The Gas Trap:
Outcompeting Coal vs. Renewables*

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Abstract

We analyze a fundamental dilemma and time-inconsistency problem facing climate-concerned producers of natural gas. In the short term, it is tempting to produce more to outcompete coal. When this policy is anticipated, however, investments in renewables fall and emissions may ultimately increase. When the coalition cannot pre-commit, its policies can be counterproductive. A simulated version applied to Europe verifies that the gas trap is quantitatively important. We discuss the robustness of this result and possible solutions, ranging from direct investments in renewables to taxes on the search and exploration of gas.

Keywords: climate change, carbon leakage, green transition, supply-side environmental policy, renewable energy, time inconsistency

JEL codes: F18, Q55, H23

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1 Introduction

- The best is the enemy of the good.
M. de Voltaire

The good can also be the enemy of the best.

Gas, coal, and renewables can be referred to as the good, the bad, and the best. The three sources of energy are competing and substitutable. To successfully address climate change, the world must stop using coal as soon as possible. The production of natural gas is good in that it can replace coal. New York Times (2024) writes that: "While nations have agreed on the necessity to transition away from fossil fuels as quickly as possible, almost all major economic powers are promoting gas as a "transition fuel."[1] After all, coal is twice as carbon-intensive, per unit of energy, as natural gas.[2] In the long run, however, all types of fossil fuels – gas as well as coal – must be replaced by renewable energy sources. Welsby et al. (2021) find that of existing reserves, only 11 percent of coal, and 44 percent of gas, can be extracted to reach the 1.5°C target. Pellegrini et al. (2024) find the numbers to be 3 percent and 19 percent, respectively.

Climate-friendly gas producers therefore face a dilemma. On the one hand, if they export more gas, the need to consume energy from coal can decline. On the other hand, a larger supply of gas can reduce the price of energy and make investments in renewables unprofitable.

Each effect travels through changes in the price of energy. The extent to which a producer reacts to a change in the price, and thus to the supply of gas, depends on the price elasticity. This price elasticity measures the percentage increase in supply given a percentage increase in the energy price.

The starting point of our paper is that the price elasticities are not fixed numbers. Instead, the ability to change the supply, because of a change in the price, depends on the time horizon. In the short term, the ability to change the supply is limited. With more time, the supply is likely to be more elastic. This qualitative insight is likely to hold for all sources of energy.

Nevertheless, there is a fundamental difference between coal and renewables. With the green transition, coal will be a declining industry. The capital that has been sunk risks becoming stranded assets. In other words, investments and capital that have accumulated over several decades will not be fully exploited when coal is being produced. Because the capacity to produce is not binding, production can increase or decrease

[1] `https://www.nytimes.com/2024/05/31/climate/greece-europe-natural-gas-lng.html`.

[2] See, for example, `https://www.eia.gov/environment/emissions/co2_vol_mass.php`

on short notice if the energy price changes unexpectedly. The price elasticity of coal in the short term is relatively large.

Renewables, in contrast, are up-and-coming. We are seeing R&D and a lot of other investments that will gradually expand the capacity to produce renewable energy. This expansion takes time, however, so the short-term price elasticity is relatively small. With a longer time horizon in mind, investors can invest in building more solar panels, for example, if the investments are expected to be profitable. Thus, supply is likely to be elastic in the long run.

The fundamental difference between the short term and the long term generates a time-inconsistency problem for climate-concerned gas producers. The optimal long-term policy is to limit gas production so that investments in renewables will materialize. In the short term, the stock of renewables is given, and it will be tempting to expand gas production to outcompete coal. This temptation is especially strong when the harm associated with climate change is large. But when the market anticipates the temptation to outcompete coal, investments in renewables fall and emissions ultimately increase. This is the *gas trap*.

The purpose of this paper is to analyze this time-inconsistency problem, its robustness, and potential solutions. We first develop an extremely simple model. The model is not intended to be general, but minimalistic in that it is just enough to capture the key mechanism driving the time-inconsistency problem. After we generalize the model to allow for multiple sources of fuels, including nuclear energy, oil, and liquefied natural gas (LNG), we simulate the outcome for the electricity market in Europe. Based on the actual market shares and the elasticities for the different types of supplies, we confirm that the gas trap is indeed present in Europe, and that it is quantitatively important. We show that the results are strengthened when we take into account learning by doing and the exhaustability of fossil fuel resources.

The quantitative analysis is also helpful in evaluating alternative solutions for dealing with the gas trap. For example, direct investments in renewables by the coalition can implement the first best, in theory, but Norway, for example, would have to multiply its export of renewable energy by 22 for this policy to be effective. A more reasonable solution is then, we argue, to regulate upstream activities, such as search and exploration of gas. When these activities are taxed, or regulated in other ways, future gas production is expected to decline, and investments in renewables will increase. We also find that the benefit of a supply-side treaty is not mainly coming from the size of the coalition, or its composition. Instead, we conclude, the primary benefit of a treaty is that it can help the participants to commit to future production cuts.

Our findings are important because economists as well as practitioners still emphasize first-best policies such as Pigou taxes, optimal when policies can be committed to. At the same time, gas producers, such as

Norway, often emphasize the need to replace coal by producing more gas. This replacement is sensible, and even optimal, in the short term when the stock of renewables is hard to change. But to avoid a decline in renewables investment, and thereby prevent the green transition from materializing, gas production must be regulated rather than subsidized.

A growing empirical literature is consistent with the assumptions of our model. Ahlvik et al. (2024) show that the supply of fossil fuel reacts to taxes, and that suppliers not subject to the tax are also responding, leading to carbon leakage. Clean and dirty energy inputs are substitutes (Papageorgiou et al., 2017; Brehm, 2019), coal production declines if the supply of wind energy is large (Fell and Kaffine, 2018) or the supply of gas is large: See Knittel et al. (2016), McGlade et al. (2018), or Coglianese et al. (2020). Reversely, Aghion et al. (2016) show how energy prices affect clean innovation.

Technically, what we refer to as renewable energy can just as well represent nuclear energy or, in fact, energy economizing capacity, so that consumption can remain high without the need to emit. Jarvis et al. (2022) found that when investments in nuclear energy fell in Germany after the Fukushima accident, coal production increased. Colmer et al. (2025), studying the effect of carbon prices in Europe, find that an explanation for marginal costs not necessarily increasing after the carbon price was introduced, was that firms invested in energy saving that were made up front. These findings are also in line with our model when we broaden the interpretation for what we refer to as investments in renewables.

The theoretical literature on supply-side environmental policies is also growing. When free riders trade with climate cooperators, Hoel (1994) shows that a climate coalition will, in general, benefit from regulating both the consumption and the production of fossil fuel. Harstad (2012a) finds that when the coalition can take advantage of the international market for fossil fuel reserves, the first-best outcome can be implemented by supply-side policies alone. In the first best, the coalition purchases coal deposits in free-riding countries. In this paper, we acknowledge that purchasing deposits in other countries can be politically challenging. Instead, we make the more realistic assumption that, although free riders trade fossil fuels internationally, the coalition does not pay them directly for consuming or producing less. Among the benefits of a supply-side treaty (Asheim et al., 2019), we uncover the value of being able to commit to future production cuts.

The empirical fact that natural gas can replace coal and renewables has been analyzed in the theoretical literature: See, for example, Gerlagh and Smulders (2024), Abuin (2024) or Acemoglu et al. (2023). In these papers, the short term effect is that gas replaces coal, but the long-term effect includes a negative effect on renewables. Consequently, the US gas boom can delay the green transition to renewables. The delay is harmful for a climate-concerned coalition, which would like to commit to reduce emissions in order to

raise the investments in renewables (Harstad, 2012b), even in other countries (Holtsmark and Midttømme, 2021). Profit-maximizing fossil-fuel producers, in contrast, can take advantage of the fact that more fossil fuel delays the transition (Gerlagh and Liski, 2011). More generally, there is an extensive literature studying different effects of increased supply of natural gas. Daubanes et al. (2021) study the effect of increased domestic natural gas supply accounting for cross-country leakages but without considering the long-term effect on renewables. McJeon et al. (2014) investigate the effects of the shale gas boom in the US including the potentially higher emissions from unconventional gas extraction in the analysis, while Gillingham and Huang (2019) find small effects on carbon emissions, but larger effects for local pollution. Several papers document short-term emission reductions following the boom, see for example Cullen and Mansur (2017).

Our contribution to this literature is to explore the consequences of the climate coalition's time inconsistency problem. We illustrate when the comparative statics are reversed (and the policy is counterproductive) in equilibrium, relative to the outcome under commitment. The simplicity of our model makes it sufficiently flexible to allow for a large number of generalizations, including multiple types of fossil fuels, many periods, learning by doing, resources that are depleted over time, and search-and-exploration activities prior to the production stage. These extensions allow us to contribute to several strands of literatures.

Our emphasis on time inconsistency connects our paper with the literature on macroeconomic policy going back to Kydland and Prescott (1977). Fischer (1980) discusses the temptation to set a positive tax on capital, after capital was sunk, even though a lower tax would have been optimal from the outset. If international tax competition reduces the tax, international cooperation to reduce the competition can be harmful (Rogoff, 1992; van der Ploeg, 1988; Kehoe, 1989). Karp and Newbery (1993) discuss several time inconsistency problem for resource extraction. More recently, Gerlagh and Liski (2018) study the value of commitment in a model with taxes on capital as well as emissions, Harstad (2020) analyze how regulating green and upstream technology can help with commitment, and Acemoglu and Rafey (2023) explain why the optimal emission tax fails to be time consistent in the presence of geoengineering.

Our paper is organized as follows. In the next section, we present the simplest version of our model. In Section 3, we compare the outcome under commitment (Proposition 1) to the equilibrium when policies are not committed to (Proposition 2). Our main result is that short-term policies are counterproductive and that the comparative statics are reversed. Section 4 allows for multiple energy sources, simulates the model to fit the European market for electricity, and confirms that the gas trap is quantitatively important. In Section 5, we argue that this finding holds when we allow for many periods, time-varying parameters, learning by doing, and depletable resources. We discuss policy implications in Section 6 and find that it may be necessary to

regulate upstream activities or sign binding supply-side treaties. Section 7 concludes. Appendix A contains all proofs and B discusses the sensitivity of the estimates for the quantitative application.

2 The Model

The model can be quite general, but it does not need to be complicated. To explain the results in a pedagogical way, in this section we present an especially simple model. Natural generalizations are analyzed in Sections 4-6.

There are two types of countries in the world. M is the set of members of a coalition that is actively regulating consumption and production of energy. N is the set of other countries.

M is producing natural gas, x_G. Gas competes with the supply of coal, x_C, and renewable energy, x_R, both produced by the rest of the world (i.e., by N). The three sources of energy are perfect substitutes and, in the world market, they trade at the same price p. (We refer to gas instead of oil because coal and renewables are rather imperfect substitutes for oil.) The energy price is endogenous and ensures that the total supply is equal to the total demand. M's consumption of energy is y_M, while y_N is the energy consumed by N.

Payoffs. The representative consumer's benefit from consumption is given by the increasing and strictly concave function $b_i(y_i)$, $i \in \{M, N\}$. The production cost is $c_j(x_j)$, $j \in \{C, G, R\}$. M experiences harm $ah(e)$ from the total emissions:

$$e = e_C x_C + e_G x_G, \tag{1}$$

where e_C is the carbon content of coal, $e_G \in (0, e_C)$ is the carbon content of gas, and $h(\cdot)$ is a weakly convex function. There are no emissions from renewable energy. The harm is written as $ah(e)$, so that we can consider a change in the harm (a) without changing the function $h(\cdot)$.

Policies. M regulates x_G and y_M or, equivalently, M imposes a production tax, τ_G, on domestic gas production and a tax, τ_M, on M's consumption. With quasi-linear utility functions, the representative consumer in M solves:

$$\max_{y_M} b(y_M) - (p + \tau_M) y_M \Rightarrow y_M = D_M(p + \tau_M) \equiv b_M'^{-1}(p + \tau_M). \tag{2}$$

The representative gas producer in M solves:

$$\max_{x_G} (p - \tau_G) x_G - c_G(x_G) \Rightarrow x_G = S_G(p - \tau_G) \equiv c_G'^{-1}(p - \tau_G). \tag{3}$$

If there is no regulation in N, N's demand for energy is $y_N = D_N(p) \equiv b_N'^{-1}(p)$, and its supply of coal is $x_C = S_C(p) \equiv c_C'^{-1}(p)$, when we assume that all consumers and producers take the price as given. Although

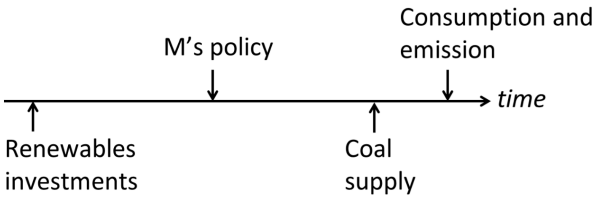


Figure 1: Timing

N's harm plays no role in the game, its demand and supply functions can take into account fixed emission taxes as well as transport costs.[3] We will assume that there are interior solutions to all these quantities. Supply equals demand when:

$$S_C(p) + S_G(p - \tau_G) + x_R = D_N(p) + D_M(p + \tau_M). \tag{4}$$

The taxes are domestic transfers, so M's policy is set to maximize M's objective:

$$b_M(y_M) - c_G(x_G) + (x_G - y_M)p - ah(e), \tag{5}$$

subject to (1)–(4).

Timing. Our key assumption is that coal production is more price elastic than renewable energy production in the short run, but the reverse holds in the long run. As explained in the Introduction, this assumption is natural when coal is a declining industry, with spare capacity that can be taken advantage of whenever profitable. Renewable energy sources, in contrast, require new capacity to be developed and built. New constructions take more time.

We formalize this assumption as follows. First, the capacity to produce x_R must be determined Δ_R units of time before the energy can be consumed. The time required to produce and supply coal is given by $\Delta_C \in [0, \Delta_R)$. The inequality $\Delta_C < \Delta_R$ implies that after x_R has been determined, it is still possible to change x_C. Consequently, the supply of coal is more price elastic than that of renewables – in the short run.

In the long run, however, the production of renewable energy is more price elastic than the supply of coal is. In fact, the supply of renewable energy can be increased to unprecedented levels if the world just builds enough windmills and solar panels. To capture this intuition in the simplest way, we assume that

[3]For example, if coal suppliers in N face unit transport cost $\tau^{tra}_{N,C}$ and emission tax $\tau^{tax}_{N,C}$, then supply is defined by $x_C = S_C(p) \equiv c_C'^{-1}\left(p - \tau^{tra}_{N,C} - \tau^{tax}_{N,C}\right)$.

there is a constant cost for each unit of renewable energy capacity that is invested in: $c_R'(x_R) = k$. The cost of producing coal, in contrast, is given by the increasing and strictly convex function $c_C(x_C)$.

We do not need to make particular assumptions about the production cost and lag for gas. For simplicity, we assume that the production cost is an increasing and strictly convex function. In the main analysis, we suppose that the time it takes to deliver gas is $\Delta_G \in (\Delta_C, \Delta_R)$, as in Figure 1. However, at the beginning of Section 3, we will also consider $\Delta_G > \Delta_R$ and the case in which M can commit to policies before x_R is decided. We end Section 3 by discussing the consequence of assuming $\Delta_G < \Delta_C$.

Generalizations. The model is simple for pedagogical reasons. In the quantitative application in Section 4, N supplies multiple types of fuels and there can be other gas producers than M. In Section 5, we explain how we can allow for many periods, an infinite time horizon, and parameters that change over time. In fact, k can be endogenous to take into account learning-by-doing effects. We also explain that if M's stock of gas is depletable, the results are strengthened. In Section 6, we allow M to invest in renewable energy sources directly, and we distinguish between the decision to explore and search for natural gas, and the decision to extract from existing reserves. In Appendix A, we explain why M cannot do better by using trade policies (such as import taxes) in addition to (τ_G,τ_M).

3 The Results

Before deriving the subgame-perfect equilibrium (SPE) of the game above, we provide two benchmark results.

In the first best (FB), all quantities are decided to maximize benefits minus costs and harms. The FB quantities require that every marginal benefit equals the marginal cost plus the marginal harm. These quantities are implemented in a decentralized economy if all producers face Pigou taxes representing the marginal harms. (In the following, we simply write h' even when the marginal harm is a function of e.)

Proposition 0. *The FB is implemented by Pigou taxes on gas and coal, but no tax on consumption or renewables:*

$$\begin{aligned} \tau_G &= e_G a h', \, \tau_C = e_C a h', \text{ and} \\ \tau_M &= \tau_N = \tau_R = 0. \end{aligned}$$

Thus: The larger a is, the larger τ_G and x_R are, and the smaller x_C, x_G, and e are.

3.1 The Commitment Solution

We now characterize the SPE if M could, at the beginning of the game, commit to (x_G, y_M) or, equivalently, the pair (τ_G, τ_M) that implements (x_G, y_M).

Proposition 1. *If M could commit, M would set a Pigou tax on domestic gas production:*

$$\begin{aligned} \tau_G &= e_G a h' \text{ and} \\ \tau_M &= 0. \end{aligned}$$

Thus: The larger a is, the larger τ_G and x_R are, and the smaller x_G and e are.

Even if M could commit, the outcome would not be FB, of course, because there would be no tax on N's coal production. Thus, we refer to this outcome as the "second best" (SB).

But the SB is qualitatively similar to the FB. M finds it optimal to set a Pigou tax on gas production, which increases in ah'. Consequently, when ah' is large, the equilibrium x_G is small and, to satisfy (4), x_R will be large. The level of x_C is unchanged, and pinned down by $S_C(p)$, given that $p = k$, in equilibrium.

When x_G is reduced, and x_C is unchanged, e is reduced.

Just as in the FB, there is no tax on domestic consumption. The intuition for this result is that regulating consumption would simply have reduced the investments in renewables. After all, the equilibrium price, $p = k$, pins down the equilibrium y_N, x_C, and, for a given τ_G, also x_G. So, committing to lower consumption does not reduce emissions, given the assumption that the supply of renewables is price elastic.[4]

3.2 Equilibrium

Instead of assuming that M commits to policies before x_R is decided, as in Section 3.1, we now consider the equilibrium without long-term commitment. We assume that after x_R is decided, but before x_C has been set, M determines (x_G, y_M) or, equivalently, the pair (τ_G, τ_M) that implements (x_G, y_M).

Our main result is that if gas is relatively green, compared to coal, the comparative statics are reversed relative to the FB and the SB. M ends up with more emissions if ah' is large. M's policy is counterproductive and does more harm than good. This is the gas trap:

[4]Generally, optimal unilateral climate policy for a fossil-energy producing country would include taxation of both production and consumption, see for example Hoel (1994). However, when the equilibrium energy price is fixed at k, taxing domestic consumption in M would only result in lower domestic consumption, without affecting global emissions or terms of trade.

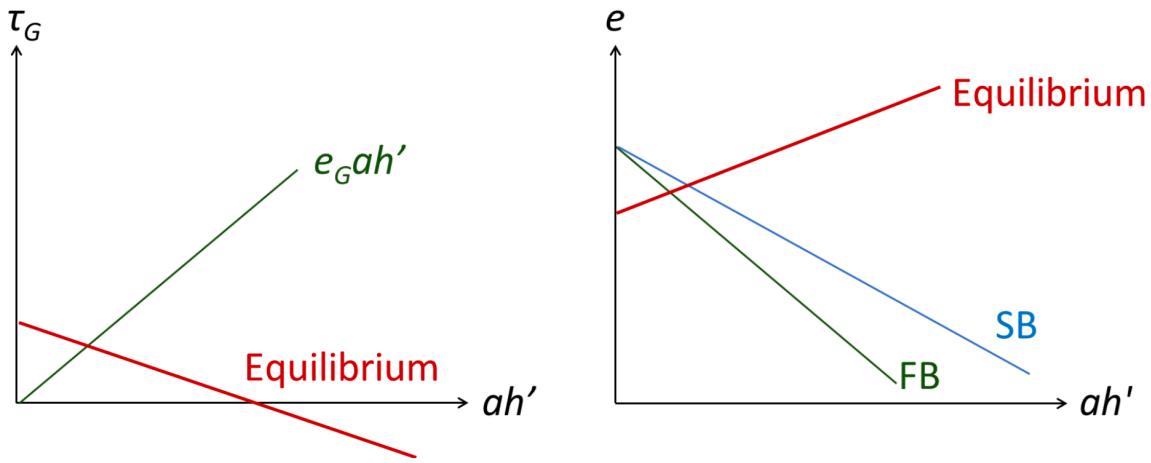


Figure 2: In contrast to the FB and the SB, if the marginal harm increases then the equilibrium gas production tax decreases and emissions increase.

Proposition 2. *In equilibrium, $p = k$, and M's policy satisfies:*

$$\begin{aligned} \tau_G &= e_G a h' - \Omega = \left(e_G - \frac{e_C S_C'(k)}{S_C'(k) - D_N'(k)} \right) a h' - \frac{D_M(k + \tau_M) - S_G(k - \tau_G)}{S_C'(k) - D_N'(k)}, \\ \tau_M &= \Omega, \text{ where } \Omega \equiv \frac{e_C S_C'(k)}{S_C'(k) - D_N'(k)} a h' + \frac{D_M(k + \tau_M) - S_G(k - \tau_G)}{S_C'(k) - D_N'(k)}. \end{aligned} \tag{6}$$

(i) Thus, the larger a is, the larger τ_M is, and the smaller y_M is.

(ii) Suppose

$$\frac{e_G}{e_C} < \frac{S_C'(k)}{S_C'(k) - D_A'(k)}, \text{ where } D_A'(p) \equiv D_M'(p) - D_N'(p). \tag{7}$$

The larger a is, the smaller τ_G and x_R are, and the larger x_G and e are.

So, if (7) holds, the comparative statics from the FB and the SB are reversed: With a larger marginal harm, the amount of renewable energy will be smaller and the emission level will be higher. Perversely, M's well-meaning climate policy contributes to more harm, especially if a is large. Figure 2 illustrates the comparative statics and contrasts them to the FB and the SB. If M is a net exporter, $\tau_G > 0$ when $ah' = 0$ because regulating production raises M's export price (for any given x_R). The production tax is less than Pigouvian if and only if $\Omega > 0$.

How can it be that M's own policy leads to an equilibrium outcome where emissions are higher and M is worse off?

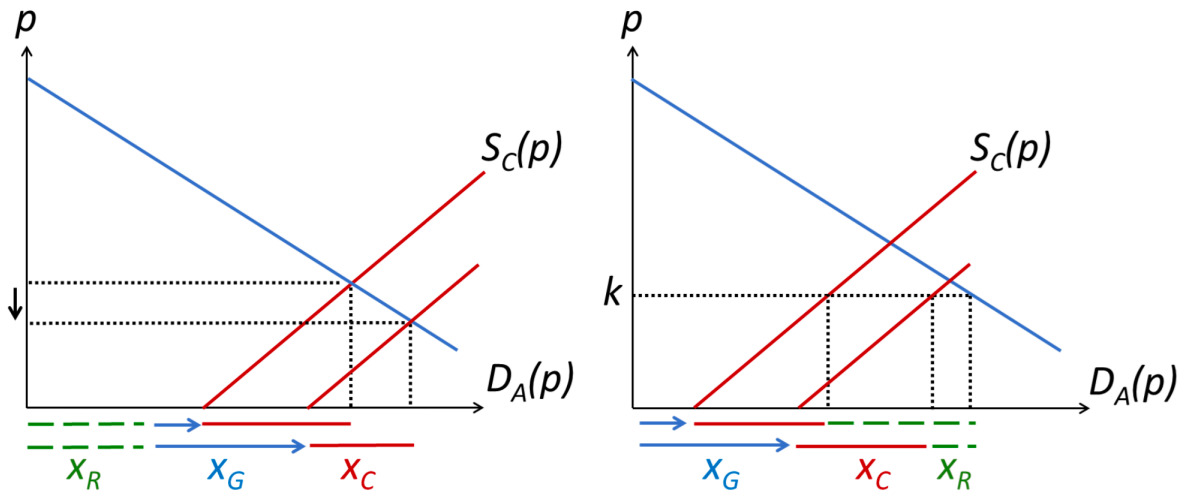


Figure 3: In the short term (left panel), the capacity to produce renewables (dashed line) is given, and more gas (arrow) reduces coal (solid line). In equilibrium (right panel), more gas replaces renewables, not coal.

The intuition is that M cannot help attempting to outcompete coal. For any given x_R, a larger x_G, and a lower y_M, will reduce the equilibrium energy price. As illustrated in Figure 3 (left panel), the lower price will reduce coal production. If coal is sufficiently dirty, relative to gas, total emissions will decline. In the subgame that starts with a given x_R, M's policy is sensible.

When M's policy is anticipated, however, investments in renewables will adjust. Rational expectations about the low τ_G, and the high τ_M, will imply that the expected p is low, for any given x_R. In equilibrium, x_R is reduced so much that the equilibrium price remains at $p = k$: See Figure 3 (right panel). The reduced x_R, and the maintained price, imply that equilibrium coal production does not fall, even if x_G increases. Because x_G is larger, equilibrium emissions increase when M attempts to outcompete coal. M's short-run solution – more gas – is a long-run trap.

Other comparative statics are also worth noticing. The larger the short-term price elasticity of coal is (i.e., $S_C'(p)$), the smaller τ_G is and the larger τ_M is, when ah' is large, because both these tax changes contribute to a smaller p and x_C, for any given x_R. Thus, it is in this situation when x_R falls the most in equilibrium, so that equilibrium x_G and e will actually increase.

Intriguingly, (7) is more likely to hold when e_G is small. That is, if gas has a lower emission intensity, relative to coal, it is more likely that gas will be subsidized and, thus, that M's policy contributes to a larger

e when a is large.

Remark on $\Delta_G < \Delta_C$. Suppose M's policy were set after both x_C and x_R. (This would require $\Delta_G < \Delta_C$.) In this case, (6) would continue to hold if we just replaced S'_C by zero. M would still take into account the harm associated with more gas production, and also how M's terms of trade (i.e., p) would change because of the policies, given x_C and x_R. For instance, if M were a net importer, M would tax supply less, and tax consumption more, than in the SB. These policies would be anticipated so, as above, x_R would be small, relative to the SB, so that, in equilibrium, p would continue to equal k.

4 Quantitative Analysis

The purpose of this section is to illustrate that the gas trap is not merely a theoretical possibility, but that its existence is consistent with a reasonable simulation of the model.

We first generalize the model by allowing N to produce many different types of fuels with varying emissions. (In the Appendix, we also allow M to supply multiple types of energy.) This generalization is, of course, important in its own right, because the model above is especially simple for pedagogical reasons. Thereafter, we simulate the model to fit the European electricity market. It is sensible to limit attention to a regional market, rather than the world as a whole, because it is costly to transport coal, gas, and electricity. The regionalization of the energy markets is backed up by the fact that the energy prices vary quite a lot between regions.[5] We have chosen the European market because of data availability and its implications for other markets with equal or greater coal production. If the gas trap can arise in Europe, where the fraction of coal is only 17.1 percent, it can also arise in the US where the fraction of coal is comparable, and certainly in Australia and Asia where the fraction is higher (IEA, 2024).

4.1 Multiple Sources of Energy

Suppose e_j and $c_j(x_j)$ are the emission content and cost function, respectively, for N's fuel of type $j \in J$. We write $S_j(p) \equiv c_j'^{-1}(p)$ for $j \in J$, and $S_N(p) \equiv \sum_{j \in J} S_j(p)$. We write $A = M \cup N$ as the set of all countries or fossil fuel supply functions, so $D'_A = D'_M + D'_N$ and $S'_A = S'_M + S'_N$. As mentioned in Section 2, the country- and fuel-specific cost of transporting the fuel to the common market and N's fixed tax for the various types of fuels can be included in the cost function.

[5] US Energy Information Administration, https://www.eia.gov/todayinenergy/detail.php?id=43535, accessed December 28, 2024.

We will emphasize three results related to the gas trap.

Effect of gas: As shown in Appendix A, if M raises x_G, the total emission decreases iff:

$$\frac{\partial e}{\partial x_G} = e_G - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_N'(p)} < 0. \tag{8}$$

Effect on the policy: When these derivatives are taken into account, M's optimal policy satisfies:

$$\tau_G = \left(e_G - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_N'(p)}\right) ah' + \frac{\sum_{l\in L} S_l(p-\tau_l) - D_M(p+\tau_M)}{S_N'(p) - D_N'(p)}, \tag{9}$$

$$\tau_M = \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_N'(p)} ah' - \frac{\sum_{l\in L} S_l(p-\tau_l) - D_M(p+\tau_M)}{S_N'(p) - D_N'(p)}. \tag{10}$$

As before, $\tau_G + \tau_M = e_l$. (Golombek et al. (1995) and Harstad (2012a) present similar results.) Below, we emphasize that because the short-term and long-term elasticities differ, the τ_G preferred in the short run might be smaller than the one preferred in the long run. If that is the case, noncommitment leads to more gas and emissions than if M could commit.

Effect of SCC: If a is larger, τ_M is larger, and M may export more, if $D_M'(p) \neq 0$. Because M's export enters positively in (9), the condition for when τ_G decreases in a is stronger than (8). The new condition is especially simple to find if N's supply of renewables (or, alternatively, nuclear energy) is elastic in the long run, so that the equilibrium price is $p = k$, while, among M's sources of energy, only gas responds to the price. In this case, the Appendix shows that:

$$\frac{d\tau_G}{da} = \frac{e_G\left(S_N'(k) - D_A'(k)\right) - \sum_{j\in J} e_j S_j'(k)}{S_A'(k) - D_A'(k)} h' = \left[e_G - \frac{\sum_{j\in J} e_j S_j'(k)}{S_N' - D_A'}\right] \frac{S_N'(k) - D_A'(k)}{S_A'(k) - D_A'(k)} h'. \tag{11}$$

If the expression within the brackets is negative, a larger a reduces M's tax on gas. When $d\tau_G/da < 0$ in the short run but not in the long run, then a larger weight on climate change induces M to implement policies that result in more emissions – when M cannot commit. This is the gas trap.

4.2 The Electricity Market in Europe

Is the gas trap empirically relevant? To shed light on this question, we must simulate (8), (11), or (9). We do this in Subsections 4.3, 4.4, and 4.5, respectively. For these exercises, we need estimates for the various parameters and functions and information on how they vary with the time horizon.

Sources. Table 1 summarizes the sources of electricity consumed in Europe, the emission intensities, and the supply-side elasticities for the short run and the long run. These estimates will be combined with

the formulae above in the next three subsections, and the reader is free to jump directly to them. In this subsection, we briefly explain the backgrounds for the numbers. Everywhere in the table, numbers in bold are borrowed directly from our sources, while the other numbers are our guesses based on the numbers in bold. In Appendix B, we discuss the numbers in more detail, alternative estimates, and we provide sensitivity analyses w.r.t. the numbers.

Source/characteristics	%	e_j	ε_j^{ST}	ε_j^{LT}	
Coal	**17.1**	**1.0**	2.4	**2.4**	
Gas_{NORWAY}	**5.1**	**0.4**	0.2	0.5	
Gas_{OTHER}	**11.6**	**0.4**	**0.2**	**0.5**	
LNG_{USA}	**3.2**	1.3	**2.0**	**2.0**	
LNG_{RUSSIA}	**1.0**	1.3	2.0	2.0	
Oil	**1.5**	0.8	0.3	**1.0**	
REN_{NORWAY}	**3.7**	**0.0**	0.0	0.0	
REN_{OTHER}	**31.1**	**0.0**	0.0	**3.0**	
Nuclear	**18.7**	**0.0**	0.0	3.0	
Other	**7.0**	0.1	1.0	1.0	
Demand $\left(\varepsilon_N^{ST}, \varepsilon_N^{LT}\right)$	**100**		-0.1	-2.0	

Table 1: Energy shares, emission intensities, and elasticities used in the main specification.

The International Energy Agency (IEA, 2024) writes that the total consumption of electricity in Europe was 4,018,737 GWh in 2022. Column 2 in Table 1 gives the market shares for the various fuel sources in European electricity generation in 2022 based on IEA (2024) and ACER (2024). The share of oil is small, as oil is not much used in European electricity generation. Most oil is used in transport, where electricity generation is an imperfect substitute. (Appendix B looks at the entire energy market.) The category "Other" lumps together biofuels, waste, and geothermal energy.

Emission coefficients. Column 3 lists the emission coefficients (e_j) for the various sources, measured as kg CO2 equivalents per kWh. The coefficients for coal, gas, and renewables are consistent with Acemoglu et al. (2023). The ratios to oil and other sources are consistent with EIA (2024) and the ratio for LNG is consistent with Howarth (2024). LNG is transported by ships, in contrast to the gas transported by pipelines from Norway, for example. (LNG is not included in the analysis of Acemoglu et al. (2023), since the paper studies the domestic US electricity market.) To liquify, gas must be cooled to extremely low temperatures, which requires substantial energy. It is also costly to transport it, and methane is leaking in the process. Therefore, LNG is about one-third more harmful than coal when it comes to climate change emissions, according to Howarth (2024).[6] All gas exported from the US to Europe is LNG, but almost all (95%) of gas

[6]Kleinberg (2024) discusses the details of how one can calculate the emission intensity of US LNG exports.

from Norway to Europe is transported by pipelines, with much smaller emission contents.

Elasticities. The price elasticity of supply for the short term (ε_j^{ST}) and for the long term (ε_j^{LT}) are given in the forth and fifth columns. The relationship between the slope of the supply curve and the elasticity is given by $\varepsilon_j = pS_j'(p)/S_j(p)$. Since Norwegian gas supply can, in principle, be regulated and adjusted within a short time frame, we consider the short term as at most one year, or even shorter.

The long-term price elasticity for coal is in line with Haggerty et al. (2015), Marten et al. (2019), Marten et al. (2024), and Lemoine (2024) (based on ten-year time periods in his analysis). For the short-term coal supply elasticity, the literature is scarce. However, the increase in coal-generated electricity in Europe following the 2022 spike in gas and electricity prices indicates that European coal supply responds substantially to price changes in the short term. Moreover, as coal use in European electricity generation has been on a decline for decades, excess capacity is likely to contribute to an elastic short-term supply.[7] We therefore use the same elasticity for the short term in our quantitative analysis.

The long-term supply elasticity of gas transported by pipeline to Europe is based on Arora and Cai (2014), Arora (2014), Marten et al. (2019), Marten et al. (2024). and Lemoine (2024). The number is also in line with the estimates provided by Prest (2022) (ranging from 0.2 for offshore drilling to more than 0.6 onshore). There are not many available estimates for the short term, so we base the short-term elasticity of 0.2 on the annual data from Abuin (2024).

Unconventional oil and gas production, however, responds differently to price changes compared to conventional natural gas extraction. Rystad Energy (2023) estimates the supply elasticity of US LNG to be 2.0 over the seven-year time period from 2023 to 2030. As unconventional gas extraction responds relatively quickly to price changes compared to conventional off-shore extraction (see for example Bornstein et al. (2023) or Prest (2022)), we set the elasticity of US supply of LNG to 2.0 both for the short and the long term. As we have not found estimates of supply elasticities for LNG imported to the EU from Russia, we use the same elasticities here as for LNG from the US.

We set the long-term elasticity for oil supply to 1, in line with Rystad Energy (2023) and Böhringer and Rosendahl (2022), and the short-term elasticity to 0.3, in line with Rao (2018) and Bornstein et al. (2023).

There are not a lot of empirical studies of price elasticities for renewables. For ten-year time steps, Lemoine (2024) estimates a supply elasticity for wind and solar of 3.0, based on a description of the supply

[7]See for example page 6 in European Electricity Review 2024 (EMBER Energy, 2024) for an overview of the development of fuel use in European electricity generation.

from these sources from Johnson et al. (2017). As is illustrated for example by Gonzales et al. (2023), the response to price changes in renewables is low in the short run, as capacity and technology are given and marginal costs are close to zero. We therefore set ε_j^{LT} to zero for renewables. Lacking a precise measure from the literature, we set the price elasticity both in the short term and in the long term for the category Other to 1.[8] Regarding nuclear energy, our initial guess is conservative, as we will explain at the end of Section 4.3.

The final row in Table 1 states the price elasticities of demand (ε_N^{ST} and ε_N^{LT}), which are also important, of course. Both numbers are consistent with Buchsbaum (2023), and the short-term elasticity is also consistent with Deryugina et al. (2020) and many other studies. (See Appendix B for details.)

In Sections 4.4-4.5, we let N represent Europe minus Norway, while M is Norway. While we abstracted from N's climate policy in Sections 2-3, the analysis is unchanged if there are taxes on the various supplies in N, as long as these taxes are exogenous: See Footnote 3. This is realistic: Although the EU has an emission trading system, the mechanisms in the so-called *Market Stability Reserve (MSR)* are effectively ensuring that the price stays within a range. Using a forecasting model for the EU Emission Trading System, Silbye and Sørensen (2023) show that the MSR makes the cap on emissions endogenous. Similarly, studying the consequences of the Covid-19 pandemic, Bruninx and Ovaere (2022) conclude that demand shocks within the system will have a limited effect on permit prices, due to the endogeneity of the cap through the MSR.[9]

4.3 Effect of Gas in the Short Term vs. the Long Term

The numbers in the previous subsection are sufficient to derive the effect of more (non-LNG) gas on total emissions (i.e., $\partial e/\partial x_G$, given by eq. (8)). Because we have $S_j'(p) = \varepsilon_j S_j(p)/p$, we can write

$$\frac{\partial e}{\partial x_G} = e_G - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_N'(p)} = e_G - \frac{\sum_{j\in J} e_j \varepsilon_j S_j(p)/S_N(p)}{\sum_{j\in J} \varepsilon_j S_j(p)/S_N(p) - \varepsilon_N D(p)/S(p)},$$

as p cancels out. Every $S_j(p)/S_N(p)$ is given by the numbers in column 2, Table 1. We set $D(p) = S(p)$ because we have, for simplicity, included Europe's import of LNG as if these were sourced within N.

Combined with the other numbers in the table, we get that with a short-term vs. a long-term time

[8] Because the supply from this category is relatively small, the number is not driving our results. A lower short-run elasticity for this category could increase the severity of the gas trap, because of its low emission coefficient.

[9] If the emission taxes within N respond to M's policy, the analysis will be different. For example, if N imposes an exogenously given cap on total emission, or adjusts the emission prices within N such that the cap is independent of M's decisions, then M cannot influence total emission in N. It is suboptimal for N to set such an exogenous cap, however, unless N's harm function is kinked and vertical at a particular emission level.

horizon, respectively:

$$\partial e/\partial x_G \mid_{ST} = -0.37 \text{ vs. } \partial e/\partial x_G \mid_{LT} = 0.26.$$

The numbers mean that if one throws in another unit of electricity (i.e., one kWh) produced by gas, emission may fall by 0.37 kg CO2 equivalents. If long-term investors anticipate the new amount of gas, however, total emissions increase by 0.26 kg CO2 equivalents.

Thus, more gas reduces total emissions when the time horizon is short, but with a long-term time horizon, total emissions increase. To reduce total emissions, a gas producer should commit to produce less. Without commitment, a climate-concerned producer is instead tempted to produce more.

The sign reversal of $\partial e/\partial x_G$ is quite robust. If Norway is excluded, the pair of numbers round to the same. If we think that ε_D is equal to -0.1 even in the long term, the pair would be $(-0.38, 0.26)$.

Not only does the sign of $\partial e/\partial x_G$ reverse, but the magnitude of it is also significant. In 2022, the quantity of gas (excluding LNG) amounted to 16.7% of total electricity consumption. In the short term, if this quantity doubled, total emissions from electricity generation in Europe would fall by 20.6%. When the doubling is anticipated, total emissions increases by 14.0%.

The difference between the short-term and the long-term effect of gas is given by the final term in eq. (8). It is reasonable that the US gas boom has increased this term, especially after the US has invested in its capacity to export LNG. With the boom and these investments, there is an abundance of supply endowed with both a high emission content and an ability to respond quickly to changes in the price. If the US supply is inelastic in the short term, we would have $\partial e/\partial x_G \mid_{ST} = -0.33$. Thus, the shale gas boom and the US capacity to export LNG strengthen the European gas trap.

All these results hold for Europe as a whole, no matter which countries that are included in M and regardless of M's marginal harm (i.e., its social cost of carbon, SCC).

Regarding the long-term $\partial e/\partial x_G$, not only the sign, but also the magnitude is close to what it would be if the other suppliers did not react at all, or if the supply of either renewables or nuclear energy is perfectly elastic. In either of these cases, $\partial e/\partial x_G = e_G = 0.4$. This number may be closer to reality in the very long term. After all, the long-term price elasticity for emission-free technology (3.0) is under-estimated by Lemoine (2024) for three reasons. First, with longer time horizons than those he considers, investors and developers will have more time to raise the capacity and to develop new technology. Second, nuclear energy plays a similar role to renewables in our analysis. Investments in nuclear energy take a long time, but we have no evidence to claim that the cost of constructing a plant is larger when many other plants are being constructed. Third, the estimates above ignores learning-by-doing effects. For example, Covert and Sweeney (2022) find

substantial learning-by-doing effects on costs in the global wind turbine industry over the last few decades. With up-and-coming technologies, such as renewables, but also nuclear energy, the learning-by-doing effects will shrink costs when the investment level is high. This effect can weaken and reverse the potential effect of marginal construction costs increasing with the investment level. Hence, assuming a perfectly elastic supply of renewables or nuclear energy in the very long term does not seem unreasonable. If either of these supply curves is flat, then comparative statics are given by the simple equation (11). We thus assume this to be the case for the long term in the next two subsections. A side effect is that the results become robust with respect to changes in the other long-term elasticities.

4.4 Effect of SCC in the Short Term vs. the Long Term

The social cost of carbon (SCC), considered by M, is summarized by ah'. If M's SCC increases, M's policy changes accordingly. In particular, M's tax on gas declines with a negative (11), which we derive under the assumption that the supply of renewables or nuclear is perfectly elastic in the long run.

To calculate the sign of (11), we need to specify which country or countries M represents. After all, the difference between D'_A and D'_N, D'_M, and the difference between S'_A and S'_N, S'_M, depends on that.

Here, we consider the case in which M is represented by Norway. Norway has for many years been riddled by an intense internal debate regarding whether its export of gas is good or bad for the climate.[10] Thus, N is Europe minus Norway. The analysis permits N to have fixed emission taxes or prices on its various supplies of energy, as previously explained.

Relying on IEA (2024), we set Norway's consumption to equal 3.3% of Europe's electricity. Of Europe's total electricity generation, we let 3.7% originate from Norway's renewable energy sources and 5.1% from its gas (IEA, 2024). Most of Norway's renewable energy comes from hydro and the capacity to expand on hydro

[10]While some parts of the political landscape argue for a rapid break in activity on the Norwegian continental shelf (see e.g. `https://e24.no/energi-og-klima/i/Jbl1A7/krever-letestans-og-utfasing-av-felt-uansvarlig`, Accessed January 14th, 2025), others strongly argue that Norwegian oil and gas is benefiting the climate. For example, the Minister of Petroleum and Energy in 2018 argued that "[the government] will produce as much as possible. Because the climate will gain." (`https://www.aftenbladet.no/aenergi/i/J15E9j/ny-oljeminister-vil-ha-full-gass-for-ren-norsk-olje`, accessed January 14th, 2025). Rystad Energy, in two reports, on behalf of the employer organization Offshore Norge and the Norwegian Ministry of Energy, respectively, concludes that higher Norwegian gas exports will mitigate climate change, see Rystad Energy (2021) and Rystad Energy (2023). Wood Mackenzie concludes similarly in a 2024 report (Wood Mackenzie, 2024). At the same time, Vista Analyse published two reports with the opposite conclusion, written on behalf of a group of environmental organizations and Equinor, respectively, see Vista Analyse (2023) and Vista Analyse (2024).

is limited for physical and political reasons. Thus, we simplify by treating this supply as inelastic. With these numbers, and those from Section 4.2, we get the following for the short-term and the long-term taxes:

$$d\tau_G^{ST}/dah' = -0.37 \text{ vs. } d\tau_G^{LT}/dah' = 0.4.$$

Here, dah' can be read as da multiplied by the level of h'. We get $d\tau_G^{ST}/dah' \approx \partial e/\partial x_G \,|_{ST}$ because $D'_A \approx D'_N$ and $S'_A \approx S'_N$. As noted already, with a Pigouvian (long-term) tax, $d\tau_G^{LT}/dah' = e_G$.

The sign reversal confirms that the gas trap is relevant in Europe. If M (i.e., Norway) gets more concerned with climate change and can commit, M will commit to a higher tax on gas. That would reduce total emissions. When M cannot commit, however, a larger a motivates M to reduce the tax on gas in an attempt to outcompete coal and LNG. When the lower τ_G is anticipated, investments in renewables or nuclear fall, and the total emission level is higher. This is the gas trap – in practice.

What is the quantitative effect on the total emission? Norway's policies reflect a SCC equal to 107 € per ton CO2 equivalents, according to OECD (2024). According to the Norwegian government, however, it will apply a SCC equal to 240 € per ton CO2 equivalents from 2030.[11] This difference should cause the tax on gas to drop by 0.050 if the government cannot commit, or increase by 0.053, if it can. To calculate the effect on quantities and emission, we need to know $S'_j(p) = \varepsilon_j S_j(p)/p$ and thus the price. In 2022, the average electricity price in the EU was around 0.2 €/kWh. With this, we get that with the new SCC, Norway's supply of gas for electricity would decreases by 13.3% if the government could commit, while it increases by 12.4% when it cannot. When the policy is anticipated, the change in total emission, relative to the existing emission from Norway's gas used in electricity generation, are exactly the same: –13.3% and 12.4% under commitment and noncommitment, respectively. The gas trap is quantitatively important.

4.5 The Policy with Noncommitment vs. Commitment

Above, we estimated the effect of a marginal change in M's concern for climate change, whether M could commit or faced a time inconsistency problem. Here, we discuss the effect of time inconsistency on the policy. When M cannot commit, it prefers to set taxes according to (9). With the numbers from Section 4.2, we get:

$$\tau_G^{ST} = -0.37 \cdot ah' + 0.016 \cdot w \text{ vs. } \tau_G^{LT} = 0.4 \cdot ah', \tag{12}$$

where ah' measures M's social cost of carbon, and w the weight M places on the revenues. The second term in (12) is positive because when Norway is a net exporter of energy, it benefits from a high energy price, and

[11] See `https://www.regjeringen.no/no/tema/okonomi-og-budsjett/statlig-okonomistyring/karbonprisbaner-for-bruk-i-samfunnsokonomiske-analyser-i-2025/id3080821/`, Accessed January 14th, 2025.

a tax on gas achieves that in the short term but not in the long term.

Because the first term is smaller, while the second term is larger, in the short term, it is an empirical question whether $\tau_G^{ST} < \tau_G^{LT}$. (We cannot observe the actual level of τ_G because the government regulates gas production with a large set of instruments, technology requirements, regulations, and mandates.)

We start by setting ah' equal to the number reported by the OECD: $ah' = 107$ €/t. Regarding the weight on M's import revenues, we set $w = 0.5$ because most oil and natural gas companies are private, but the government owns 67% of Equinor, which is responsible for 70% of Norway's gas extraction ($0.67 \cdot 0.70 = 0.47$).[12] With these numbers, the government does indeed prefer to subsidize gas in the short term, while a tax would be preferred if it could commit:

$$\tau_G^{ST} = -0.033 \text{ vs. } \tau_G^{LT} = 0.043.$$

Because $\tau_G^{ST} < \tau_G^{LT}$, M's gas producers will, in equilibrium, face a higher price and end up supplying more gas just because the government cannot commit. The capacity to supply clean energy (whether renewables or nuclear) will fall and total emissions will be larger than if commitment were possible.

Again, the result is quite robust. If $w = 1$, $\tau_G^{ST} = -0.025$ while τ_G^{LT} is unchanged. With the SCC of 240 €/t, as announced by the Norwegian government, $\tau_G^{ST} = -0.084$. and $\tau_G^{LT} = 0.096$.

The difference between τ_G^{ST} and τ_G^{LT} has large implications for the total level of emissions. With the numbers above, moving from $\tau_G^{LT} = 0.043$ to $\tau_G^{ST} = -0.033$ leads to 19% larger amount of Norwegian gas being used in electricity production in Europe. With an SCC of 240 €/t, the difference is 45%.

5 Robustness

We have designed the model to be simple so that the mechanism can be easily understood, and also because it is then straightforward to develop the framework in various directions. In this section, we explain why the main result is quite robust and, in fact, is strengthened by reasonable extensions. In Section 6, we study extensions that can contribute to a solution to M's time-inconsistency problem. Each extension can be read in isolation, because they do not build on one another.

[12] `https://www.equinor.com/energy/fields-and-platforms`, accessed January 14th, 2025)

5.1 Multiple Periods

The proofs and the results hold if there are many periods. In fact, if we simply add a variable superscript denoting time t, then the above results hold for every possible t if we abstract from the possibility that payoff-relevant stocks can change over time. In this case, the extensive-form stage game above is repeated. The SPE characterized in Section 3 is the unique Markov-perfect equilibrium (MPE) of the dynamic game. Other than M, the players are price takers, and if their strategies are Markov, M's strategy will be Markov as well. (M cannot benefit from using history-dependent strategies when no one else does.)

The exogenously given parameters can change over time. We can even take into account that emissions and the investment in renewable energy contribute to stocks that change over time. Regarding renewables, suppose that $x_R^t = q_R x_R^{t-1} + I_R^t$, where $1 - q_R \in [0, 1]$ measures how much the stock at time $t-1$ has depreciated when we enter period t, while I_R^t measures the investments in renewable energy at time t. If K^t measures the unit cost of investment, the net cost of raising x_R^t at time t is $K^t - \delta q_R K^{t+1}$, where δ is the discount factor, because after one period of usage, the investor can cash in by selling the remaining capacity at price $q_R K^{t+1}$. With $k^t \equiv K^t - \delta q_R K^{t+1}$, the analysis above is unchanged if, on the equilibrium path, the inequality $I_R^t \geq 0$ does not bind.

Regarding emissions, suppose that the accumulated emissions at time t are $E^t = q_E E^{t-1} + e^t$, where $1 - q_E \in [0, 1]$ measures how much the greenhouse-gas stock at time $t-1$ has depreciated when we enter period t. The analysis above is unchanged if $q_E = 0$. If, instead, $q_E > 0$, and M's one-period harm from each unit of E^t can be approximated by some constant, H^t, then the present-discounted cost of a unit of emissions equals $h' \equiv \sum_{i=t}^{\infty} (\delta q_E)^{i-1} H^i$, which equals $H/(1 - \delta q_E)$ if $H^i = H$ happens to be invariant in time. With this definition of h', M can account for the marginal present-discounted cost immediately, and this accounting leaves the analysis above unchanged.

Proposition 3. *Suppose there are multiple periods, and the environmental harm is linear in the accumulated stock of emissions. The analysis leading up to consumption and emissions at time t holds for every such t, if, for each period, h' is replaced by $h^t \equiv \sum_{i=t}^{\infty} (\delta q_E)^{i-1} H^i$ and k by $k^t \equiv K^t - \delta q_R K^{t+1}$.*

Although the main result in Section 3 continues to hold, time-varying parameters can lead to additional results. Suppose, for example, that H^t is expected to be larger in the future, when t is large. That would increase the present-discounted cost of emitting at every earlier point in time also, and the contrast between the commitment solution (described in Proposition 1) and the equilibrium (Proposition 2) will be larger.

Furthermore, this difference will be even larger in the future, because also h' will increase in t when H^t increases in t.

If the investment cost K^{t+1} is expected to decrease in t, then renewables are going to be more competitive relative to coal and gas. In the short term, however, x_R^t can decline, and emissions can increase. To see this, note that $k^t \equiv K^t - \delta q_R K^{t+1}$ is larger when K^{t+1} is small, for any given K^t. The intuition is that the net cost of investing is higher at time t when the declining costs reduce the value of the stock that survives to time $t+1$. The larger k^t leads to lower investments in renewables at time t, a higher energy price, and more production of coal.

If both $q_R > 0$ and the harm is nonlinear in the stock, then (strategically) high emissions level today will reduce how much it will be optimal to emit in the future (Calvo and Rubio, 2012; Harstad, 2012b).

If the time horizon is infinite, there can be multiple SPEs, of course. If the discount factor is large, it can then be possible to sustain better equilibria in which M acts as if it can commit on the equilibrium path. These equilibria cannot be supported if the time horizon is finite, however, and they may thus be unfeasible to sustain given the fact that gas is a depletable resource.

5.2 Learning by Doing

In Section 5.1, we considered the reasonable situation in which the cost of renewable energy investment can change over time. In reality, this change is likely to be endogenous. The cost of solar panels, for example, falls over time not by chance, but because of R&D and learning by doing: Baker et al. (2013) survey the evidence when it comes to solar panels; Covert and Sweeney (2022) document considerable learning by doing in wind turbine manufacturing.

To capture the effects of learning by doing, consider a two-period model where the first period is as in Sections 2 and 3. Here, we refer to the first-period cost as k^1. In the second period, the unit cost of renewable energy capacity is $k^2 = f\left(x_R^1\right)$, where f is a decreasing function of the amount of renewable energy in period 1, x_R^1. To simplify, we henceforth assume that the present-discounted harm from emissions is h^t at time t, and that renewables are not accumulating over time.[13]

If M could commit, M would benefit from a larger x_R^1 in order to reduce k^2. Although the reduction in k_2 harms M if M exports a lot, it also reduces the production of coal and gas, especially if the supplies of coal and gas are price elastic. This possibility may motivate M to raise the tax on gas even more and to subsidize

[13]That is, $q_R = 0$, using the notation in the previous subsection. This helps us to abstract from the benefit of investing less now, because of lower investment costs in the future.

domestic consumption, because both changes raise the demand for energy and, therefore, x_R^1 increases. The commitment solution coincides with the FB outcome, except that N's fossil fuel production is taxed in the FB, in line with Proposition 0.

Proposition 4. *Suppose the first-period unit cost of x_R^1 is k^1, while the unit cost of x_R^2 is $k^2 = f\left(x_R^2\right)$.*
(i) If M could commit, M's first-period policy would be:

$$\begin{aligned}
\tau_G^1 &= e_G a h^1 + \Omega^2 \left(-f'\right) \left(S_N'\left(k^2\right) - D_N'\left(k^2\right)\right), \\
\tau_M^1 &= -\Omega^2 \left(-f'\right) \left(S_N'\left(k^2\right) - D_N'\left(k^2\right)\right), \text{ where} \\
\Omega^t &\equiv \frac{e_C S_C'\left(k^t\right) a h^t - \left(x_G^t - y_M^t\right)}{S_N'\left(k^t\right) - D_N'\left(k^t\right)},\ t \in \{1,2\}, \qquad (13)
\end{aligned}$$

while M's second-period policy would be in line with Proposition 1:

$$\tau_G^t = e_G a h^t \text{ and } \tau_M^t = 0, \text{ for } t = 2.$$

(ii) When M cannot commit, M's policies in both periods are in line with Proposition 2:

$$\tau_G^t = e_G a h^t - \Omega^t \text{ and } \tau_M^t = \Omega^t,\ t \in \{1,2\}.$$

When M cannot commit, however, x_R^1 is already given at the time when M decides on its policy. In this case, M cannot influence k^2. Therefore, M's policy is characterized by Proposition 2, just as before.

The contrast between the commitment solution and the equilibrium under noncommitment is even starker than in Section 3. When M cannot commit, M may be tempted to reduce τ_G in order to outcompete coal, and to tax consumption to further reduce the demand for energy, especially when a is large. If M could commit, then M would set a Pigou tax on gas extraction, and no tax on consumption, in the absence of any learning-by-doing effect. With learning by doing, M would further raise τ_G^1, and M would subsidize domestic consumption, especially if h^t were large, because both these policy changes would raise the investments in renewables, and k^2 would decline. A smaller k^2 generates a positive externality on M's payoff because N produces less coal as a result. With this result, we broaden the justification for policy intervention in the presence of learning by doing: van Benthem et al. (2008), Borenstein (2017), and Baker et al. (2013), for example, argue that learning by doing justifies policy intervention only when there are knowledge spillovers to other firms. Here, subsidizing learning by doing is also beneficial because the government's temptation can reduce equilibrium investments.

5.3 Depleting Resources

Fossil fuel stocks are exhaustible and shrink over time when they are exploited. In this subsection, we argue that our main result is strengthened when we incorporate exhaustibility into the model. We show that when M cannot commit, M is further reducing its tax (or raising its subsidy) on the production of gas, because of exhaustibility. In the short term, investments in renewables will fall, emissions will increase, and the stock will be depleted faster than if M could commit. The intuition for this result is that M seeks a way to commit to reducing gas production in the future. If this reduction is credible, investments in renewables will increase and emissions will decrease. When M controls a limited amount of natural gas, M will indeed produce less in the future if M reduces the tax and produces more today: See Cruz and Rossi-Hansberg (2024), for instance.

We illustrate this insight in a simple two-period model. The world is not going to run out of coal anytime soon, but we will assume that M's marginal cost of producing x_G^t at time $t = 2$ increases in M's first-period production level: M's production cost is $c\left(x_G^t\right)$ and time $t = 1$, as before, but $c^2\left(x_G^2, x_G^1\right)$ at $t = 2$, where the derivatives are $c_1^2 > 0$, $c_{11}^2 > 0$, $c_2^2 > 0$, and $c_{12}^2 > 0$. This way of capturing exhaustibility is more general and reasonable than a fixed constraint on $x_G^1 + x_G^2$, because gas production will not end, in reality, when there is not a single unit left in the reserves. Instead, it will end when it is too costly to extract the next unit. To abstract from the possibility that the marginal harm is endogenous, we henceforth assume h^t to be a constant for each $t \in \{1, 2\}$.

In the second period, when x_G^1 is fixed, the model and the analysis are no different from those in Sections 2 and 3. Policies would still be characterized by Proposition 1 if M could commit, and by Proposition 2 when M cannot. The model extension has bite only in period 1, because the choice of x_G^1 will influence the cost, the policies, and the quantities in the second period. The larger x_G^1 is, the larger the marginal cost of x_G^2 is, and the smaller we may expect x_G^2 to be.

The desire to influence second-period policies would be absent if M could commit. In that case, M's second-period policy would be just fine, even from the first-period point of view. The fact that x_G^1 raises the cost of x_G^2 will be taken into account by the market participants. Thus, if M could commit to policies at the beginning of each period, $t \in \{1, 2\}$, M would set a Pigou tax on x_G^t, but no tax on consumption, just as in Proposition 1. In line with Proposition 0, the commitment solution coincides with the FB outcome except that even N's fossil fuel production is taxed in the FB.

When M cannot commit to future policies, M is in each period setting quantities or, equivalently, taxes, after x_R^t has been determined. As before, M is tempted to outcompete coal but when this temptation is anticipated, x_R^t falls. M's second-period policy is in line with Proposition 2, but in the first period, M

takes into account that the second-period policies and quantities will depend on x_G^1. By contributing to a larger x_G^1, equilibrium x_G^2 falls, and x_R^2 increases. Thus, M prefers to set a smaller tax (or a larger subsidy) on the production of gas in the first period in order to make it credible that x_G^1 will be smaller.

Proposition 5. *Suppose the second-period cost is* $c^2\left(x_G^2, x_G^1\right)$*, with* $c_1^2 > 0$*,* $c_2^2 > 0$*,* $c_{11}^2 > 0$*,* $c_{12}^2 > 0$*.*
(i) If M could commit to policies for period $t \in \{1, 2\}$ *at the beginning of period* t*, M's policy would be in line with Proposition 1:* $\tau_G^t = e_G a h^t$ and $\tau_M^t = 0$*,* $t \in \{1, 2\}$*.*
(ii) When M cannot commit, M's second-period policy is in line with Proposition 2, M's first-period consumption tax is in line with Proposition 2, but M's first-period production tax is reduced if and only if $c_{12}^2 > 0$*:*

$$\begin{aligned}\tau_G^1 &= e_G a h^1 - \Omega^1 - \delta \frac{\left(e_G a h^2 - \tau_G^2\right)\left[S_C'(k^2) - D_A'(k^2)\right] + \tau_M^2 D_M'(k^2)}{S_A'(k^2) - D_A'(k^2)} \frac{c_{12}^2}{c_{11}^2} \\ &= e_G a h^1 - \Omega^1 - \delta\Omega^2 \frac{S_C'(k^2) - D_N'(k^2)}{S_A'(k^2) - D_A'(k^2)} \frac{c_{12}^2}{c_{11}^2}\end{aligned}$$

As before, Ω^t is given by (13) for $t \in \{1, 2\}$.

If the model permits an infinite number of periods, the desire to commit will be present in every period. In that case, τ_G^t will always be less than the one in Proposition 2 when M cannot commit, $\Omega^t > 0$, and the future marginal production cost increases in x_G^t. As a consequence, the stock is being depleted faster when M cannot commit.

6 Policy Implications

6.1 Credibility by Investing in Renewables

Consider the possibility that also M can invest (or incentivize domestic investments) in renewables. Let $x_{R,M}$ denote M's level of investment. Because $x_{R,M}$ is a result of M's policy, suppose $x_{R,M}$ must be decided before N's investors determine $x_{R,N}$.

As a start, suppose that M's cost of investing in renewables is the same as for N, k. When the investment cost is, for simplicity, linear, then it may be reasonable to consider constraints on how much it might be possible to invest to avoid "bang-bang" corner solutions. We will assume that M can invest at most $\overline{x}_{R,M}$, where $\overline{x}_{R,M}$ is so small that, in equilibrium, there will be a strictly positive level of investments in renewables also by the investors in N.[14] We discuss the consequence of relaxing this assumption in the proof

[14] That is,

$$x_{R,M} \leq \overline{x}_{R,M} := D_A(k) - S_C(k) - S_G\left(k - e_G a h'\right).$$

of Proposition 6.

If M could commit to (τ_G, τ_M), M would not strictly benefit from investing in renewables. The cost coincides with the price, and the investment will not alter M's payoff or any of the variables of interest.

When M cannot commit, then a larger $x_{R,M}$ will influence M's equilibrium policies. As Proposition 2 uncovers, if M exports more (or imports less) then M will raise τ_G and reduce τ_M, attempting to raise the price and thus M's terms of trade. Although M will not succeed with raising p, when x_R is endogenous, M's desire to raise τ_G and reduce τ_M can change M's short-term policy in the direction that M would have preferred if M could commit. In fact, M's policies under commitment and noncommitment coincide if M just produces so much energy that M's desire to outcompete coal is balanced by the desire to improve the terms of trade (i.e., $\Omega = 0$). This follows from a comparison of Propositions 1 and 2.

Proposition 6. *Suppose M can invest $x_{R,M} \leq \overline{x}_{R,M}$ directly in renewables at the beginning of the game.*
(i) If M could commit, it would be optimal for M to not invest in renewables.
(ii) When M cannot commit, M implements the commitment solution if and only if M invests:

$$x_{R,M} = e_C S'_C(k)\, ah' + D_M(k) - S_G(k - e_G h'). \tag{14}$$

In other words, when M faces a temptation to outcompete coal, with the result that investments in renewables will fall, M gains credibility by investing directly (or by incentivizing domestic investments) in renewables. When these investments are sunk, and (14) holds, M finds it optimal to set $\tau_G = e_G ah'$ and $\tau_M = 0$ even in the short run. With this, M gains credibility in that M will no longer be expected to produce a lot of gas. Equilibrium x_R ends up being the same as if M could commit to (τ_G, τ_M).

Unfortunately, the quantitative application reveals that this solution is unrealistic in the European context. Returning to the simulated version of the model in Section 4.5, for Norway's equilibrium tax to coincide with the preferred tax under commitment, we can show that Norway's export must be multiplied by ten, and its export of renewable energy must be multiplied by 22. With the SCC equal to 240 €/t, its export of renewable energy must be multiplied by 56. Either expansion would crowd out all other renewables in Europe (so, $x_{R,M} \leq \overline{x}_{R,M}$ would fail) and it is unrealistic because, as mentioned, additional investments in waterpower and windmills are politically difficult in Norway. Huge investments in solar technology cannot be a viable solution, either, if we consider that these investment costs (per kWh) will be higher in Norway than in the lowest-cost environment in Europe.

6.2 Upstream Regulation

The gas trap arises because M can adjust x_G after x_R is sunk. This timing seems reasonable but, in reality, x_G is not decided at a single point in time. By regulating the early stages of the process, M can influence the market's beliefs about how much M will end up producing.

We now modify the game in Section 2 by including a search-and-exploration stage at the very beginning of the game. We let s measure the expenses of search and exploration, and we account for the fact that when s is small, the production cost will be high. In particular, the cost of producing gas will be given by the function $c^x(x_G, s)$, where the derivatives satisfy $c^x_1 > 0$, $c^x_{11} > 0$, $c^x_2 < 0$, $c^x_{22} < 0$, and, crucially, $c^x_{12} < 0$.

If M could commit, M would prefer that s be set to take into account the benefit $-c^x_2$. In the competitive market, those paying for s will indeed be able to cash in the benefit $-c^x_2$ when the services are sold to the gas producers. Thus, the market's decision on s would be in line with M's preferred s, and M does not benefit from regulating s: $\tau_s = 0$. As above, the commitment solution coincides with the FB outcome, except that even N's fossil fuel production is taxed in the FB, in line with Proposition 0.

When M cannot commit, M will be tempted to outcompete coal and, when this temptation is anticipated, x_R declines. M's short-term policy is suboptimal from the long-term point of view. Thus, M benefits from making it credible that x_G will be small because, then, x_R will be large. To gain this credibility, M benefits from taxing or reducing search and exploration – especially when equilibrium τ_M will be small relative to the Pigouvian level (i.e., when Ω is large).

Proposition 7. *Suppose M can regulate search-and-exploration activities, s, at the beginning of the game.*
(i) If M could also commit to (τ_G, τ_M) at the beginning of the period, M's policy would involve $\tau_s = 0$ and otherwise be in line with Proposition 1.
(ii) When M cannot commit, equilibrium (τ_G, τ_M) is in line with Proposition 2 and M imposes the following tax on search and exploration:

$$\tau_s = \frac{(e_G a h' - \tau_G)\left[S'_C(k) - D'_A(k)\right] + \tau_M D'_M}{S'_A(k) - D'_A(k)} \left(-\frac{c^x_{12}}{c^x_{11}}\right) = \Omega \frac{S'_C(k) - D'_N(k)}{S'_A(k) - D'_A(k)} \left(-\frac{c^x_{12}}{c^x_{11}}\right).$$

As before, Ω is as defined in Proposition 2. When ah' is large, Ω is large, and M will tax production less and consumption more. To mitigate the discouraging effect on renewables, M benefits from taxing search-and-exploration activities more when ah' is large.

The assumptions in this subsection are empirically reasonable. It does indeed take several years to progress from search-and-exploration, find and develop reserves, and exploit the reserves: See Venables (2014),

Anderson et al. (2018), or Ahlvik et al. (2024). Arezki et al. (2017) find lags ranging from 4 to 6 years lag between discovery and production for oil and gas. Bornstein et al. (2023) estimate the average lag between investments in exploration and subsequent production in a dataset containing all oil fields with production between 1971 and 2015, collected by Rystad Energy. Their estimate implies an average time lag between investment and extraction of conventional oil of 12 years. (These fields contain gas also.)

The institutional setting in Norway makes regulating search-and-exploration an attractive tool for committing to lower future gas production. The Parliament or the Ministry of Energy must approve activity at several stages before the extraction of oil and gas can start in a new field. First, the Parliament must approve the area for petroleum-related activities. Next, when areas are opened for exploration, companies must apply to the Ministry of Energy for licenses to explore.[15]

Keeping new areas closed for exploration, or even limiting the number of licenses provided to the industry in already opened areas, must be expected to affect future extraction, and can thus pose as a commitment mechanism. The system for upstream regulation of the Norwegian oil and gas industry therefore seems well-suited to provide a climate-motivated government with commitment. Empirically, Ahlvik et al. (2024) document that search-and-exploration activities do respond to taxes. A tax on search-and-exploration activity can therefore provide an alternative to direct regulation for limiting future extraction.

For these reasons, the policy implication of Proposition 7 resonates well with the institutional setting and the policy debate in Norway (see Footnote 10). There are still large unopened areas on the Norwegian Continental Shelf, including the Barents See North, the north-eastern part of the Norwegian Sea, and the area around Jan Mayen. The trade-off involving search-and-exploration regulation is qualitatively different from the trade-off regarding current production, according to our analysis: Increased production today can outcompete coal and reduce total emissions but, exactly for that reason, regulating search-and-exploration is necessary to encourage investments in renewables.

In light of this discussion, it may not be surprising that building the LNG export facilities in the US was controversial under the Biden administration.[16] In just one decade, the US has become the world's number one exporter of LNG. The EIA projects a further doubling of exports from 2024 to 2028, thanks to investments in ports and related infrastructure.[17] The capacity to export will, according to our analysis,

[15]For the current regulation of the process from opening, through search and exploration, to extraction, see: `https://www.norskpetroleum.no/en/framework/the-petroleum-act-and-the-licensing-system/`, accessed January 29, 2025.

[16]See for example `https://www.csis.org/analysis/us-lng-export-boom-defining-national-interests`. Accessed January 2024.

[17]See `https://www.eia.gov/todayinenergy/detail.php?id=64128`. Accessed January 2024.

discourage investments in green technology in Europe. Although building infrastructure for LNG exports requires less time than search-and-exploration for offshore gas, a climate-motivated US government could benefit from tightening the approval process for such facilities as a way to commit and avoid the gas trap.

6.3 Coalition Composition and International Treaties

In general, a larger coalition will not necessarily help. On the one hand, a larger coalition implies that the harm facing a larger number of members will be internalized. In the model, this effect can be captured by a larger ah'. As shown above, a larger ah' can enlarge the difference between the commitment solution and the noncommitment equilibrium.

On the other hand, if the coalition exports more, it will be motivated to maintain a high price on its export. This motivation can weaken the temptation of reducing the price to outcompete coal.

Another implication from our analysis is that the composition of the climate coalition will influence the gas trap. In fact, it can be helpful to include members that export a lot of energy, even coal. If the coalition as a whole is a large net exporter, then the incentive to maintain a high price on exports will counter the temptation to reduce the price (by producing more gas) as a way to outcompete coal. Equilibrium policies coincide with those under commitment if M exports so much that $\Omega = 0$. That is, if:

$$x_M - y_M = \sum_{j \in J} e_j S_j'(k)\, ah'. \tag{15}$$

Here, J is the set of fossil fuels supplied by N (as in Section 4.1). If large exporters are included in M, the left-hand side of (15), $x_M - y_M$, can be large. Unfortunately, the quantitative analysis suggests that, for our quantitative example, M's export may need to increase by a factor of 10 for M's policy to be time consistent.

A more promising solution might be that $\sum_{j \in J} e_j S_j'(k)$, on the right-hand side of (15), will decline if the number of coal producers in N is reduced if some of them are included in M. The condition is more likely to hold if the new coalition members are more concerned with profit than with the climate (so that ah' is limited). This inclusion can help ensure that the right-hand side of (15) is no larger than the left-hand side.

If countries can decide whether or not to be a member of M, the decision may depend on how much a country exports, what it exports, and its concern for climate change. It is not at all clear that the right types of countries will be those that in equilibrium benefit from being members. Suppose, however, that a potential member country considers how its membership will influence the possibility to commit or to ensure that (15) holds. Then, the benefit of being a member will be especially large for those countries that can

contribute to beneficial policy rather than a damaging one. Whether this effect is sufficient for the coalition's policy to be efficient is an open question that should be explored in future research.[18]

In practice, a more important benefit from signing a treaty is that it can help the participants to commit. If future production costs are not simply announced by a government, but also specified in an international treaty, then defection might be politically costly (or even be associated with international sanctions). Therefore, nations often use and refer to treaties as a way to commit to future actions (see the literature discussed by Harstad and Kessler (2024)). A binding supply-side treaty, with costs or sanctions being imposed on defectors, can help the members commit to limiting the future production of gas. One interpretation of our main result is to illustrate just how important such a commitment may be. Without it, well-meaning climate policies can be counterproductive.

7 Conclusions

Is gas green? Natural gas is a substitute for black energy (coal), on the one hand, and green energy (renewables), on the other. Coal consumption must be replaced for there to be any hope of getting close to the UN's 1.5°C target. Gas can substitute for coal but, at the same time, gas will be competing with renewable energy which, ultimately, should replace all kinds of fossil energy.

In this paper, we begin by arguing that the extent to which gas outcompetes coal vs. renewables depends on the time horizon. When gas production increases, the energy price declines, and the supply of other energy sources declines – depending on how price elastic the various sources are. The price elasticity is not a fixed number, but it depends on the time horizon. The more time one has to adjust, the more supply can increase in response to a change in the price. Coal and renewables are fundamentally different, however: Renewable energy is limited by the capacity that has been invested in so far. This capacity can increase, but that requires investments in advance. Coal, in contrast, is a declining industry. The green transition will ensure that there will be stranded assets in the coal sector, implying that the capacity to supply coal might not be binding in the short run. Thus, coal supply is likely to be more elastic in the short run, but the supply of renewable energy is likely to be more price elastic in the long term.

The difference means that governments concerned with climate change face a time-inconsistency prob-

[18] For literature surveys, see Calvo and Rubio (2012) or Buchholz and Sandler (2021). Battaglini and Harstad (2016) analyze how the equilibrium coalition depends on whether or not investments in renewables can be contracted on in addition to the emission levels.

lem. A long-term solution would be to set Pigou taxes on all energy sources one can control. These taxes will make renewable energy more competitive, and investments in renewables will increase. In the short term, however, when the stock of renewable energy is given and inelastic, then it is more tempting to raise the production of natural gas in order to outcompete coal. The larger the environmental harm is, the larger the temptation to outcompete coal will be. When this temptation is anticipated, before the policy is set, investments in renewables will be held back. The overall effect is that total emissions will increase when policymakers cannot commit to future policies. The outcome is a gas trap. The effects of larger environmental harm, and of the lower emission content in natural gas, are exactly the reverse in the noncommitment equilibrium of those in the scenario where policymakers can commit.

We have explained why these negative findings are robust to the introduction of many types of fuels, many periods, learning by doing, and depletable resources. When we simulate the model to the European market, we find that the gas trap is real and quantitatively important. The quantitative analysis also uncovers that the climate-concerned countries might not invest in renewables as a way to commit, because the necessary investment level is unrealistic. Instead, a more reasonable solution is to regulate upstream activities, such as search-and-exploration in new gas fields. The right type of upstream regulation will limit future gas production, and, when this is anticipated, investments in renewables increase and the gas trap is avoided.

The quantitative analysis also shows that the size and the composition of the climate coalition may be insufficient to avoid the gas trap. The benefit of an international supply-side treaty is, instead, that countries can make future production cuts binding and credible.

Future research should deepen our understanding of the gas trap. Theoretically, our multiple-period treatment of learning by doing and resource depletion is promising but preliminary. We have abstracted from, for example, the possibility of building a reputation for time consistent policies. Empirically, the application to the European market is preliminary, because we need more research on how the price elasticities of various types of fuels change with the time horizon. We also believe that the model can be applied to other regions. As continued climate change forces countries to pay more attention to greenhouse gas emissions at home and abroad, the gas trap can emerge everywhere.

Appendices

A Proofs

The proofs allow N to have a set J of different fossil fuel types with supply function $S_j(p)$ and emission content e_j, $j \in J$. We write $S_N(p) \equiv \sum_{j \in J} S_j(p)$. Similarly, we begin by allowing M to supply multiple types of fossil fuels, L, with cost $c_l(x_l)$ and $S_l(p) \equiv c_l'^{-1}(p)$ for $l \in L$, and we write $S_M(p) \equiv \sum_{l \in L} S_l(p)$. The proofs consider a general supply function of renewables from N equal to $x_{R,N} = S_R(p)$. We allow M to be endowed with fixed $x_{R,M}$ units of renewables (to be endogenized in the proof of Proposition 6d), in addition to the $x_{R,N}$ units in N. We write $x_R = x_{R,M} + x_{R,N}$ and $x_M = S_M(p) + x_{R,M}$. We write $A = M \cup N$ as the set of all countries or fossil fuel supply functions, so $D'_A = D'_M + D'_N$ and $S'_A = S'_M + S'_N$. Unless discussed, the second-order conditions will hold, thanks to our assumptions.

Proof of Proposition 1.

(i) *Effect of quotas:* If we differentiate foreign supply and demand conditions, we get

$$dx_j = S'_j dp, \; dx_{R,N} = S'_R dp, \; dy_N = D'_N dp. \tag{16}$$

When these equations are combined with the differentiation of the market clearing condition,

$$\sum_{j \in J} S_j(p) + x_{R,N} + x_M = D_N(p) + y_M, \tag{17}$$

$$dp = \frac{dy_M - dx_M}{S'_N - D'_N}. \tag{18}$$

Effect of taxes: With taxes, for every $l \in L$ produced by M,

$$dx_l = S'_l(dp - d\tau_l) \text{ and } dy_M = D'_M(dp + d\tau_M).$$

Combined with (16) and the differentiation of (17), we get:

$$dp = \frac{D'_M(dp + d\tau_M) - \sum_{l \in L} S'_l(dp - d\tau_l)}{S'_N + S'_R(p) - D'_N} = \frac{\sum_{l \in L} S'_l d\tau_l + D'_M d\tau_M}{S'_A + S'_R(p) - D'_A}. \tag{19}$$

M's optimal quantities maximize

$$b_M(y_M) - \sum_{l \in L} c_l(x_l) + p(x_M - y_M) - ah(e),$$

subject to (16)-(18). The solution is (in line with Lemma 4 in Harstad, 2012):

$$\begin{aligned} p - c_l' &= \left(e_l - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)}\right) ah' - \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}, \\ b_M' - p &= \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)} ah' + \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}. \end{aligned}$$

And, because $c_l' = p - \tau_l$ and $b_M' = p + \tau_M$, M's optimal outcome can be implemented by taxes that satisfy:

$$\begin{aligned} \tau_l &= \left(e_l - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)}\right) ah' - \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}, \\ \tau_M &= b_M' - p = \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)} ah' + \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}. \end{aligned} \tag{20}$$

When $x_{R,N}$ is endogenous and $S_R' \to \infty$, (20) gives:

$$\tau_l \to e_l ah' \text{ and } \tau_M \to 0.$$

So, in equilibrium, when $x_{R,N} > 0$, $p = k$, $x_j = S_j(k)$, and $x_l = S_l(k - e_l ah')$, then:

$$\begin{aligned} \frac{\partial x_l}{\partial a} &= -e_l h' S_l'(k - e_l ah') < 0, \\ x_{R,N} &= D_A(k) - S_N(k) - \sum_{l\in L} S_l(k - e_l ah') - x_{R,M}, \text{ so} \\ \frac{\partial x_{R,N}}{\partial a} &= \sum_{l\in L} e_l h' S_l'(k - e_l ah') > 0, \text{ and} \\ e &= \sum_{j\in J} e_j S_j(k) + \sum_{l\in L} e_l S_l(k - e_l ah'), \text{ so} \\ \frac{\partial e}{\partial a} &= -\sum_{l\in L} e_l^2 h' S_l'(k - e_l ah') < 0. \end{aligned}$$

Remark on trade policies. M cannot do better than the SB by adding trade policies among its instruments. If, for example, M imposes a tariff on energy imports, then M's domestic energy price will be $p_M = p + \tau_I$, M's producers supply according to $c_l' = p_M - \tau_l = p + \tau_I - \tau_l$, and M's consumers consume according to $b_M' = p_M + \tau_M = p + \tau_I + \tau_M$. Clearly, M implements (20) by any two taxes as long as:

$$\begin{aligned} \tau_l - \tau_I &= \left(e_l - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)}\right) ah' - \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}, \\ \tau_M + \tau_I &= b_M' - p = \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) + S_R'(p) - D_N'(p)} ah' + \frac{y_M - x_M}{S_N'(p) + S_R'(p) - D_N'(p)}. \end{aligned}$$

QED

Proof of Proposition 2.

(i) At the time when the taxes are decided on, $x_{R,N}$ and $x_{R,M}$ are fixed, so (20) holds with $S'_R = 0$. In equilibrium, $p = k$ when $x_{R,N} > 0$, so (20) becomes

$$\begin{aligned} \tau_l &= \left(e_l - \frac{\sum_{j\in J} e_j S'_j(k)}{S'_N(k) - D'_N(k)}\right) ah' - \frac{D_M(k+\tau_M) - \sum_{l\in L} S_l(k-\tau_l) - x_{R,M}}{S'_N(k) - D'_N(k)}, \\ \tau_M &= \frac{\sum_{j\in J} e_j S'_j(k)}{S'_N(k) - D'_N(k)} ah' + \frac{D_M(k+\tau_M) - \sum_{l\in L} S_l(k-\tau_l) - x_{R,M}}{S'_N(k) - D'_N(k)}, \end{aligned} \tag{21}$$

which, in the main model, simplifies to (6).

(ii) If we differentiate (20), we must take into account that $I = y_M - x_M$ is endogenous:

$$\begin{aligned} d\tau_l &= \left(e_l - \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)}\right) h' da - \frac{dI}{S'_N(p) - D'_N(p)}, \\ d\tau_M &= \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)} h' da + \frac{dI}{S'_N(p) - D'_N(p)}. \end{aligned} \tag{22}$$

The above proofs, where M can have multiple types of fuels, are referred to in Sections 4 and 6. From now on, however, we restrict attention to the setting (in Sections 2-3) in which M is endowed with only gas.

When $p = k$ is given, we have $dI = D'_M d\tau_M + S'_G d\tau_G$. With this, (22) becomes:

$$\begin{aligned} d\tau_G &= \left(e_G - \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)}\right) h' da - \frac{S'_G d\tau_G + D'_M d\tau_M}{S'_N(p) - D'_N(p)}, \\ d\tau_M &= \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)} h' da + \frac{S'_G d\tau_G + D'_M d\tau_M}{S'_N(p) - D'_N(p)}. \end{aligned} \tag{23}$$

So,

$$d\tau_M = \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_A(p)} h' da + \frac{S'_G d\tau_G}{S'_N(p) - D'_A(p)},$$

which we can use to find $d\tau_G$:

$$\begin{aligned} d\tau_G = \left(e_G - \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)}\right) h' da - \frac{S'_G d\tau_G}{S'_N(p) - D'_N(p)} \\ - \frac{D'_M}{S'_N(p) - D'_N(p)} \left[\frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_A(p)} h' da + \frac{S'_G d\tau_G}{S'_N(p) - D'_A(p)}\right] \quad \Leftrightarrow \\ d\tau_G \left[1 + \frac{S'_G}{S'_N(p) - D'_N(p)} \left(1 - \frac{-D'_M}{S'_N(p) - D'_A(p)}\right)\right] \\ = \left(e_G - \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_N(p)}\right) h' da - \frac{D'_M}{S'_N(p) - D'_N(p)} \left[da \frac{\sum_{j\in J} e_j S'_j(p)}{S'_N(p) - D'_A(p)} h'\right]. \end{aligned}$$

The bracket on the l.h.s. is positive. Thus, $d\tau_G/da < 0$ iff

$$\begin{aligned} & e_G - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_N'(p)} - \frac{D_M'}{S_N'(p) - D_N'(p)} \left[\frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_A'(p)} \right] \\ = \; & e_G - \frac{1}{S_N'(p) - D_N'(p)} \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_A'(p)} \left[S_N'(p) - D_A'(p) + D_M' \right] \\ = \; & e_G - \frac{\sum_{j\in J} e_j S_j'(p)}{S_N'(p) - D_A'(p)} < 0. \end{aligned}$$

Under this condition, if a increases, τ_G decreases, and thus $x_G = S_G(p - \tau_G)$ increases when $p = k$ is fixed. Consequently, e must increase, because $x_j = S_j(p)$ and $x_N = S_N(p)$ are given by $p = k$. QED

Proof of Proposition 4.

(i) Suppose that M can commit. M's equilibrium payoff level in the second period is:

$$\max_{x_M^2, y_M^2} b_M\left(y_M^2\right) - c_G\left(x_G^2\right) + \left(x_G^2 - y_M^2\right) k^2 - ah^2 \left(\sum_{j\in J} e_j S_j\left(k^2\right) + e_G x_G^2 \right),$$

whose first-order conditions (f.o.c.'s) are as in Proposition 1. Using the Envelope theorem, the benefit of a larger k^2 is:

$$\left(x_G^2 - y_M^2\right) - \left(\sum_{j\in J} e_j S_j'\left(k^2\right) \right) ah^2.$$

With the decreasing function $k^2 = f\left(x_R^1\right)$, where:

$$x_R^1 = D_N\left(k^1\right) + y_M^1 - S_C\left(k^1\right) - x_G^1,$$

M's first-period problem is to solve:

$$\max_{x_G^1, y_M^1} b_M\left(y_M^1\right) - c_G\left(x_G^1\right) + \left(x_G^1 - y_M^1\right) k^1 - ah^1 \left(\sum_{j\in J} e_j S_j'\left(k^1\right) + e_G x_G^1 \right) + \delta V\left(k^2\right),$$

where $V\left(k^2\right)$ is the continuation value, as a function of k^2. The f.o.c.'s are:

$$\begin{aligned} 0 &= k^1 - c_G'\left(x_G^1\right) - e_G ah^1 + \delta V'\left(k^2\right) \frac{\partial k^2}{\partial x_G^1} \Leftrightarrow \\ 0 &= k^1 - c_G'\left(x_G^1\right) - e_G ah^1 + \delta \left[\left(x_G^2 - y_M^2\right) - \sum_{j\in J} e_j S_j'\left(k^2\right) ah^2 \right] (-f') \Leftrightarrow \\ \tau_G^1 &= k^1 - c_G'\left(x_G^1\right) = e_G ah^1 + \delta \left[\sum_{j\in J} e_j S_j'\left(k^2\right) ah^2 - \left(x_G^2 - y_M^2\right) \right] (-f'), \end{aligned}$$

and

$$\begin{aligned} 0 &= b'_M\left(y_M^1\right) - k^1 + \delta V'\left(k^2\right)\frac{\partial k^2}{\partial y_M^1} \Leftrightarrow \\ 0 &= b'_M\left(y_{M,1}\right) - k^1 + \delta\left[\left(x_G^2 - y_M^2\right) - \sum_{j\in J} e_j S'_j\left(k^2\right) ah^2\right] f' \Leftrightarrow \\ \tau_M^1 &= b'_M\left(y_M^1\right) - k^1 = -\delta\left[\sum_{j\in J} e_j S'_j\left(k^2\right) ah^2 - \left(x_G^2 - y_M^2\right)\right](-f'). \end{aligned}$$

where the last bracket is positive if $\Omega^2 > 0$. Under this condition, M prefers to commit to $\tau_G^1 > e_G a h^1$ and $\tau_M^1 < 0$ as a way to encourage investments in renewables, especially if the learning-by-doing effect is large.

(ii) When M cannot commit, M sets policies for period t at the time when x_R^t and thus the future k^{t+1} are given. Therefore, M's optimal policy does not take into account any learning-by-doing effect, and M's policy satisfies Proposition 2, as if this effect were absent. QED

Proof of Proposition 5.

Second period: To accommodate the next proof, let the second-period extraction cost be $c^x\left(x_G^2, s\right)$, and the first-period extraction level be s, instead of $c^2\left(x_G^2, x_G^1\right)$ and x_G^1. In the second period, when $t = 2$, M's equilibrium payoff is:

$$\begin{aligned} V(s) &= b_M\left(y_M^t\right) - c^x\left(x_G^t, s\right) + \left(x_G^t - y_M^t\right)k^t - ah^t e, \text{ so} \\ V'(s) &= \left(b'_M\left(y_M^t\right) - k^t\right)\frac{y_M^t}{ds} - \left(c_1^x - k^t + e_G a h^t\right)\frac{dx_G^t}{ds} - c_2^x. \end{aligned} \tag{24}$$

Lemma 1

$$\frac{dy_M^t}{ds} = \frac{D'_M(k^t)}{S'_A(k^t) - D'_A(k^t)}\frac{c_{12}^x}{c_{11}^x} \text{ and } \frac{dx_G^t}{ds} = -\left(\frac{S'_C(k^t) - D'_A(k^t)}{S'_A(k^t) - D'_A(k^t)}\right)\frac{c_{12}^x}{c_{11}^x} \text{ for } t = 2. \tag{25}$$

Proof. Given the production tax τ_G^t in period $t \in \{1, 2\}$, the representative gas producer would like to maximize:

$$\left(k^1 - \tau_G^1\right)x_G^1 - c_G^1\left(x_G^1\right) + \delta\left[\left(k^2 - \tau_G^2\right)x_G^2 - c^x\left(x_G^2, x_G^1\right)\right], \text{ so}$$

$$\partial c_G^1\left(x_G^1\right)/\partial x_G^1 = k^1 - \tau_G^1 - \delta c_2^x, \text{ for the first period quantity, and} \tag{26}$$

$$c_1^x\left(x_G^2, s\right) = k^2 - \tau_G^2, \text{ for the second period quantity,} \tag{27}$$

which implicitly defines second-period supply x_G^2 as a function of s and $k^t - \tau_G^t$, written $x_G^t = S^x\left(k^t - \tau_G^t, s\right)$. By differentiating (27), we get:

$$c_{11}^x\left(x_G^t, s\right)dx_G^t + c_{12}^x\left(x_G^t, s\right)ds = -d\tau_G^t, \tag{28}$$

making it easy to confirm that $S_1^x = 1/c_{11}^x$ and $S_2^x = -c_{12}^x/c_{11}^x$. By differentiating (6), we get for $t = 2$:

$$\begin{aligned}
d\tau_y^t &= \frac{1}{S'_C(k^t) - D'_N(k^t)} \left[D'_M(k^t + \tau_y^t) d\tau_y^t + S_1^x d\tau_x^t - S_2^x ds \right] \\
&= \frac{1}{S'_C(k^t) - D'_A(k^t)} \left[S_1^x d\tau_x^t - S_2^x ds \right], \\
d\tau_x^t &= -\frac{1}{S'_C(k^t) - D'_N(k^t)} \left[D'_M(k^t + \tau_y^t) d\tau_y^t + S_1^x d\tau_x^t - S_2^x ds \right] \\
&= -\frac{1}{S'_C(k^t) - D'_N(k^t)} \left[D'_M(k^t + \tau_y^t) \frac{1}{S'_C(k^t) - D'_A(k^t)} \left[S_1^x d\tau_x^t - S_2^x ds \right] + S_1^x d\tau_x^t - S_2^x ds \right] \\
&= -\frac{1}{S'_C(k^t) - D'_N(k^t)} \left[\frac{S'_C(k^t) - D'_N(k^t)}{S'_C(k^t) - D'_A(k^t)} \left[S_1^x d\tau_x^t - S_2^x ds \right] \right] \Leftrightarrow \\
\frac{d\tau_x^t}{ds} &= \frac{S_2^x}{S'_C(k^t) + S_1^x - D'_A(k^t)}, \text{ so} \\
\frac{d\tau_y^t}{ds} &= -\frac{d\tau_x^t}{ds} = \frac{-S_2^x}{S'_C(k^t) + S_1^x - D'_A(k^t)}.
\end{aligned}$$

From the f.o.c. for M's consumption level, we get $dy_M^t = D'_M d\tau_M^t$, so, at $t = 2$:

$$\frac{dy_M^t}{ds} = \frac{D'_M d\tau_M^t}{ds} = \frac{-D'_M S_2^x}{S'_C(k^t) + S_1^x - D'_A(k^t)}.$$

From (28), we get at $t = 2$:

$$\begin{aligned}
c_{11}^x \left(x_G^t, s \right) dx_G^t + c_{12}^x \left(x_G^t, s \right) ds &= -d\tau_G^t \Leftrightarrow \\
c_{11}^x \left(x_G^t, s \right) \frac{dx_G^t}{ds} &= -\frac{d\tau_G^t}{ds} - c_{12}^x \left(x_G^t, s \right) \Leftrightarrow \\
\frac{dx_G^t}{ds} &= -\frac{1}{c_{11}^x} \frac{d\tau_G^t}{ds} - \frac{c_{12}^x}{c_{11}^x} \\
&= -\frac{1}{c_{11}^x} \frac{S_2^x}{S'_C(k^t) + S_1^x - D'_A(k^t)} - \frac{c_{12}^x}{c_{11}^x}.
\end{aligned}$$

Because $S_2^x = -c_{12}^x/c_{11}^x$ and $S_1^x = 1/c_{11}^x$, at $t = 2$ we have:

$$\begin{aligned}
\frac{dx_G^t}{ds} &= -\frac{1}{c_{11}^x} \frac{-c_{12}^x/c_{11}^x}{S'_A(k^t) - D'_A(k^t)} - \frac{c_{12}^x}{c_{11}^x} = \left(\frac{S_1^x(k^t)}{S'_C(k^t) + S_1^x - D'_A(k^t)} - 1 \right) \frac{c_{12}^x}{c_{11}^x} \\
&= -\left(\frac{S'_C(k^t) - D'_A(k^t)}{S_1^A(k^t, s) - D'_A(k^t)} \right) \frac{c_{12}^x}{c_{11}^x} \text{ where } S_1^A \left(k^t, s \right) \equiv S'_C(k^t) + S_1^x \left(k^t, s \right). \| \qquad (29)
\end{aligned}$$

Substituting (25) into (24), we get, with $t = 2$:

$$\begin{aligned}
V'(s) + c_2^x &= \frac{(b'_M - k) D'_M + (c_1^x - k^t + e_G a h^t) [S'_C(k^t) - D'_A(k^t)]}{S_1^A(k^t, s) - D'_A(k^t)} \frac{c_{12}^x}{c_{11}^x} \\
&= \frac{\tau_M^t D'_M + (e_G a h^t - \tau_G^t) [S'_C(k^t) - D'_A(k^t)]}{S_1^A(k^t, s) - D'_A(k^t)} \frac{c_{12}^x}{c_{11}^x},
\end{aligned}$$

which would be zero if M could commit. When M cannot commit, taxes at $t = 2$ are given by (6), so:

$$\begin{aligned} V'(s) + c_2^x &= \left[\frac{e_C S_C'(k^t)\, ah^t}{S_C'(k^t) - D_N'(k^t)} + \frac{y_M^t - x_G^t}{S_C'(k^t) - D_N'(k^t)}\right] \frac{S_C'(k^t) - D_N'(k^t)}{S_1^A(k^t, s) - D_A'(k^t)} \frac{c_{12}^x}{c_{11}^x} \\ &= \frac{e_C S_C'(k^t)\, ah^t + y_M^t - x_G^t}{S_1^A(k^t, s) - D_A'(k^t)} \frac{c_{12}^x}{c_{11}^x}. \end{aligned} \tag{30}$$

First period: Compared to Section 3, the difference is the continuation value $\delta V(s)$, here discounted. This continuation value depends only on first-period extraction and not on M's first-period consumption. The f.o.c.'s for M's policy will satisfy:

$$k^1 - c_l' = \left(e_l - \frac{\sum_{j\in J} e_j S_j'(k^1)}{S_N'(k^1) + S_R'(k^1) - D_N'(k^1)}\right) ah^1 - \frac{y_M^1 - x_M^1}{S_N'(k^1) + S_R'(k^1) - D_N'(k^1)} - \delta V'(s), \tag{31}$$

$$b_M' - k^1 = \frac{\sum_{j\in J} e_j S_j'(k^1)}{S_N'(k^1) + S_R'(k^1) - D_N'(k^1)} ah^1 + \frac{y_M^1 - x_M^1}{S_N'(k^1) + S_R'(k^1) - D_N'(k^1)}. \tag{32}$$

(i) If M could commit in period 2, $\delta V'(s) = -\delta c_2^x$ and, when M sets its policies, $S_R'(k^1) \to \infty$. Note that (26) and (31) then coincide if $\tau_G^1 = e_l ah^1$. With $\tau_M^1 = 0$, the representative consumer ensures that $b_M' = k^1$, which is in line with (32) when $S_R'(k^1) \to \infty$. Thus, Proposition 1 holds for both periods.

(ii) When M cannot commit, M's continuation value follows from (30), and, in the first-period, M sets policies given that $S_R' = 0$. Both equations can be substituted into (31) to determine M's optimal quantities. Combined with (26), the necessary production tax is:

$$\begin{aligned} \tau_G^1 &= \left(e_G - \frac{e_C S_C'(k^1)}{S_C'(k^1) - D_N'(k^1)}\right) ah^1 - \frac{D_M(k^1 + \tau_M^1) - S_G(k^1 - \tau_G^1)}{S_C'(k^1) - D_N'(k^1)} - \delta V'(s) - \delta c_2^x \\ &= \left(e_G - \frac{e_C S_C'(k^1)}{S_C'(k^1) - D_N'(k^1)}\right) ah^1 - \frac{D_M(k^1 + \tau_M^1) - S_G(k^1 - \tau_G^1)}{S_C'(k^1) - D_N'(k^1)} - \delta \frac{e_C S_C'(k^2)\, ah^2 + y_M^2 - x_G^2}{S_A'(k^2) - D_A'(k^2)} \frac{c_{12}^x}{c_{11}^x}, \end{aligned}$$

when $S_A'(k^2) \equiv S_1^A(k^2, s)$ is naturally defined as the slope of the supply curve given the equilibrium s. The necessary consumption tax is simply (32) with $S_R' = 0$. Compared to the model without depletion, τ_G^1 is further reduced when $c_{12}^x > 0$ when M cannot commit. In equilibrium, a lower τ_G^1 increases x_G^1 and decreases x_R^1, for the same reasons as in the proof of Proposition 2. QED

Proof of Proposition 6.

The above proofs permit M to produce $x_{R,M}$ units of renewable energy. We believe that it is unrealistic to permit M to invest so much that investors in N will not invest in renewables at all, so we will assume away this possibility:

Assumption R. *M can invest in $x_{R,M}$ at unit cost k, but M cannot invest so much that M crowds out all investment in renewables by N. I.e.:*

$$x_{R,M} \leq \overline{x}_{R,M} \equiv D_A(k) - S_C(k) - S_G(k - e_G a h').$$

With this assumption, in equilibrium, $x_{R,N} > 0$. If the assumption failed, $x_{R,M}$ could be so large that the energy price would be less than k, and then the larger $x_{R,M}$ would be gradually crowding out coal and gas. In this case, M can produce so much renewables that the equilibrium energy price is below the cost of investing, and coal can be outcompeted without having to worry about reduced investments in renewables in other countries.

(i) If M could commit to policies, M would set $\tau_G = e_G a h'$ and $\tau_M = 0$, regardless of $x_{R,M}$. If M increased $x_{R,M}$, then $x_{R,N}$ would decline by the same amount, so that the market clearing condition holds:

$$x_{R,M} + x_{R,N} = D_A(k) - S_C(k) - S_G(k - e_G a h').$$

Thus, M would change neither policies, nor quantities, by increasing $x_{R,M}$. The cost would coincide with the revenue, so it is optimal for M to invest nothing (or anything) in $x_{R,M}$, and M does not strictly benefit from subsidizing these investments.

(ii) When M cannot commit, M would prefer to commit to policies that are in line with Proposition 1, but, in equilibrium, M's policies are in line with Proposition 2. The two are equal only if (14) holds. Equation (14) does not need to violate Assumption R as long as:

$$\sum_{j \in J} e_j S_j'(k_2) a h' < D_N(k) - S_C(k) - S_G(k).$$

Thus, with enough investment, M implements its commitment solution at no cost, since the equlibrium price of energy equals the unit cost of $x_{R,M}$. It is not necessary to subsidize investments to achieve this goal, since it is an equilibrium that private investors invest (14) as long as $p = k$. (There are multiple equilibria when it comes to where the investors are located.) It is easy to check that an even larger investment by M is suboptimal, as long as Assumption R holds. QED

Proof of Proposition 7.

This proof draws on the proof of Proposition 5. At the beginning of the period, M's objective is to maximize:

$$b_M(y_M) - c^x(x_G, s) + (x_G - y_M)k - ah(e) - c_s(s),$$

where $c_s(s)$ is the cost of s. This problem gives the f.o.c.:

$$(b'_M - k)\frac{y_M}{ds} - c_2^x - (c_1^x - k + e_G a h')\frac{dx_G}{ds} = c'_s,$$

while, in equilibrium, the market invests in s according to:

$$c'_s = -c_2^x - \tau_s.$$

Thus, M's optimal τ_s is:

$$\tau_s = (e_G a h' - \tau_G)\frac{dx_G}{ds} - \tau_M \frac{y_M}{ds}. \tag{33}$$

(i) From Proposition 1, it follows that if M could commit, $e_G a h' - \tau_G = \tau_M = 0$ and, therefore, $\tau_s = 0$.

(ii) Lemma 1 and (25) present $\frac{dx_G}{ds}$ and $\frac{y_M}{ds}$ for the last period. (In that proof, the last period is $t = 2$, but here there is only one period.) When the two expressions are substituted into (33), we get:

$$\begin{aligned}\tau_s &= (e_G a h' - \tau_G)\left(-\left(\frac{S'_C(k) - D'_A(k)}{S_1^A(k,s) - D'_A(k)}\right)\frac{c_{12}^x}{c_{11}^x}\right) - \tau_M D'_M\left(\frac{c_{12}^x/c_{11}^x}{S_1^A(k,s) - D'_A(k)}\right) \\ &= \frac{(e_G a h' - \tau_G)[S'_C(k) - D'_A(k)] + \tau_M D'_M}{S_1^A(k,s) - D'_A(k)}\left(-\frac{c_{12}^x}{c_{11}^x}\right).\end{aligned}$$

When M cannot commit, we can substitute in with (6) to get:

$$\begin{aligned}\tau_s &= \left[\frac{e_C S'_C(k)}{S'_C(k) - D'_N(k)} a h' + \frac{y_M - x_G}{S'_C(k) - D'_N(k)}\right]\frac{S'_C(k) - D'_N(k)}{S_1^A(k,s) - D'_A(k)}\left(-\frac{c_{12}^x}{c_{11}^x}\right) \\ &= \frac{e_C S'_C(k) a h' + y_M - x_G}{S'_A(k) - D'_A(k)}\frac{-c_{12}^x}{c_{11}^x},\end{aligned}$$

when $S'_A(k) \equiv S_1^A(k,s)$ is naturally defined as the slope of the supply curve given the equilibrium s. QED

B Sensitivity Analysis

Some readers might have different suggestions for the numbers in Table 1. We believe, however, that the results are quite robust, qualitatively. In fact, most of the numbers in Table 1 have little impact on the estimates, because the market shares for some of the sources are small. In the following, we discuss the background for the numbers and the consequences of selecting alternative estimates.

Regarding the electricity market in Europe, the share for each fuel comes from IEA (2024). ACER (2024) reports that the share of gas that is imported to the EU is 80%, while the European Council (2024) reports the origins of EU gas imports. Together, these numbers allow us to calculate the share of gas from each source, provided in Table 1. Based on the total generation of electricity from renewables in Norway and Europe, respectively, we calculate the share of the European renewables-based electricity supply from Norway.

Emission coefficients. We have not been able to find an official source that provides emission coefficients for the different fuels in European electricity generation. Scarlat et al. (2022) estimate the emissions along the entire pathway from extraction to electricity generation in Europe. However, the paper does not provide the exact coefficient for each fuel type.[19] The US Energy Information Administration (EIA, 2024) provides emission coefficients based on the energy content for a range of fuels, but these are not specific to the use in electricity generation. In our analysis of the European electricity generation sector, we have therefore chosen to follow Acemoglu et al. (2023) for emission coefficients for electricity generation based on coal and natural gas. Acemoglu et al. (2023) study emissions from US electricity generation and use emission coefficients adjusted for the efficiency of the different fuels in electricity generation.

Since oil is not included in the analysis of Acemoglu et al. (2023), we use the ratio between the heat content of coal and oil provided by the EIA (2024) together with the coefficient for coal used by Acemoglu et al. (2023) to calculate an emission coefficient for oil. Note that since the share of electricity generated by oil is small, this coefficient does not affect the results significantly. We use the same method to calculate the emission coefficient for Other, based on the ratio between coal and geothermal provided by the EIA (2024).

Finally, the emission coefficients for renewables and nuclear are all rounded down to zero, in line with Acemoglu et al. (2023), Abuin (2024), Holland et al. (2022) and others. The most uncertain emission

[19] Note that Figure 9 in Scarlat et al. (2022) present emissions for each fuel, including upstream and transport. The range presented in the figure indicates that the emissions from coal-generated electricity relative to those from gas-generated electricity may be somewhat larger than the numbers we use. If we were to use the numbers from Scarlat et al. (2022), we would therefore get a more severe Gas Trap in this application.

coefficient might be the one for LNG. But even if this is reduced to 0.4, as for non-liquefied gas, we would face a gas trap in that:

$$\partial e/\partial x_G \mid_{ST} = -0.27 \text{ vs. } \partial e/\partial x_G \mid_{LT} = 0.28,$$

and $d\tau_G^{ST}/dah' = -0.27$.

Supply-side elasticities. Both for the short and the long term, several of the estimated ε_j's are quite uncertain and the estimates vary greatly between different articles. The supply-side elasticity for coal, 2.4, falls within the range of a list of other reported estimates, see for example Böhringer and Rosendahl (2022) and US Bureau of Ocean Energy Management (2023), who apply a higher supply-elasticity for coal (3.0 and 4.39, respectively), or Abuin (2024), who estimates an elasticity of 0.769. It is not clear whether we use the most relevant supply-side elasticities for oil, but this choice does not matter much for the results, given that the share of electricity generated by oil is small. Thus, the elasticity of oil drilling w.r.t. the gas price is small (0.12 according to Prest (2022)). However, for the small share of electricity that is based on oil, we must assume that the supply responds to changes in the electricity price as a consequence of changes to the use of other fuels, particularly gas. Anderson et al. (2018) showed that changes in the oil price, while only weakly affecting oil supply in the short term, can quite strongly affect drilling activity. They conclude that the short-term supply elasticity of oil is close to zero, while they find a long-term elasticity of 0.7. Rao (2018) finds a short-term elasticity (within one year) of 0.30-0.37, while Baumeister and Hamilton (2019) report 0.15, considering even shorter time periods. Within the same range, Bornstein et al. (2023) find an elasticity of 0.28 for the short term (within a year). For the long term, Ahlvik et al. (2024) find an elasticity in exploration for oil of 1.8, while Prest (2022) reports a cumulative elasticity of drilling over several years of 1.24 for onshore drilling, lower for offshore drilling. Including the expected response until 2030, Rystad Energy (2023) finds an elasticity of 1 for oil supply, building on their own substantial cost data and on IEA scenarios. Finally, Böhringer and Rosendahl (2022) also report an elasticity of 1. Oil and natural gas are often extracted from the same reservoirs, and the pattern of short-term versus long-term elasticities can be expected to be similar for natural gas. The elasticities for oil matter little, however, because the market share of oil is so small.

Demand-side elasticities. It has been shown that the demand-side elasticity varies greatly with the time horizon, because consumers will have several opportunities to adjust their selection of durable goods when the time horizon is large. For example, Deryugina et al. (2020) find an elasticity of electricity demand in Illinois of -0.09 in the first six months, growing to -0.27 when the time horizon is two years. Buchsbaum (2023) find a similar short-term elasticity of residential electricity demand of -0.14. Considering a time horizon of 30

to 40 years, he estimates the long-term elasticity to be as large as -2.25. Feehan (2018) considers a 20-year time horizon, and finds a somewhat lower long-term elasticity of -1.2 for electricity demand in Canada. Based on these estimates, we set the short-term elasticity to -0.1, and the long-term elasticity to -2.0.

We believe these numbers are in line with estimates also in other contributions to the literature, which mainly focus on the short to medium term. For example, the literature review in Labandeira et al. (2017) reports an average short-term estimate of -0.21 and -0.61 for the long term. In their review, however, they include all estimates for more than one year in the long-term group. Considering very short time lags, as low as one month or less, and focusing on the period after the spring of 2022, Jamissen et al. (2024) find very small numbers for the demand response in Germany (elasticities of -0.01 for wholesale prices and -0.04 for retail prices). Peersman and Wauters (2024) find that the response to price changes depends on the direction of the change, reporting elasticities of -0.36 when the price increases and -0.07 when the price decreases, based on yearly survey data from Belgium. Based on data from 1995 to 2015, Cialani and Mortazavi (2018) estimate elasticities for EU electricity demand of -0.04 (residential sector) and -0.3 to -0.05 (industrial sector) for the short term. Using a one-year lag, long-term elasticities are estimated to be -0.19 to -0.30 (residential sector) and -0.12 to -0.20 (industrial sector). Cao et al. (2016) find elasticities for Chinese electricity demand between -0.49 and -0.57 and for overall energy demand between -0.18 and -0.37, based on yearly data. With US data, Li et al. (2022) report elasticities for commercial energy demand between -0.137 and -0.261 for the short term and between -0.281 -0.463 for the long term, while Li et al. (2021) study energy use in buildings, also in the US, and find very low demand elasticities, ranging from 0, for the short term, to -0.069 for a longer horizon (but within a few years). The difference between short-run and long-run demand-side elasticities strengthens the results but does not drive them. If we assumed that the long-term demand-side elasticity was -0.1, as for the short term, then:

$$\partial e/\partial x_G \mid_{ST} = -0.37 \text{ vs. } \partial e/\partial x_G \mid_{LT} = 0.15.$$

The results in Sections 4.4-4.5 are unchanged because the other long-term elasticities do not matter when either renewable or nuclear energy is perfectly elastic in the long term.

All energy not used for transport. Both coal and gas are used in direct heating and are thus not always consumed through the generation of electricity. If we look at energy use overall, excluding the transport sector, the market shares for the various sources are as in Table 2, based on the fuel shares provided by EIA (2024). This replaces Table 1.

Source/characteristics	%	e_j	ε_j^{ST}	ε_j^{LT}	
Coal	**17.0**	**1.0**	2.4	**2.4**	
Gas_{NORWAY}	**7.4**	**0.4**	0.2	0.5	
Gas_{OTHER}	**17.0**	**0.4**	**0.2**	**0.5**	
LNG_{USA}	**4.7**	1.3	**2.0**	**2.0**	
LNG_{RUSSIA}	**1.5**	1.3	2.0	2.0	
Oil	**16.7**	**0.8**	0.3	**1.0**	
RE Norway	**0.8**	**0.0**	0.0	0.0	
RE other	**9.3**	**0.0**	0.0	**3.0**	
Nuclear	**13.5**	**0.0**	0.0	3.0	
Other	**12.1**	**0.1**	1.0	1.0	
Demand $\left(\varepsilon_N^{ST}, \varepsilon_N^{LT}\right)$			-0.1	-2.0	

Table 2: Fuel shares, emission intensities and elasticities based on total European energy consumption, excluding transport.

The fuel shares are calculated based on the total supply of energy in Europe (production plus imports minus exports), and the total consumption of each fuel in transport is subtracted. As for Table 1, the shares of gas from the different origins are based on an EU import share of 80% (ACER, 2024) and market shares provided by the European Council (2024), while the share of renewables from Norway is calculated based on the supply of hydro-based electricity from Norway.

We exclude transport because the other sources of fuels are imperfect substitutes for oil when it comes to transport. Nevertheless, oil has a much larger market share in Table 2 than in Table 1. With these numbers, we get that

$$\partial e/\partial x_G \mid_{ST} = -0.36 \text{ vs. } \partial e/\partial x_G \mid_{LT} = 0.19.$$

And, if renewables or nuclear energy sources are completely elastic in the very long term:

$$d\tau_G^{ST}/dah' = -0.35 \text{ vs. } d\tau_G^{LT}/dah' = 0.4.$$

All energy. Finally, one might worry that including the full European oil consumption in the analysis might change the conclusion. Oil is more polluting than natural gas. At the same time, it is well-documented in the literature that production does not respond strongly to price changes in the short term, while the long-term supply elasticity is larger (see for example Anderson et al. (2018) and Ahlvik et al. (2024). In Table 3, we include all energy use in Europe and make the simplifying assumption that oil is a perfect substitute to electricity also in the transport sector:

Source/characteristics	%	e_j	ε_j^{ST}	ε_j^{LT}	
Coal	**13.5**	**1.0**	2.4	**2.4**	
Gas_{NORWAY}	**6.0**	**0.4**	0.2	0.5	
Gas_{OTHER}	**13.7**	**0.4**	**0.2**	**0.5**	
LNG_{USA}	**3.8**	1.3	**2.0**	**2.0**	
LNG_{RUSSIA}	**1.2**	1.3	2.0	2.0	
Oil	**32.3**	**0.8**	0.3	**1.0**	
RE Norway	**0.8**	**0.0**	0.0	0.0	
RE other	**7.2**	**0.0**	0.0	**3.0**	
Nuclear	**10.8**	**0.0**	0.0	3.0	
Other	**10.7**	**0.1**	1.0	1.0	
Demand $\left(\varepsilon_N^{ST}, \varepsilon_N^{LT}\right)$	**100**		-0.1	-2.0	

Table 3: Fuel shares, emission intensities and elasticities based on total European energy supply.

As before, the fuel shares are collected from IEA (2024), here as the total supply (production plus imports minus exports), and the shares from each origin are calculated as in Table 1 and 2. With these numbers, we get that

$$\partial e/\partial x_G \mid_{ST} = -0.34 \text{ vs. } \partial e/\partial x_G \mid_{LT} = 0.18.$$

And, if renewables or nuclear energy sources are completely elastic in the very long term:

$$d\tau_G^{ST}/dah' = -0.33 \text{ vs. } d\tau_G^{LT}/dah' = 0.4.$$

Thus, the above insight is robust to whether we concentrate on the European energy market, excluding or including transport, or the electricity subset of this market. In Section 5, we argue that these estimates are conservative: The results are strengthened if we consider a dynamic model with learning-by-doing effects or exhaustible gas supplies.

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