E_{i,t}^*} + \zeta\frac{\partial \Pi_{i,t}^*}{\partial E_{i,t}^*} = \mathbf{I}(i)\beta\Theta g_t Y_t^* \tag{27}$$

where we used indicator $\mathbf{I}(i = D) = 1$. The trade-off of the agent is now presented in money-metric terms; indeed, we want to interpret the equilibrium allocation through prices on energy use (the next Section). Anticipating this interpretation, the left side implicitly defines the price that the consumers should pay for energy, and the second term includes the price that producers receive for energy by sector. On the right, there is the marginal social cost of emissions in money. But first we pull out the implications of the above trade-off:

**Proposition 2** *The unique truthful homogeneous MPE policies $E_t^* = (E_{D,t}^*, E_{C,t}^*) > 0$ satisfy:*

$$\frac{\partial Y_t^*}{\partial E_{C,t}^*} = -\frac{\zeta}{1 + \zeta\beta\Xi_{t+1}}\frac{\partial \Pi_{C,t}}{\partial E_{C,t}} \tag{28}$$

$$\frac{\partial Y_t^*}{\partial E_{D,t}^*} = \frac{1}{1 + \zeta\beta\Xi_{t+1}}\Big(\beta\Theta g_t Y_t^* - \zeta\frac{\partial \Pi_{D,t}}{\partial E_{D,t}}\Big). \tag{29}$$

For the clean energy, from (28) it follows

$$\frac{\partial Y_t^*}{\partial E_{C,t}^*} = \Omega(h_t)\Big(f_t'(\sum_i E_{i,t}) - c_{C,t}'(E_C)\Big) < 0$$

so the policy maker chooses to overuse clean energy as long as the industry rents have some weight. This outcome can be obtained by subsidizing clean energy. However, for dirty energy, the policy maker may choose a tax ($\partial Y_t/\partial E_{D,t} > 0$) or subsidy ($\partial Y_t/\partial E_{D,t} < 0$), depending on if the income-dependent externality cost dominates the industry rents of the right-hand side of (29).

## 3.2 Equilibrium taxes and subsidies

**Policy game** We can now establish the outcome equivalence of the dynamic agency game where the agent chooses the energy quantities directly (Theorem 1) and the game where the agent uses energy unit prices $\tau = (\tau_{D,t}, \tau_{C,t})$ as instruments. By Proposition 1, efficient allocation $E_{i,t}^*(h_t)$ can be implemented period-by-period as a competitive decentralized outcome (the second welfare theorem). However, since the allocation arises as an outcome of a game, one must also demonstrate that the Markov strategies of the game can be equivalently written terms of prices while maintaining the homogeneity and truthfulness properties. Formally, we can repeat the steps above to define the Markov strategies $\big(T_{i,n}(\tau_n, h_n)\big)_{n\geq t}$ and $\big(\tau_n(T_n(\cdot), h_n)\big)$. The main difference is that taxes, not only reward schedules, are proportional to history-dependent $\Omega(h_t)$, $\tau_{i,t} \sim \Omega(h_t)$. The history-invariance of energy is consistent with the linearly homogeneous taxes. With these equivalences between prices and quantities as policy instruments, we can rewrite the policy maker's trade-off (27):

$$(1+\zeta\beta\Xi_{t+1})(\tau_{i,t}+\mu_{i,t}) + (\zeta\frac{1}{\sigma} - (1+\zeta\beta\Xi_{t+1}))\mu_{i,t} = \mathbf{I}(i)\beta\Theta g_t Y_t$$

where we substituted $\mu_{i,t}$ energy price for the marginal costs of energy production and used energy market demand (7). The policies are now expressed as prices and with explicit links to rents, as captured by $\sigma$:

**Proposition 3** *The unique truthful homogeneous MPE tax policies $\tau_t^* = (\tau_{D,t}^*, \tau_{C,t}^*)$ satisfy:*

$$\tau_{C,t}^* = -\frac{\zeta}{1+\zeta\beta\Xi_{t+1}}\frac{1}{\sigma}\mu_{C,t}, \quad (30)$$

$$\tau_{D,t}^* = \frac{g_t}{1+\zeta\beta\Xi_{t+1}}\beta\Theta Y_t^* - \frac{\zeta}{1+\zeta\beta\Xi_{t+1}}\frac{1}{\sigma}\mu_{D,t}. \quad (31)$$

The equilibrium subsidy on green energy has three determinants, in eq. (30): (i) Ricardian rents ($\mu_C/\sigma$), (ii) weight on current rents ($\zeta$), and (iii) weight on future rents ($\zeta\beta\Xi_{t+1}$). The rent-dependent distortions follow for resources with inelastic supply (low $\sigma$), generating large (competitive) Ricardian rents that receive a weight in policy making, independent on climate externalities. As $\sigma \to \infty$, constant returns to scale prevail in the energy sectors of the economy and rents get dissipated by competition. Weight $\zeta$ on current rent is a given parameter but future rents arise endogenously in equilibrium depending, for example, on how the energy sectors develop over time: large future shares of output as rents, captured by $\beta\Xi_{t+1}$, reduce the subsidy today and thus losses in the future. Promise of future rents is a stake of the future economy that disciplines distortions today.

The same determinants enter the equilibrium tax on dirty energy, the last term in eq. (31). Considering again elastically supplied energy resources ($\sigma \to \infty$), we know that the rent distortion vanishes also for dirty energy taxes. But then we must have

$$\tau^*_{D,t} \to \beta\Theta Y^*_t,$$

the socially optimal tax on the polluting energy. At first, this may seem surprising given that rents do not directly appear in the first term of eq. (31). However, if there are no current rents, also the future rents disappear and thus firms have no future values $\beta\Xi_{t+1} \to 0$, and the policy maker's consumption becomes representative $g_t = 1$. Off this limit, interestingly, the stand-alone impact of income tends to increase the tax on fossil fuel as the policy maker is wealthier than the representative consumer, $g_t > 1$, and thus values the environment more.

# 4 Quantitative analysis

## 4.1 Climate parameters

The quantitative model has two sectors, denoted by $i =\in D, C$, and 60 periods of each 5 years, starting with the period labeled '2015' for the period [2013-2017]. The damages time structure $\theta_i$ is based on a system of carbon reservoirs where flows between reservoirs are linear in stocks. The atmospheric $CO_2$ content is described through a series of exponential $CO_2$ decay functions. Damages follow temperature, which slowly converges to its equilibrium level for given atmospheric $CO_2$ described through a series of exponential temperature-adjustment functions; a higher atmospheric $CO_2$ content leads to slowly increasing damages. The reduced form (Gerlagh and Liski 2017, Theorem 1), is given by a 'multi-box' representation,

$$\theta_i = \sum\nolimits_i \sum\nolimits_k a_j b_k \pi \varepsilon_k \frac{(1-\eta_j)^i - (1-\varepsilon_k)^i}{\varepsilon_k - \eta_j}, \tag{32}$$

where $\eta_j$ are the atmospheric depreciation rates, $\varepsilon_k$ are the temperature adjustment speeds, $a_j$ and $b_k$ are the shares of the relevant processes, and $\pi$ is the long-run emissions-damages sensitivity. We take an annual parametric form from van den Bijgaart et al. 2016, Table 6 and 7, for the median carbon model, $a = (0.220, 0.279, 0.278, 0.222)$, $\eta = (0, 0.0035, 0.0507, 0.2892)$, and temperature models, $b = (0.2218, 0.3306, 0.4476)$, $\varepsilon = (0.9787, 0.1980, 0.0036)$, $\pi = 0.0167$. These parameters indicate that 22 per cent of emissions remain in the atmosphere 'forever', while the same share very quickly transits to other carbon reservoirs (at about 30% per year). Also, about 22% of temperature adjustment is virtually immediate, while almost half of temperature adjustment only happens after more than a century. For our model with 5-year periods, we average annual damages within periods.

## 4.2 Technology and Preferences Calibration

We assume a pure time preference of 2 per cent per year, $\beta = exp(-5 \cdot .02)$, elasticity of supply by the fossil fuel and renewable energy sector of $\sigma = 1$. We assume a myopic industry's strategy, $\Xi_t = 0$, and a thirty per cent distortion in the policy maker's objective (24), $\zeta = 0.30$. As we will see in the results, this amounts to an energy subsidy distortion of about 2 to 3 percent of GDP. We define the 'energy subsidy' as the second part of (31) and all of (30), multiplied by energy use, and divided by output. This is a conservative estimation compared to Coady et al. (2015), who report an estimated energy subsidy valued above five percent of GDP.[8]

We target 4 variables, Population, GDP, emissions, the energy price for the Business as Usual scenario,

Labour supply is set equal to population. It follows a logistic growth curve,

$$L_{t+1} = L_t(1 + \psi n - \psi n L_t / \overline{L})$$

[8](Coady, Parry, Sears, & Shang, 2015) define pre-tax energy subsidies, defined relative to the situation of no energy taxes. This measure is useful for our RSE scenario. They also define post-tax energy subsidies, which compares actual taxes to Pigouvian levels. This measure is useful for our Markov-Perfect Equilibrium.

which tracks the historic 1950-2014 trend, with $L_{2000} = 6.13$ [bn], $L_{2010} = 6.92$, $n = 5$ denotes the number of years per period, $\psi = 0.0282$ [/yr] is the unconstrained population growth rate, and $\overline{L} = 11.9$ [bn] is the long-term convergent population level.

We assume Cobb-Douglas production for the consumer good and for energy:

$$F_t(E_{D,t}, E_{C,t}, L_t) = A_t\big(E_{D,t} + E_{C,t}\big)^{\gamma_t} L_t^{1-\gamma_t}, \tag{33}$$

$$E_{i,t} = X_{i,t} c_{i,t}^{\frac{\sigma}{\sigma+1}}. \tag{34}$$

We calibrate the parameters to fit data on population, output, emissions, the share of clean energy, for the years 2000, 2005, 2010. We use bars on top of variables to refer to target variables. We target GDP in the year 2010 at $\overline{Y}_t = 63$ [tn EUR2015/yr], and per capita GDP increasing by 1.62 per cent per year for the remaining of the century:

$$\begin{aligned}
\overline{Y}_{2000} &= 0.043n \\
\overline{Y}_{2010} &= 0.063n \\
\overline{Y}_{t+1} &= (1.0162)^n \frac{L_{t+1}}{L_t} \overline{Y}_t
\end{aligned}$$

Emissions are targeted in 2010 at $\overline{E}_{D,t} = 31.5$ [GtCO2/yr], and after 2010, per capita emissions rise with a half per cent per year (between the historic average 1970-2010 that is close to zero, and the average over 2000-2010 that is 1 per cent per year). Indeed, Jackson et al. (2016) show a substantial drop in the growth of fossil fuel related CO2 emissions over the period 2010-2015.

$$\begin{aligned}
\overline{E}_{D,2000} &= 0.0239n \\
\overline{E}_{D,2010} &= 0.0315n \\
\overline{E}_{D,t+1} &= (1.005)^n \frac{L_{t+1}}{L_t} \overline{E}_{D,t}
\end{aligned}$$

We assume clean energy to make up 10% in 2000, increasing its share following a logistic growth curve

$$\begin{aligned}
\overline{E}_{C,2000} &= 0.1\overline{E}_{D,2000} \\
\overline{E}_{C,t+1} &= (1.01)^n \frac{\overline{E}_{D,t+1}}{\overline{E}_{D,t}} \overline{E}_{C,t}
\end{aligned}$$

The price of energy for the final goods sector (including taxes) is targeted at $\nu_t = \mu_t + \tau_t = 0.050$ [EUR2015/tCO2] and assumed stable. The MPE equilibrium conditions are inverted, so that the 3 target variables (GDP, emissions, energy price) determine dynamically the parameters $A_t$, $X_t$, and $\gamma_t$.

| Par | Description | Value | Reference and Targets |
|---|---|---|---|
| constant parameters | | | |
| $\beta$ | Altruism | 0.90 | discount rate ($2\%/yr$) (Golosov et al., 2014) |
| $\Theta$ | damage response | 0.0548 | NPV of long-run climate damages |
| $\sigma$ | Elasticity of energy supply | 1.0 | energy rents |
| $\zeta$ | reward efficiency | 0.4 | distortionary taxes 1.2 per cent |
| State variables and dynamic parameters 2020 | | | |
| $L$ | Population | 7.84 | World population |
| $\gamma$ | Energy share | 0.0282 | long-run fertility ($f_\infty = 0.95$) |
| $A$ | TFP | 0.0537 | GDP at 373 tn €per period |
| dynamic parameters | | | |
| $\widehat{A}$ | TFP growth | 1.21 | long-run economic growth (1.5%/yr) |

Table 1: **Parameters**

## 4.3 Results

We run three scenarios. First we calculate the Markov-Perfect Equilibrium, which we consider the baseline on which we calibrate all parameters. It is a strong assumption that the planner fully includes future climate damages in its objective function. Our baseline is potentially too optimistic about future emissions and climate change. The aim of the illustration is to present the potential implications of interest groups for climate policy and a relatively simple baseline assumption is helpful for that purpose. The other two scenarios are counterfactuals for reference: the Social Optimum and a scenario with zero taxes, $\tau_{i,t} = 0$, that is, also no subsidies.

Table 1 below summarizes parameters and initial value used to calibrate our model and carry out the simulations presented in the next section.

The model is calibrated on the years 2000, 2005, 2010, 2015, 2020, for GDP, emissions from fossil fuels, share of renewables in primary energy, and population. GDP is taken from World Bank (converted to constant 2015 euros), the other data are from *World in data*. To estimate the energy share in output, we use a constant fuel price at 50 €/tCO2eq, where we measure both fuels in (prevented) CO2 equivalents. To extrapolate the parameters to the future, we assume logistic population growth leveling at 11.9 billion, TFP growth of 1.6 per cent per year. The share of clean energy grows from 7.8 per cent in 2000 to 13.5 in 2020, and we extrapolate this to continue at 3 per cent per year, following a logistic growth curve.

We report carbon taxes $\tau_{D,t}$, renewable taxes (which are negative, thus subsidies),

$\tau_{C,t}$ for the first two scenarios. We report the energy subsidy distortion as share of GDP for the MPE scenario only. We report emissions $E_{D,t}$ for all three scenarios. We use the color black for the MPE, blue for the SO, consistent with the contour plots Fig 1. We use purple for the zero-tax scenario.

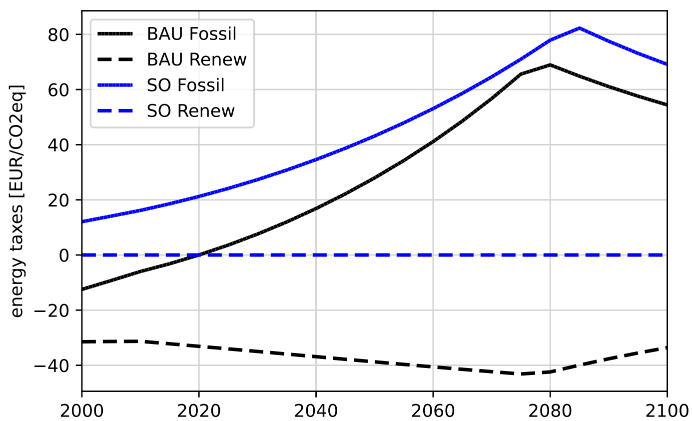



Figure 2: Taxes on energy sources

The first figure shows taxes. The Social Optimum has no tax nor subsidy for renewables, and a carbon tax slightly above 20 Euro/tCO2, in 2020, rising to 80 €/tCO2 in 2080. After emissions reach zero, carbon taxes follow the price of energy, so that the price for fossil fuels is zero. Though a price of 80 €/tonCO2 might seem low for full decarbonization, notice that the price in the EU-ETS currently is at that level, while allowances remain valid throughout the ETS including when net supply of allowances is expected to reach zero around 2040. That is, the current EU-ETS is the best market estimate available for the long-term carbon tax that will choke demand for fossil fuels.

In the baseline equilibrium, fuel owners reward the planner for subsidizing fuels. We find subsidies for renewables above 20 €/tonCO2, throughout the century. For fossil fuels, the lobby succeeds to induce subsidies initially. Thus, our BAU scenario describes the tendency of regulators to implement climate policy mainly through subsidies on renewables, possibly complemented by reduced subsidies for fossil fuels. Based on our parameters by 2020 fossil fuel subsidies turn into carbon taxes, well below the social costs of carbon, though.

The gap between the social cost of carbon and the carbon tax is a measure for the post-tax fossil fuel subsidy, as defined by Coady et al. (2015). We present the value of the gap, relative to GDP, in the next figure. In the MPE scenario, the fossil fuel post-tax

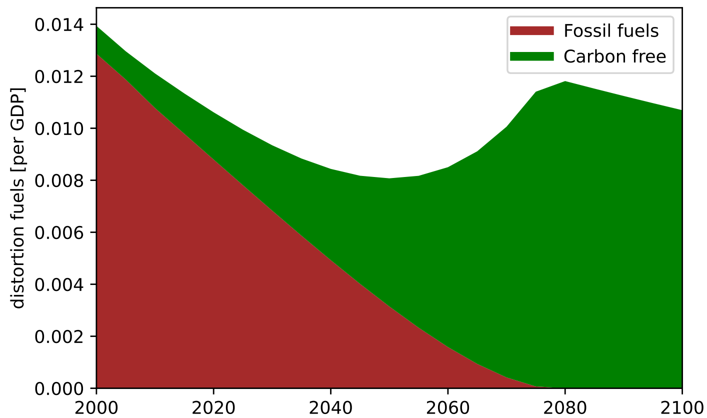



Figure 3: Implicit subsidies for energy sources, relative to GDP

subsidy amounts to about 1 per cent of GDP, a conservative result compared to the 6 per cent presented by Coady et al. (2015). We also see a robust increase in the total volume of renewables subsidies, overtaking the fossil fuel post-tax subsidies before 2050. The overall level of distortionary subsidies as share of GDP shows a U-curve, a consequence of transition costs with higher overall energy prices during the phase out of fossil fuels.

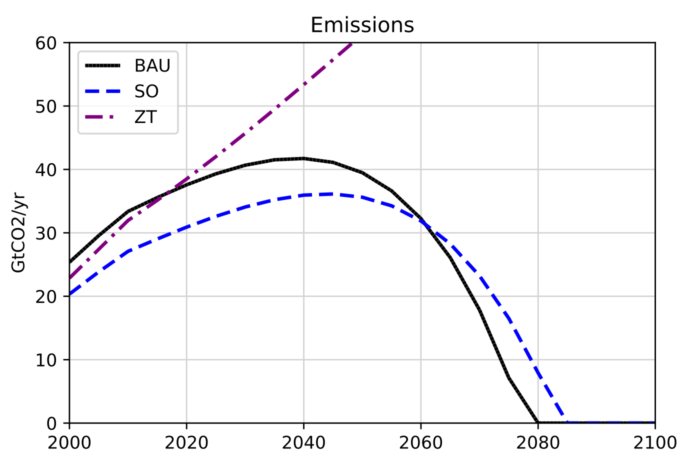



Figure 4: Energy-related emissions

Finally, the next figure presents the implications of fuel interests through policies on emissions. Fossil fuel subsidies push up emissions considerably; initially, the baseline equilibrium remains above the zero-tax scenario. Due to fuel interests, policies before 2020 increased emissions compared to a neutral policy without fuel taxes. Removing energy subsidies would reduce emissions substantially, and bringing carbon taxes to the social optimum reduces emissions by about 20 per cent, consistent with the estimate by Coady et al. (2015). The outcomes suggest that, in 2020, we are close to the point where the effects on emissions of renewable subsidies offset those of fossil fuel subsidies: emissions are the same in the MPE as in the zero-tax scenario. In the future, fossil fuel taxes start to bite, and removing all taxes and subsidies on both fossil fuels and renewables will increase emissions. Remarkably, after 2060 the effect of energy subsidies, relative to the Social Optimum, reverses. The subsidies for renewables exceed the implicit subsidies for fossil fuels, and emissions in the MPE fall below those in the Social Optimum.

# 5 Discussion

[add discussion]

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# A Appendix: Proofs

Below we provide proofs for the first lemmas and theorem. The remaining lemmas and propositions follow from arguments provided in main text.

## A.1 Proof of Lemma 1

The lemma separates the utility and welfare sequences into exogenous growth sources, for example technology, from those that capture the burden of past emissions. We can prove the lemma by solving the full welfare program, but a more insightful proof uses an induction argument.

**Proof.** Assume that the lemma is valid for all future periods $t+1, t+2, t+3, ....$ Then we show that the lemma also holds for $t$. The social optimum maximizes $\ln(Y_t)+\beta W_{t+1}(h_{t+1})$.

We substitute (1) for $Y_t$ and (2) for $\Omega(h_t)$, this gives

$$\ln(Y_t) = -\sum\nolimits_{n=1}^{\infty} \theta_n E_{D,t-n} + \ln(L_t f_t(\frac{E_{D,t}+E_{C,t}}{L_t}) - \sum\nolimits_{i=D,C} c_i(E_{i,t})).$$

By backwards induction, for the next period, there is a value $\overline{W}_{t+1}^{SO}$, so that

$$\beta W_{t+1}(h_{t+1}) = \beta \overline{W}_{t+1}^{SO} - \beta \sum\nolimits_{n=1}^{\infty} \sum\nolimits_{i=0}^{\infty} \beta^i \theta_{n+i} E_{D,t+1-n}.$$

It follows that

$$\begin{aligned} W_t = {} & \ln(L_t f_t(\frac{E_{D,t}+E_{C,t}}{L_t}) - \sum\nolimits_{i=D,C} c_i(E_{i,t})) - \sum\nolimits_{n=1}^{\infty} \theta_n E_{D,t-n} \\ & + \beta \overline{W}_{t+1}^{SO} - \beta \sum\nolimits_{n=1}^{\infty} \sum\nolimits_{i=0}^{\infty} \beta^i \theta_{n+i} E_{D,t+1-n}. \end{aligned} \tag{A.1}$$

We can separate past emissions $E_{D,t}$ for past $t$ and solve for the social optimum $E_{i,t}^{SO}$, independent of history, as the allocation that maximizes

$$\ln(L_t f_t(\frac{E_{D,t}+E_{C,t}}{L_t}) - \sum\nolimits_{i=D,C} c_i(E_{i,t})) - \sum\nolimits_{i=0}^{\infty} \beta^{i+1} \theta_{1+i} E_{D,t} \tag{A.2}$$

and we can subsequently construct the current period utility and value function:

$$\begin{aligned} \overline{U}_t^{SO} &= \ln(L_t f_t(\frac{E_{D,t}^{SO}+E_{C,t}^{SO}}{L_t}) - \sum_i c_i(E_{i,t}^{SO})) \\ \overline{W}_t^{SO} &= U_t^{SO} - \sum\nolimits_{i=0}^{\infty} \beta^{i+1} \theta_{1+i} E_{D,t}^{SO} + \beta \overline{W}_{t+1}^{SO} \end{aligned}$$

Q.E.D ■

## A.2 Proof of Lemma 2

**Proof.** The proof is conditional on existence, and goes by an induction argument as for the social optimum. The induction hypothesis is that the lemma is valid for all future periods $t+1, t+2, \ldots\ldots$ For two arbitrary histories, $\widetilde{h}_t$ and $\widehat{h}_t$. Both output $Y_t(.)$ and transfers $T_t(.)$ in Definition 2 are proportional to $\Omega(h_t)$ (see (3) for output and Def 5 for transfers), so that (after taking logs), the best response $E_t^*$ is independent of history: $E_{i,t}^{MPE} \equiv \widetilde{E}_{i,t} = \widehat{E}_{i,t}$. From this observation, it immediately follows that output, transfers, taxes, and consumption of the policy maker all scale with TFP:

$$\frac{\widetilde{Y}_t}{\Omega(\widetilde{h}_t)} = \frac{\widehat{Y}_t}{\Omega(\widehat{h}_t)},$$
$$\frac{\widetilde{T}_t}{\Omega(\widetilde{h}_t)} = \frac{\widehat{T}_t}{\Omega(\widehat{h}_t)},$$
$$\frac{\widetilde{G}_t}{\Omega(\widetilde{h_t})} = \frac{\widehat{G}_t}{\Omega(\widehat{h_t})},$$
$$\frac{\widetilde{\tau}_{i,t}}{\Omega(\widetilde{h}_t)} = \frac{\widehat{\tau}_{i,t}}{\Omega(\widehat{h}_t)}.$$

It then follows that

$$\overline{U}_t^{MPE} \equiv \widetilde{U}_t + \sum\nolimits_{n=1}^{\infty} \theta_n \widetilde{E}_{D,t-n} = \widehat{U}_t + \sum\nolimits_{n=1}^{\infty} \theta_n \widehat{E}_{D,t-n}$$

is also well-defined, independent of history (the second terms on the right-hand side are the logs of $\Omega(h_t)$). Finally, we can then construct

$$\overline{W}_t^{MPE} = \widetilde{U}_t - \sum\nolimits_{i=0}^{\infty} \beta^{i+1} \theta_{1+i} E_{D,t}^{MPE} + \beta \overline{W}_{t+1}^{MPE}.$$

Q.E.D. ■

## A.3 Proof of Lemma 3

**Proof.** Consider net profits

$$\Pi_t - T_t = \xi_t Y_t \tag{A.3}$$

For the previous lemma we establised that output and transfers are proportional to TFP, $Y_t \sim \Omega(h_t)$, $T_t \sim \Omega(h_t)$. Also, total energy cost $\Omega(h_t) \sum_i c_{i,t}(E_{i,t})$ is proportional to TFP. Then, from (11)-(12), we have that gross profits scale as well: $\Pi_t \sim \Omega(h_t)$. Thus, fraction $\xi_t$ of $Y_t$, left as net rents for firms, is free of history. Using the definition of equilibrium discount factor $R_{t+1}$ from (16), we obtain

$$\begin{aligned} R_{t+1}\big(\Pi_{t+1} - T_{t+1}\big) &= \beta \xi_{t+1} Y_t \\ R_{t+1} V_{t+1} &= Y_t \sum_{n=1}^{\infty} \beta^n \xi_{t+n} \end{aligned}$$

where the second equation just sums over the future horizon. Q.E.D. ■

## A.4 Proof of Theorem 1

**Proof.** We first establish uniqueness and existence of a solution to the objective function (24). We need to show that there is a (unique) optimal control $E_t^*$ with consistent $\Xi_t$ and $V_{i,t}^*$. We rewrite it as period-by-period optimization

$$\max_{E_{D,t},E_{C,t}} \ln\Big((1+\zeta\beta\Xi_{t+1})Y_t(E_{D,t},E_{C,t})+\zeta\big(\Pi_t(E_{D,t},E_{C,t})-\overline{V}_t\big)\Big)-\beta\Theta E_{D,t}$$

where we separate period choices by cutting the link between past emissions and current history, setting $h_t = 0$, and we replaced the equilibrium firm valuation $V_t^*$ by an arbitrary exogenous sequence $\overline{V}_t$. The period-by-period optimization takes as given the vector of rent shares and values $(\Xi_1, \overline{V}_1, \Xi_2, \overline{V}_2, ...)$ and produces a sequence of energy use, $E_t$, output $Y_t$, rents $\Pi_t$, and rent values $V_t$ and shares $\xi_t, \Xi_t$. That is, it defines a mapping of the vector $(\Xi_1, \overline{V}_1, \Xi_2, \overline{V}_2, ...)$ onto $(\Xi_1, V_1, \Xi_2, V_2, ...)$. If we substitute these values back into the optimization, we can employ Brouwer's fixed-point.

We now ensure the mapping is defined on a compact domain. We set the domain through $\Xi_t \in [0, 1/(1-\beta)]$, and $0 \le \overline{V}_t \le \max\{Y_t\}/(1-\beta)$, meaning that we ensure a strictly positive value within the log-operator. It is then immediate that a solution exists and that it satisfies the boundary constraints assumed. Furthermore, the objective function is concave, the production set strictly convex, so that the solution is unique.

Further, to apply Brouwer's fixed point theorem, we must remain within a finite number of periods. Thus, we restrict the mapping from $(\Xi_1, V_1, \Xi_2, V_2, ...)$ to itself to the time window $t = 1, ...t^{max}$, leaving the vector beyond that period, i.e. $(\Xi_t, \overline{V}_t)_t$ beyond that period window, as exogenous to the mapping. For any finite period length, $t = 1, ...t^{max}$, the above procedure constructs a continuous mapping of a compact space onto itself. Thus, by Brouwer's theorem, there is a fixed point. Furthermore, the dependence of $\Xi_1$ and $\overline{V}_1$ on choices beyond $t^{max}$ decreases exponentially by factor $\beta$ with increasing $t^{max}$. Thus, by increasing $t^{max}$, the fixed point converges to some $\Xi_1^*, \overline{V}_1^*$. We repeat the same procedure for next periods, and thus construct the complete sequence $(\Xi_t^*, \overline{V}_t^*)$.

Finally, we note that the values for $E_{i,t}$ and the ratios $\Pi_t/Y_t$ and $T_t/Y_t$ are invariant with respect to history, thus extend beyond the condition $h_t = 0$, so that the equilibrium conditions of our fixed point also hold for arbitrary $h_t$. That is, we can keep the fixed point values for $E_{i,t}$, and construct the equilibrium $h_t$ by forward shooting $h_{t+1} = (h_t, E_{D,t})$.

Now that we have constructed a candidate equilibrium allocation, we prove that it is the MPE equilibrium. Definition 2 is satisfied by the truthfulness property, included in the above construction, as that keeps the common agent (policy maker) indifferent between the equilibrium allocation and the one-shot social optimal deviation. Definition 3 is slightly more subtle. It demands the reward schedule to be optimal for the principal. Locally, the condition is guaranteed by the truthfulness condition. But, specifically, it also requires the individual principal not to gain from a full drop out of the reward scheme. In a standard menu auction model with multiple symmetric principals, the condition is typically satisfied by a truthful reward schedule. Conceptually, if one small principal (energy firm) deviates and does not pay its contribution to the reward, the common agent (policy maker) falls back to the reference (one-shot social optimum). As profits in the menu auction equilibrium minus reward payments are strictly above profits in the reference allocation, no principal has an incentive to shirk. In terms of our model, let us rewrite (21) the reward schedule as

$$T_{i,t} = \max\{0, \Pi_{i,t} - \overline{\Pi}_{i,t}\} \tag{A.4}$$

where $\overline{\Pi}_{i,t}$ is the principal agent's net profit in equilibrium. If $\overline{\Pi}_{i,t} > \Pi^{**}_{i,t}$, then principals from sector $i$ prefer the equilibrium above the reference one-shot-first-best allocation $**$. In an economy with heterogeneous principals, the condition is not obviously met for all principals. For example, in Fig 5b we see lower profits for the fossil fuel industry in the MPE equilibrium as compared to the one-shot first best. Each fossil fuel principle would like to withdraw from the reward scheme if such would let the equilibrium collapse back to one-shot first best. Below we will show that, even in such context, the MPE equilibrium is supported because the fossil fuel owners understand that if they withdraw, the equilibrium moves to the alternative equilibrium, denoted by superscript $*C$, where only renewable energy owners offer a reward function. Each fossil fuel owner prefers the MPE equilibrium $*$ above $*C$, and thus will not shirk. We now make this analysis more precise.

Let us differentiate between 4 candidate equilibria: the MPE equilibrium denoted by $*$, the one-shot social optimal deviation, denoted by superscript $**$, the one-shot deviation where only the fossil fuel owners pay a reward schedule, denoted by superscript $*D$, and the one-shot deviation where only the renewable energy firms pay a reward schedule, $*C$. See Fig 5 for an illustration based on the quantitative model. Note that the reward schedule satisfies $T^{*D}_{C,t} = T^{*C}_{D,t} = T^{**}_{C,t} = T^{**}_{D,t} = 0$.

We now prove stability of $*$ by showing that no principal agent can gain from shirking moving the allocation to one of the other 3 candidate equilibria. The MPE allocation * constructed above maximizes

$$\ln(Y_t(E_{D,t}, E_{C,t}) + \zeta \sum_i \left(\Pi_{i,t}(E_{D,t}, E_{C,t}) - \overline{\Pi}_{i,t}\right) - \beta\Theta E_{D,t} \tag{A.5}$$

while setting the pair $\overline{\Pi}_{i,t}$ such that their sum satisfies

$$\begin{aligned} &\ln(Y_t(E^{**}_{D,t}, E^{**}_{C,t})) - \beta\Theta E^{**}_{D,t} = \\ &\ln(Y_t(E^{*}_{D,t}, E^{*}_{C,t}) + \zeta \sum_i \left(\Pi_{i,t}(E^{*}_{D,t}, E^{*}_{C,t}) - \overline{\Pi}_{i,t}\right) - \beta\Theta E^{*}_{D,t}. \end{aligned} \tag{A.6}$$

As the MPE constructed includes profits in the objective, we have $\Pi^*_{D,t} + \Pi^*_{C,t} > \overline{\Pi}_{D,t} + \overline{\Pi}_{C,t} > \Pi^{**}_{D,t} + \Pi^{**}_{C,t}$. First consider the symmetric case that $\Pi^*_{D,t} > \Pi^{**}_{D,t}$ and $\Pi^*_{C,t} > \Pi^{**}_{C,t}$. As both fuels are substitutes, we have $\Pi^{**}_{C,t} > \Pi^{*D}_{C,t}$ and $\Pi^{**}_{D,t} > \Pi^{*C}_{D,t}$, that is $\Pi^*_{D,t} > \Pi^{**}_{D,t} > \Pi^{*C}_{D,t}$ and $\Pi^*_{C,t} > \Pi^{**}_{C,t} > \Pi^{*D}_{C,t}$. We can thus choose $\overline{\Pi}_{D,t}, \overline{\Pi}_{C,t}$ to satisfy $\Pi^{*D}_{D,t} > \Pi^*_{D,t} > \overline{\Pi}_{D,t} > \Pi^{**}_{D,t} > \Pi^{*C}_{D,t}$ and $\Pi^{*C}_{C,t} > \Pi^*_{C,t} > \overline{\Pi}_{C,t} > \Pi^{**}_{C,t} > \Pi^{*D}_{C,t}$. This is the constellation drawn in Fig 5a. It immediately implies that the fossil fuel principals cannot gain from shirking as their MPE net profits exceed profits in the alternative to which the allocation can collapse: $*C$ and $**$. Similarly, renewable principals have no incentive to shirk, as their alternatives also have lower profits compared to their net profit in equilibrium. Thus, the MPE is stable. The Fig visualizes the concept through arrows: an arrow from allocation $A$ to $B$ means that no principal gains from collapsing back from $B$ to $A$.

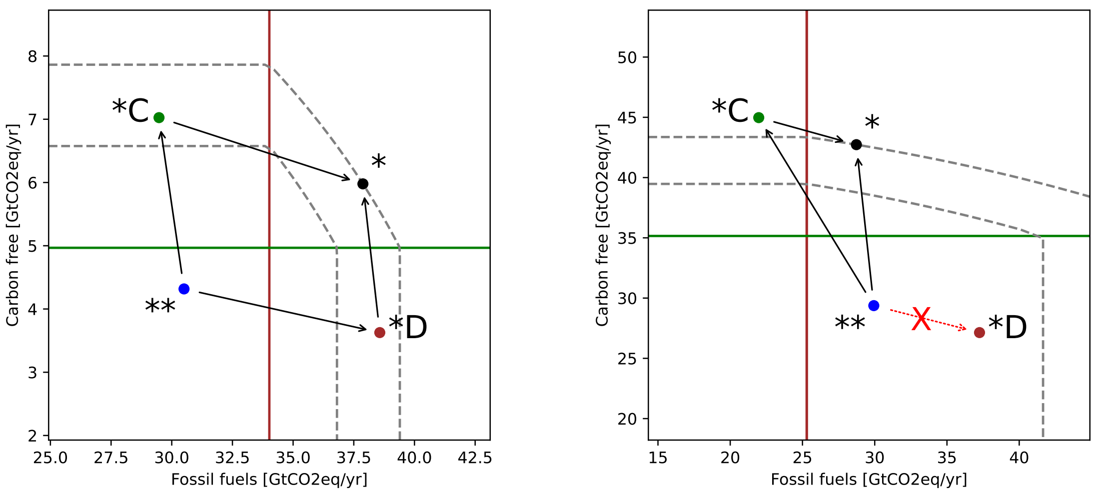
Next consider the asymmetric case, without loss of generality, that $\Pi^{**}_{D,t} > \Pi^*_{D,t}$ and $\Pi^*_{C,t} > \Pi^{**}_{C,t}$, as shown in Fig 5b. Because of substitutability, as above, the conditions are extended to $\Pi^{**}_{D,t} > \Pi^*_{D,t} > \Pi^{*C}_{D,t}$ and $\Pi^*_{C,t} > \Pi^{**}_{C,t} > \Pi^{*D}_{C,t}$. We now construct $\overline{\Pi}_{C,t}$ such that, while $*C$ maximizes

$$\ln(Y_t(E_{D,t}, E_{C,t}) + \zeta(\Pi_{C,t}(E_{C,t}, E_{C,t}) - \overline{\Pi}_{C,t})) - \beta\Theta E_{D,t}, \tag{A.7}$$

the optimum satisfies

$$\begin{aligned} &\ln(Y_t(E^{**}_{D,t}, E^{**}_{C,t})) - \beta\Theta E^{**}_{D,t} = \\ &\ln(Y_t(E^{*C}_{D,t}, E^{*C}_{C,t}) + \zeta(\Pi_{C,t}(E^{*C}_{D,t}, E^{*C}_{C,t}) - \overline{\Pi}_{C,t}) - \beta\Theta E^{*C}_{D,t}. \end{aligned} \tag{A.8}$$

and (A.6) still holds determining $\overline{\Pi}_{D,t}$. It follows that $*C$ is downwards stable: no individual renewable energy has an incentive to shirk as (by construction) $\Pi^{*C}_{C,t} > \overline{\Pi}_{C,t} > \Pi^{**}_{C,t}$. Given transfers by only the clean energy firms, the policy maker is indifferent between ** and *C, both strictly preferred to *, thus $\overline{\Pi}_{D,t} < \Pi^*_{D,t}$. With transfers by the




(a) 2020

(b) 2060

Figure 5: Both panels based on calibrated parameters. They show the MPE equilbria $*$ (black), with alternative candidates $*C$ (green), $*D$ (brown-read), $**$ (blue) for 2020 and 2060, respectively. The green line marks allocations for which $T_{C,t}(E_t) = 0$, while the red line marks $T_{D,t}(E_t) = 0$, as in (A.4). Transfers for each sector are positive right of (above) the lines and zero left of (below) the lines. Gray dashed lines present constant rewards: $\sum_i T_{i,t}$. An arrow from ** to *C shows that no individual renewable principal has an incentive to deviate from the reward function. The arrow from $*C$ to $*$ shows that no individual fossil fuel principal has an incentive to deviate from the reward function. The red crossed arrow shows that in *D each fossil fuel principal can deviate so that it collapses to $**$.

dirty energy firms, allocation * is equally valued by the policy maker, thus $\Pi^{*C}_{D,t} < \overline{\Pi}_{D,t}$. That is, the dirty firms will have to make a strict positive contribution to make the policy maker indifferent between * and **; the reward $T_{D,t}$ moves the equilibrium from $*C$ to $*$, we have $\Pi^{*}_{D,t} > \overline{\Pi}_{D,t} > \Pi^{*C}_{D,t}$. It follows that if a fossil fuel firm has no incentive to shirk in the MPE equilibrium $*$ because it knows that the equilibrium will collapse to $*C$ which has strictly lower profits for fossil fuels. On the other hand, as $\overline{\Pi}_{C,t} > \Pi^{**}_{C,t} > \Pi^{*D}_{C,t}$, in equilibrium $*$ also no renewable firm has an incentive to shirk as any alternative will also strictly reduce profits. Thus, the MPE $*$ is stable. ■

# B Appendix: Quantitative model

The model is simulated using python, an open source language. The code is freely available. We calculated the scenarios using two formats, with FOCs included, and without FOCs. Results are the identical which suggests consistency of the algebra derivations in the paper.

**Social Optimum** We set $t_L = 30$ periods of 5 years each. Welfare is given by

$$W = \sum_{t=t_F}^{t_L} \beta^t \ln(C_t) - \beta^{t_L} \sum_{n=1}^{t_L} \sum_{i=0}^{\infty} \beta^i \theta_{n+i} E_{D,t-n} \tag{B.1}$$

**Zero Taxes** The scenario with zero taxes

[still working on the fine-tuning of the procedure to calculate scenarios and calibration.] We can calculate the MPE equilibrium as follows. For given $\overline{V}_{i,t}, \Xi_t$, we can solve the program based on equations: $(33, Y_t)$, $(12, c_{i,t})$, $(11, \Pi_{i,t})$, $(??, \mu_{i,t})$.

$$\max W_t = \ln\Big((1 + \zeta\beta\Xi_{t+1})Y_t + \zeta \sum_i \left(\Pi_{i,t} - \overline{V}_{i,t}\right)\Big) + \beta W_{t+1} \tag{B.2}$$

subject to

$$Y_t = L_t f(e_t) - \sum_j c_{i,t} \tag{B.3}$$

$$c_{i,t} = \frac{\sigma}{\sigma+1}\mu_{i,t}E_{i,t} \tag{B.4}$$

$$\Pi_{i,t} = \frac{1}{\sigma+1}\mu_{i,t}E_{i,t} \tag{B.5}$$

$$E_{i,t} = \chi_{i,t}\mu_{i,t}^{\sigma} \tag{B.6}$$

using $E_{i,t}$ as control variables, and where we substitute

$$f_t(e_t) = A_t e_t^{\gamma_t} \tag{B.7}$$

$$e_t = \frac{E_{D,t} + E_{C,t}}{L_t} \tag{B.8}$$

We can pull out taxes and wages that support the allocation through $(7, E_{i,t})$, $(8, w_t)$. That is, we can add these FOCs and they should not change the allocation:

$$\mu_{i,t} = \max\{0, \Omega(h_t) f_t'(e_t) - \tau_{i,t}\} \tag{B.9}$$

$$w_t = \Omega(h_t)[f_t(e_t) - f_t'(e_t)e_t] \tag{B.10}$$

But, the above program can only be solved after we have the values for $\overline{V}_{i,t}, \Xi_t$. We can calculate these parameters iteratively, over a loop, or we can solve the equilibrium using the explicit tax conditions. That is, we add the equations $(31, \tau_{D,t})$, $(30, \tau_{C,t})$, $(26, g_t, T_t)$, $(22, 22, \Xi_t)$. We note that the solution to the full set of equations should be independent of the objective function.

$$\tau_{D,t} = \frac{1}{1+\zeta\beta\Xi_{t+1}} g_t \beta \Theta Y_t - \frac{1}{1+\zeta\beta\Xi_{t+1}} \frac{1}{\sigma} \mu_{D,t} \tag{B.11}$$

$$\tau_{C,t} = -\frac{\zeta}{1+\zeta\beta\Xi_{t+1}} \frac{1}{\sigma} \mu_{C,t} \tag{B.12}$$

$$g_t = exp(\beta\Theta(E_{D,t} - E_{D,t}^{SO})) \tag{B.13}$$

$$g_t = 1 + \zeta \frac{T_t}{Y_t} \tag{B.14}$$

$$\Xi_t = \sum_{n=0}^{\infty} \beta^n \frac{\Pi_{t+n} - T_{t+n}}{Y_{t+n}} \tag{B.15}$$

where we need an a priori calculation for $E_{D,t}^{SO}$. We test the model by first solving the full set of equations. Then we calculate

$$\sum_i \overline{V}_{i,t} = \Xi_t Y_t \tag{B.16}$$

and we can, as a check, solve the first adjusted welfare program above without the FOCs, to see whether it replicates the allocation.