Why is there still investment in polluting capital?
Stranded assets and climate policy uncertainty

Raphaël Huleux*

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Abstract

Despite governments' commitments to limit global warming to 1.5 degree Celcius, there is still investment in carbon-intensive capital. This paper uses a growth model featuring irreversible investment, capacity utilisation, clean and polluting capital to study this apparent paradox. It shows that current investment in polluting capital and CO_2 emissions are coherent with expectations of a future carbon tax, if investors also expect a bailout of polluting capital. This result implies that governments' credibility can play an important role in reducing the cost of implementing an optimal carbon tax by committing not to bail out. However, there exists a temptation for a short-sighted government to boost output and consumption in the short run by announcing a future bailout.

Keywords: Climate change, stranded assets, policy uncertainty

JEL codes: E22, O44, Q43, Q58

*Copenhagen Business School, rah.eco@cbs.dk

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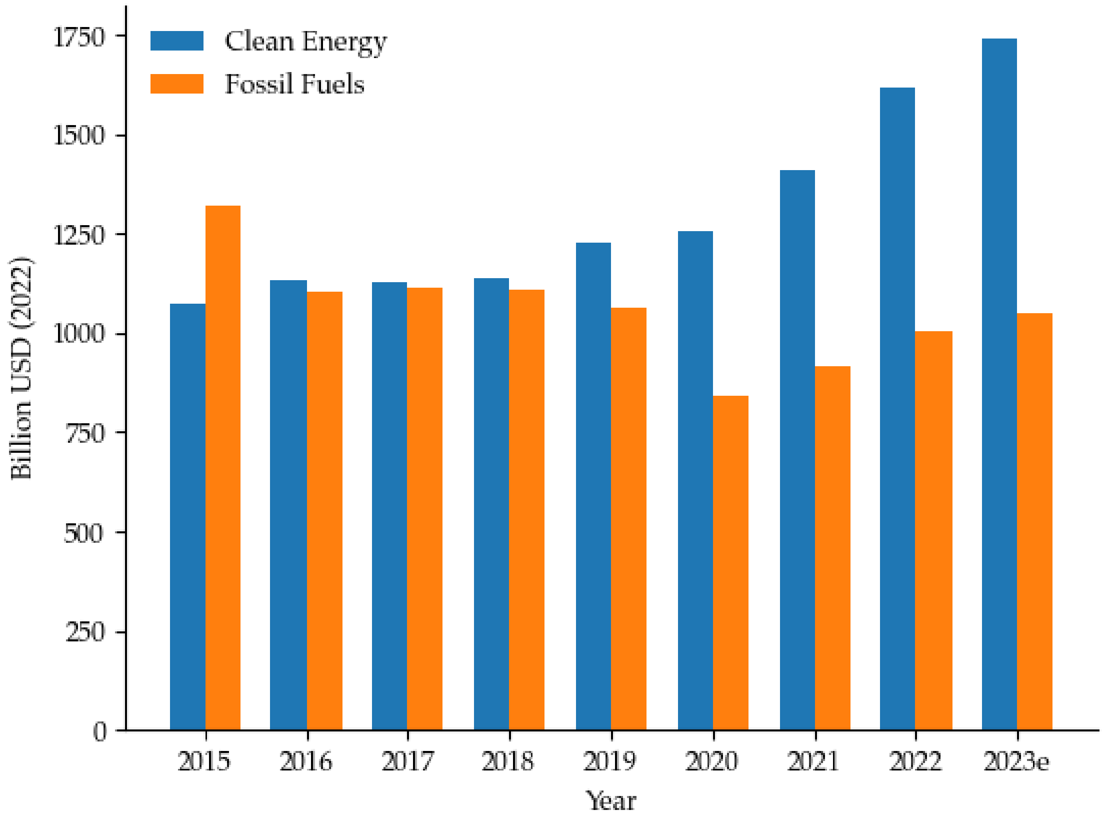

Figure 1: Global energy investment in clean energy and in fossil fuels, 2015-2023e

Note: Data from the IEA. Measured in billions of dollars.

The climate literature has shown that the CO_2 emissions implied by the existing stock of polluting capital already exceed the remaining carbon budget to limit global warming to 2°C or less (Davis & Socolow 2014, Pfeiffer et al. 2016, 2018). Figure 2 shows the shrinking world carbon budget. The total carbon budget to keep global warming below 1.5°C with 80% probability is only equal to 2.5 years of annual emissions. Some of the existing polluting capital stock must become 'stranded' to meet our climate objectives. However, despite this overaccumulation of polluting capital and the government's commitment to respect this carbon budget, firms and households keep investing in polluting capital.

This paper studies this apparent paradox in the allocation of resources towards polluting capital, focusing on the role of climate policy uncertainty. Indeed, although there is evidence that firms and households expect climate policy to become more stringent in

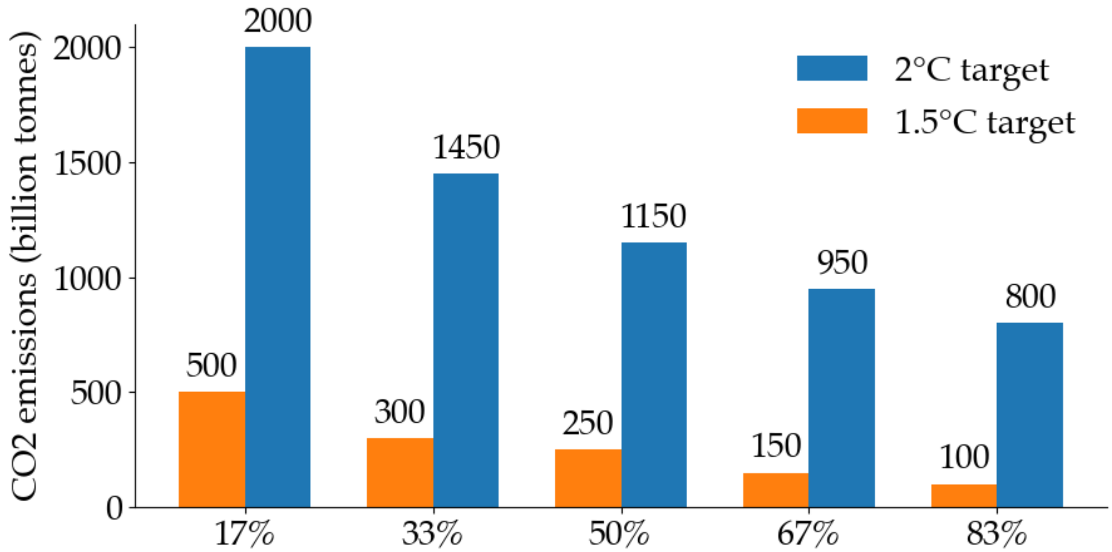

Figure 2: Remaining carbon budget for the 2°C and 1.5°C target.

Note: This figure shows the remaining carbon budget in 2022 depending on the likelihood of keeping global warming below 1.5°C or 2°C. Sources are from Our World in Data.

the future, there is still uncertainty surrounding when a carbon tax will be imposed and precisely what type of policy will be implemented. More precisely, there appears to be a lot of uncertainty about whether owners of stranded assets will be bailed out or compensated by governments. For example, Sen & von Schickfus (2019) shows that, in Germany, investors expected that the tax on the lignite coal power plants would be accompanied by a form of bailout to compensate stockholders for their financial losses. Only when a court decided this policy was against national and European legislation did the value of the firms owning those lignite coal power plants decrease.

Thus, one potential explanation for the persistent investment in polluting capital is that households and firms expect compensation for future losses due to a more stringent climate policy. Indeed, if polluting capital is more productive than clean capital, it can be optimal for investors to keep investing and using polluting capital if they expect a bailout compensating them for the potentially stranded assets.

In this work, I study the impact of climate policy uncertainty on investment in polluting capital and the existence of stranded assets. We use a two-asset neo-classical model along the lines of Rozenberg et al. (2018) with three key features: (1.) irreversibility in polluting capital, (2.) capacity utilization of polluting capital, (3.) uncertainty about future climate policy. A key feature of our model is in line with Sen & von Schickfus (2019), firms are unsure about both the timing of climate policy and whether the government will bail out stranded assets or not.

We first show that non-punitive climate policies such as subsidies on clean capital are probably not feasible under the current level of polluting capital, which makes it more likely that investors expect a future carbon tax. Secondly, in a stochastic equilibrium where investors expect a future bailout, the steady-state level of polluting capital can be above the laissez-faire equilibrium if the bailout is sufficiently large. Thus, expectations of a future climate policy can be coherent with an increase in current emissions when we include the possibility of a bailout. Finally, we show that a short-term government might want to commit to a future bailout of polluting capital to temporarily increase output and consumption at the cost of a longer transition and more stranded assets. Conversely, committing never to bail out polluting capital reduces output today but decreases the cost of transition and the amount of stranded assets in the future. Finally, we show that, despite the absence of any financial frictions in our model, the price of clean and polluting firms will overreact to climate policy commitments in the future, confirming that expectations about future climate policies might have a large impact on financial markets.

Literature review

There are two types of stranded assets. The first ones are the known fossil fuel reserves that need to remain under the ground to respect the objective of 2°C set by the 2015 Paris Agreement. Indeed, as shown by McGlade & Ekins (2015), known reserves in 2015 vastly exceeded the carbon budget of 1,100 gigatonnes of carbon dioxide, and around a third of oil reserves, half of gas reserves, and 80% of coal reserves need to remain unused. This overabundance of fossil fuels has thus shifted attention from the risk of "peak oil" to the risk of stranded assets (van der Ploeg & Rezai 2019).

A second type of stranded asset is the infrastructure and capital that directly or indirectly requires carbon fuels to operate. Such assets can be directly related to the energy sector, such as a coal plant, an oil refinery, or an oil tanker, but they are not limited to it: airports, highways, and central heating systems can also be affected. Davis & Socolow (2014) estimated that the committed emissions – that is, the cumulative emissions that would be emitted if an asset is used for its total lifetime at its expected use rate – implied by those carbon-intensive infrastructures were increasing at 4% a year in the energy sector. Subsequent studies found that the committed emissions from total carbon-intensive infrastructures already exceeded the current carbon budget, making the appearance of stranded assets inevitable (Pfeiffer et al. 2016, 2018). The main conclusion from the empirical literature on stranded assets is that there is too much carbon fuel at our disposal and too much carbon-intensive infrastructure to use compared to our remaining carbon budget. This over-abundance makes it more likely that a climate transition will imply stranded assets.

In theory, stranded assets can be the most efficient solution and are a desirable consequence of a carbon tax. If investors made mistakes in the past and didn't properly internalize the climate constraint and the social cost of carbon, it can be more efficient today not to use those assets once the climate constraint is revealed (Rozenberg et al. 2018). In that sense, stranded assets are a typical example of avoiding a sunk-cost fallacy. If the marginal cost of using those assets is superior to the implied marginal benefit, it is best not to use them, whatever the previous cost of investing in them. However, in practice, stranded assets might create risks for financial stability and incentivize politicians not to implement efficient climate policies. Many central bankers, especially in Europe, (Carney 2016, ECB 2019, Andersson & Baccianti 2020, Batten 2018) have thus focused on the risk that those assets could pose to financial stability. Banks that have carbon assets on their balance sheets could become insolvent due to the decrease in the value of those assets following a more stringent climate policy (Lucia et al. 2019). Secondly, investors who own potentially stranded assets might be able to lobby against climate policies and block efficient and needed action against climate change. In addition, investors might demand financial compensation, increasing the cost of climate policies and pushing the government to delay climate policies.

Given the overabundance of polluting capital of fossil fuel reserves and the potentially harmful effects of stranded assets, a natural question arises: why do investors keep financing carbon-intensive capital when most governments have already committed to limiting climate change to 1.5-2C° with the 2015 Paris Agreement? Indeed, as shown by Pfeiffer et al. (2018), investment in carbon-intensive capital is still positive even though the climate constraint has long been discovered. Batten et al. (2016) found that although the Paris Agreement positively impacted the valuation of renewable companies, it had no significant effect on carbon-emitting companies. A good example of this paradox is coal: although it is the most polluting carbon fuel, the installed capacity of coal-fueled electricity plants has constantly risen in previous years. Three potential factors can explain such a paradox.

The first would be that investors have not internalized governments' commitment to limit global warming or believe this commitment is not credible. However, this would be at odds with numerous studies that find that investors expect some kind of climate policy and have already priced in the risks associated with climate policies and global warming (Batten et al. 2016, Byrd & Cooperman 2018). Bolton & Kacperczyk (2019) finds that investors consider a carbon risk in the sense that they demand higher returns for higher CO_2 intensive firms, which indicates that they expect a climate policy in the future. Fried et al. (2019) also provides evidence that some large US firms use an internal carbon price to guide their investment decisions, indicating that they expect a more stringent climate policy in the future. Thus, even though firms doubt the timing of climate policies (or, equivalently, the actual size of the carbon budget), they expect some action against climate change will be taken in the future.

A second explanation could be that investors expect that technological innovations, such as carbon capture, will allow the retrofitting of carbon-intensive capital. In that sense, they expect that the irreversibility of polluting capital will not be binding and that it will be transformed into cleaner capital in the future (Byrd & Cooperman 2018, van der Ploeg & Rezai 2019). There is indeed evidence that the potential of carbon capture could limit the carbon intensity of some coal plants and other polluting capital (Fisch-Romito et al. 2020).

A last reason could be that investors expect to be compensated for their losses by governments. If investors expect governments to bail out stranded assets, investing in carbon-intensive infrastructures can be rational and profitable even though the climate constraint is already known. In this sense, the uncertainty about climate policy is deeply related to the political economy issues previously mentioned (van der Ploeg & Rezai 2019). Sen & von Schickfus (2019) provides some evidence of investors expecting a bailout in Germany, where the federal government announced a future ban on lignite coal plants. Their study found that the prices of coal-related firms weren't affected by the announcement of the ban but dropped only after a court ruled that any kind of compensation would be illegal.

This work is related to recent theoretical works that have shown the impact of a carbon tax on the level of stranded assets. Rozenberg et al. (2018) found that, in a Ramsey growth model with polluting and clean capital, a tradeoff exists for the social planner between intertemporal efficiency and the level of stranded assets. However, their study didn't take into account the anticipation of climate policy by investors and the potential commitment issues from the government: they assumed that once the climate constraint is discovered, there is an immediate and optimal carbon tax imposed. This is a potential issue as there has been a lot of debate about the impact of expectations of climate policy on current emissions. For example, Sinn (2012) showed that expectations about a future carbon tax could push carbon-intensive sectors to increase their use of carbon fuel in the short term to limit the amount of future carbon reserves under the ground. On the contrary, Fried et al. (2019) showed that if investors expect an efficient carbon tax to be imposed in the future, they will reduce their current investment in polluting infrastructures, and the cost of actually implementing the carbon tax will be smaller.

This model contributes to the debate by showing that this "Green paradox" versus "reversed Green paradox" depends on the ability of the government to commit to a clean climate policy. Suppose the government credibly announces that it will not bail out future stranded assets. In that case, our model suggests that emissions should decrease before the implementation of the policy, compared to the laissez-faire equilibrium, and the cost of imposing a carbon tax will be lower. Previous works also investigate the impact of investors' expectations on stranded assets but didn't account for some of the general equilibrium effects or the impact on the cost of climate policy that we investigate. van der Ploeg & Rezai (2018) and van der Ploeg & Rezai (2020) study the impact of policy uncertainty on investment in polluting capital in a model of the energy sector and found that polluting firms' profits were higher when the carbon tax was delayed or when a subsidy on clean capital was imposed instead. However, their model didn't account for general equilibrium effects and the impact of climate policy on output. Finally, in a larger sense, this work belongs to an older but large literature on investment under uncertainty and irreversible investment (Arrow & Kurz 1970, Abel 1983, Abel & Eberly 1993, Dixit et al. 1994, Dixit 1995).

This paper is structured in three parts. In the first part, we present and solve the model for the laissez-faire equilibrium and the planner's solution. In the second part, we study a decentralized equilibrium under an optimal carbon tax, a second-best subsidy on clean capital, and an optimal carbon tax associated with a bailout. In the third part, we study the stochastic equilibrium before a climate policy is imposed and when investors expect either an optimal carbon tax or a tax jointly with a bailout. We calibrate the model and present some numerical simulations.

1 A growth model with clean and polluting capital

In this section, we present the main model without policy uncertainty. It is a neoclassical model with two assets in discrete time, similar to Rozenberg et al. (2018). We first solve for the decentralized equilibrium under "laissez-faire", that is, without the climate constraint. We then solve the central planner's problem under the climate constraint.

1.1 Laissez-faire equilibrium

The economy comprises three sectors: a final goods producer, an intermediate clean producer, and an intermediate polluting sector. The representative household owns shares in the two clean and polluting firms.

Firms

Final goods producer. A final goods producer produces total output y_t using an intermediate good x_t and labor l, with the following aggregate production function

$$y_t = x_t^{\alpha} l^{1-\alpha}.$$

The intermediate good x_t is a composite of the clean and polluting intermediate goods x_t^c and x_t^p

$$x_t = \left(\left(x_t^c\right)^{\frac{\varepsilon-1}{\varepsilon}} + \left(x_t^p\right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

The first-order conditions of the final good producer determines the price of the intermediary goods

$$p_t^c = \alpha \left(\left(x_t^c\right)^{\frac{\varepsilon-1}{\varepsilon}} + \left(x_t^p\right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}\alpha-1} \left(x_t^c\right)^{\frac{-1}{\varepsilon}},$$
$$p_t^p = \alpha \left(\left(x_t^c\right)^{\frac{\varepsilon-1}{\varepsilon}} + \left(x_t^p\right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}\alpha-1} \left(x_t^p\right)^{\frac{-1}{\varepsilon}}.$$

Clean intermediate good. A clean intermediary firm owns the stock of clean capital and makes investment decisions to maximize its stock market value, subject to a linear production function

$$V(k_t^c) = \max_{k_{t+1}^c} \left\{ d_t^c + \frac{V(k_{t+1}^c)}{1+r_{t+1}^c} \right\} \quad \text{s.t.} \quad x_t^c = z^c k_t^c$$
$$d_t^c = p_t^c x_t^c - k_{t+1}^c + (1-\delta)k_t^c.$$

The first-order condition yields the usual equation for the productivity of capital

$$r_t^c = p_t^c z^c - \delta. \tag{1}$$

Polluting intermediate good. The polluting firm owns the stock of polluting capital and makes investment decisions but is also subject to an irreversibility constraint on investment to represent the difficulty of transforming polluting capital into clean capital, as in Arrow & Kurz (1970). We also allow the firm to use only part of its installed stock of capital $q_t^p \leq k_t^p$ to produce the intermediary good. We say that the economy has stranded assets if $q_t^p < k_t^p$.

$$V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1+r_{t+1}^p} \right\} \quad \text{s.t.} \quad x_t^p = z^p q_t^p$$
$$d_t^p = p_t^p x_t^p - k_{t+1}^p + (1-\delta)k_t^p$$
$$k_{t+1}^p \geq (1-\delta)k_t^p$$
$$k_t^p \geq q_t^p$$

The corresponding Lagrangian is

$$L = d_t^p + \frac{V(k_{t+1}^p)}{1 + r_{t+1}^p} + \psi_t(k_{t+1}^p - (1-\delta)k_t^p) + \nu_t(k_t^p - q_t^p).$$

This yields the following first-order conditions

$$\begin{aligned} 1 - \psi_t &= \frac{V'(k_{t+1}^p)}{1 + r_{t+1}^p}, \\ p_t^p z^p &= \nu_t. \end{aligned} \tag{2}$$

Along with the associated Karush-Kuhn-Tucker conditions

$$\nu_t(q_t^p - k_t^p) = 0, \quad \nu_t \geq 0, \tag{3}$$

$$\psi_t(k_{t+1}^p - (1-\delta)k_t^p) = 0, \quad \psi_t \geq 0. \tag{4}$$

The associated envelope condition is

$$V'(k_t^p) = -\psi_t(1-\delta) + \nu_t,$$

so that the investment decision of the polluting firm is determined by the following equation

$$(1 - \psi_t)(1 + r_{t+1}^p) = p_{t+1}^p z^p + (1 - \psi_{t+1})(1 - \delta). \tag{5}$$

Proposition 1. *In the laissez-faire equilibrium, assets are never stranded.*

Proof. Since the aggregate production function respects the Inada conditions, the marginal productivity of capital goes to infinity as x_t^p goes to 0 and thus, p_t^p will always be strictly positive. Equation 2 thus implies that the multiplier on the capacity constraint ν_t will be strictly positive. Equation 3 then implies that $q_t^p = k_t^p$, and the economy will not display stranded assets. □

The intuition behind this result is straightforward: there is no cost associated with using polluting capital, so it is always efficient to use all of the installed capacity. The investment decision is only based on the tradeoff between consuming today and consuming tomorrow, without taking into account emissions or the social cost of carbon.

Households

The economy is composed of a representative household that maximizes its expected discounted sum of utilities over an infinite horizon

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t u(c_t).$$

The household owns shares in the clean firm s_t^c, whose price is v_t^c, and the polluting firm s_t^p, with price v_t^p. The budget constraint is thus

$$c_t + v_t^c s_{t+1}^c + v_t^p s_{t+1}^p = s_t^c (v_t^c + d_t^c) + s_t^p (v_t^p + d_t^p).$$

The instantaneous utility function is a CRRA function of the form

$$u(c_t) = \frac{c_t^{\chi-1}}{\chi - 1}.$$

The following two Euler equations characterize the optimal consumption-saving decision of the household

$$v_t^c c_t^{-\chi} = \beta c_{t+1}^{-\chi} (d_{t+1}^c + v_{t+1}^c) \quad (6)$$

$$v_t^p c_t^{-\chi} = \beta c_{t+1}^{-\chi} (d_{t+1}^p + v_{t+1}^p) \quad (7)$$

Proposition 2. *In the laissez-faire equilibrium, assuming the absence of irreversibility costs, the marginal productivity of installed polluting capital is equal to the marginal productivity of clean capital.*

Proof. Let us first define the (stochastic) discount factor of the households as

$$1 + r_{t+1}^c = \frac{d_{t+1}^c + v_{t+1}^c}{v_t^c}, \quad 1 + r_{t+1}^p = \frac{d_{t+1}^p + v_{t+1}^p}{v_t^p}.$$

Equation 6 and 7 imply that

$$r_{t+1}^c = r_{t+1}^p.$$

If we substitute Equations 1 and 5 and assume that $\psi_{t+1} = \psi_t = 0$, we obtain

$$p_t^c z^c = p_t^p z^p.$$

□

The main conclusion of the laissez-faire equilibrium is that, in the absence of a carbon tax on the use of polluting capital, there are never stranded assets and the marginal productivity of polluting and clean capital will be equal. Assuming a higher marginal productivity of using fossil fuel, we will thus have a higher share of polluting capital in this economy.

1.2 Central planner's solution under a climate constraint

We now focus on the social planner's problem, taking into account the carbon constraint.

The climate constraint is represented by a carbon budget $m_t \leq \bar{m}$ where $\bar{m}$ represents the maximum level of cumulative emissions to limit global warming to 2°C. This is coherent with the literature on climate change that has shown that global warming is closely related to cumulative past emissions (Allen et al. 2009, Matthews 2016).

This allows us to model the complex carbon cycle through a simple law of motion of cumulative CO_2 emissions, represented by $m_{t+1} = e_t + (1 - \varepsilon)m_t$ with e_t being the emissions of CO_2 at each period and ε a coefficient measuring the dissipation rate of CO_2. In practice, ε is so small compared to the depreciation of capital δ that it is negligible in the short and medium term, but we take it into account to simplify some calculations. Finally, the use of q_t^p causes emissions at a rate G, which represents the carbon-intensity of polluting capital, so that $e_t = q_t^p G$.

The social planner maximizes the representative household's utility subject to the resource constraint of the economy, the law of motion of carbon emissions and of clean and polluting capital, the physical constraint on the use of polluting capital, the irreversibility constraint, and the carbon budget constraint. The problem of the social planner is thus

$$\max_{c_t; i_{t,p}, i_{t,c}} \sum_{t=0}^{\infty} \beta^t u(c_t) \quad \text{s.t.} \quad c_t + k^c_{t+1} + k^p_{t+1} = y_t + (1-\delta)(k^c_t + k^p_t)$$

$$y_t = \left(\left((x^c_t)^{\frac{\varepsilon-1}{\varepsilon}} + (x^p_t)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \right)^{\alpha}$$

$$x^c_t = z^c k^c_t, \quad x^p_t = z_p q^p_t$$

$$m_{t+1} = q^p_t G + (1-\varepsilon) m_t$$

$$k^p_t \geq q^p_t$$

$$k^p_{t+1} \geq (1-\delta) k^p_t$$

$$\bar{m} \geq m_t$$

The associated Bellman equation of the problem is

$$\begin{aligned} V_t(k^c_t, k^p_t, m_t) = \max_{k^c_{t+1}, k^p_{t+1}, q^p_t} & \left\{ u(c_t) + \beta V_{t+1}(k^c_{t+1}, k^p_{t+1}, m_{t+1}) \right\} \\ & + \psi_t (k^p_{t+1} - (1-\delta) k^p_t) \\ & + \nu_t (k^p_t - q^p_t) \\ & + \mu_t (m_{t+1} - G q^p_t - (1-\varepsilon) m_t) \\ & + \phi_t (\bar{m} - m_t) \end{aligned}$$

The first-order conditions are

$$u'(c_t) = \beta \frac{\partial V_{t+1}(k^c_t, k^p_t)}{\partial k^c_{t+1}}$$

$$u'(c_t) = \beta \frac{\partial V_{t+1}(k^c_t, k^p_t)}{\partial k^p_{t+1}} + \psi_t$$

$$\nu_t = u'(c_t) \frac{\partial y(k^c_t, q^p_t)}{\partial q^p_t} - G\mu_t \tag{8}$$

$$-\mu_t = \beta \frac{\partial V_{t+1}(k^c_t, k^p_t)}{\partial m_{t+1}}. \tag{9}$$

and the Karush-Kuhn-Tucker conditions are

$$
\begin{aligned}
\psi_t(k^p_{t+1} - (1-\delta)k^p_t) &= 0, \quad \psi_t \geq 0 \\
\nu_t(k^p_t - q^p_t) &= 0, \quad \nu_t \geq 0 \\
\phi_t(\bar{m} - m_t) &= 0, \quad \phi_t \geq 0
\end{aligned}
$$

The envelope conditions are

$$
\begin{aligned}
\frac{\partial V_t(k^c_t, k^p_t, m_t)}{\partial k^c_t} &= u'(c_t)\left(\frac{\partial y(k^c_t, q^p_t)}{\partial k^c_t} + 1 - \delta\right) \\
\frac{\partial V_t(k^c_t, k^p_t, m_t)}{\partial k^p_t} &= u'(c_t)(1-\delta) - (1-\delta)\psi_t + \nu_t \\
\frac{\partial V_t(k^c_t, k^p_t, m_t)}{\partial m_t} &= -(1-\varepsilon)\mu_t - \phi_t
\end{aligned}
$$

Substituting the envelope conditions inside the first-order conditions, we find

$$
u'(c_t) = \beta u'(c_{t+1})\left(\frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial k^c_{t+1}} + 1 - \delta\right) \tag{10}
$$

$$
u'(c_t) = \beta u'(c_{t+1})\left(\frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial q^p_{t+1}} + 1 - \delta - G\frac{\mu_{t+1}}{u'(c_{t+1})} - \ell_{t+1}\right) \tag{11}
$$

$$
\mu_{t+1} = \frac{1}{1-\varepsilon}\left(\frac{\mu_t}{\beta} - \phi_{t+1}\right) \tag{12}
$$

with $\ell_{t+1} = \frac{\beta(1-\delta)\psi_{t+1} - \psi_t}{\beta u'(c_{t+1})}$ being the legacy costs associated with the excess of polluting capital that cannot be disinvested.

Proposition 3. *The economy features stranded assets if*

$$
\frac{\partial y(k^c_t, k^p_t)}{\partial q^p_t} < G\mu_t.
$$

Proof. The optimal choice of q^p_t is determined by Equation 8. Let us assume that $q^p_t = k^p_t$. If the marginal productivity of polluting capital when using all of the installed capital $\frac{\partial y(k^c_t, k^p_t)}{\partial q^p_t}$ is below the marginal value of an extra unit of CO_2 $G\mu_t$. Then since $\nu_t \geq 0$ by construction, $q^p_t < k^p_t$ for equation 8 to hold. □

Equations 10 and 11 also state no-arbitrage conditions between the clean and polluting capital, but taking into account the social cost of carbon. The planner will thus invest in types of both capitals until their discounted marginal value is equal to the marginal value of consuming today. If the level of polluting capital is too high, the planner cannot adjust it instantaneously, and it will bear the cost ψ_t.

Proposition 4. *The social cost of carbon μ_t will increase at the rate $1/(\beta(1-\varepsilon))$ as long as $m_t < \bar{m}$.*

Proof. The first-order condition, jointly with the envelope condition, imply that $\mu_{t+1} = \frac{1}{1-\varepsilon}\left(\frac{\mu_t}{\beta} - \phi_{t+1}\right)$, and the Karush-Kuhn-Tucker condition implies that $\phi_t = 0$ when $m_t < \bar{m}$. □

This result comes from the fact that, in this model, carbon emissions do not provoke any direct damage but can be considered as an almost finite resource. Thus, we can interpret this result as a modified Hotelling rule, which states that the scarcity rent of a non-renewable resource will grow at the rate of the discount rate. Here, carbon emissions are a (almost non) renewable resource, and this rate is modified to take into account the dispersion rate ε. Note that when we have $\varepsilon = 0$, we get the usual Hotelling rule in discrete time.

Proposition 5. *When the economy features stranded assets at t, the irreversibility constraint was binding at $t-1$, and there was no investment in polluting capital.*

Proof. From Proposition 3, we know that if the economy features stranded assets, we have

$$\frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial q^p_{t+1}} = G\frac{\mu_{t+1}}{u'(c_{t+1})}.$$

Thus, the relative level of used polluting capital and clean capital is

$$\begin{aligned}\frac{\partial y(k^c_{t+1}, q^p_t)}{\partial k^p_{t+1}} &= \frac{\partial y(k^c_{t+1}, q^p_t)}{\partial q^p_{t+1}} - G\frac{\mu_{t+1}}{u'(c_{t+1})} - \ell_{t+1} \\ &= -\ell_{t+1}\end{aligned}$$

Because of the Inada conditions, we know that $\frac{\partial y(k^c_{t+1}, q^p_t)}{\partial k^p_{t+1}} > 0$ when the level of capital is finite. Thus, we have $\psi_t - \beta(1-\delta)\psi_{t+1} > 0 \rightarrow \psi_t > 0$ which implies that $i_{t,p} = 0$ by the Karush-Kuhn-Tucker conditions. □

The intuition behind this result is straightforward: if the planner uses an amount of polluting capital inferior to the installed capacity $q^p_{t+1} < k^p_{t+1}$, it means that there is too much polluting and the planner was constrained when it made the investment decision.

Proposition 6. *The steady-state equilibrium of the constrained economy is defined as*

$$
\begin{aligned}
m_{ss} &= \bar{m} \\
q_{ss,p} = k_{ss,p} &= \frac{\bar{m}\varepsilon}{G} \\
i_{ss,c} &= \delta k_{ss,c} \\
i_{ss,p} &= \delta k_{ss,p} > 0 \\
\psi_{ss} &= 0 \\
\frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial k^c_{t+1}} &= \frac{\partial y(k^c_{t+1}, q^p_{t+1})}{\partial k^p_{t+1}} - G\frac{\mu_{t+1}}{u'(c_{t+1})}
\end{aligned}
$$

Proof. See appendix. □

Note that, in practice, ε is very small, and the amount of polluting capital will be close to zero. This steady state is thus equivalent to a fully decarbonized economy.

To sum up what we have learned so far, the main result from this section is an insight already shown by Rozenberg et al. (2018): in the presence of an excessive amount of polluting capital and irreversible investment, it can be the most efficient solution to have stranded assets. This result comes from the fact that, contrary to the investment decision which is by essence intertemporal, the level of polluting capital used is an intra-temporal decision. Using the entire stock of installed polluting capital would be falling prey to a sunk-cost fallacy: the central planner might wish it had invested less in polluting capital in the past, but it is optimal, today, to "strand" some of those assets. However, this decision is costly from the point of view of production: lowering q^p_t reduces production and, hence, consumption in the short run. Moreover, when the economy transitions from the laissez-faire equilibrium to the constrained equilibrium, if the level of polluting capital is too high, it will feature a phase with stranded assets and zero investment in polluting capital.

2 Three types of decentralized equilibriums

In this section, we compare three ways to meet the climate constraint in a decentralized equilibrium. We focus on an optimal carbon tax, a subsidy on clean capital, and an optimal carbon tax with compensation for owners of stranded assets.

2.1 Decentralized equilibrium with a tax

We now show that we can decentralize the previous allocation through a carbon tax τ_t. The problems of the household, the final representative firm, and the clean intermediary firm remain similar as in the 'laissez-faire' equilibrium. The dividends of the polluting firm, however, become

$$d_t^p = p_t^p z^p q_t^p - k_{t+1}^p + (1-\delta)k_t^p - q_t^p G \tau_t$$

where τ_t is the carbon tax per ton of CO_2. We assume that the proceeds from the tax are redistributed through a lump-sum transfer to the households. The problem of the polluting firm is now

$$V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1+r_{t+1}^p} \right\} \quad \text{s.t.} \quad \begin{aligned} x_t^p &= z^p q_t^p \\ d_t^p &= p_t^p x_t^p - k_{t+1}^p + (1-\delta)k_t^p - q_t^p \tau_t \\ k_{t+1}^p &\geq (1-\delta)k_t^p \\ k_t^p &\geq q_t^p \end{aligned}$$

which yields the following first-order conditions

$$
\begin{aligned}
1 - \psi_t &= \frac{V'(k^p_{t+1})}{1 + r^p_{t+1}}, \\
p^p_t z^p - G\tau_t &= \nu_t.
\end{aligned}
\tag{13}
$$

The envelope condition is

$$V'(k^p_t) = \nu_t - (1-\delta)(1-\psi_t).$$

Substituting, we get

$$(1 + r^p_{t+1})(1-\psi_t) = p^p_t z^p - G\tau_t - (1-\psi_{t+1})(1-\delta)$$

Proposition 7. *The decentralized equilibrium with a carbon tax is equivalent to the social planner's allocation if* $\tau_t = \frac{\mu_t}{u'(c_t)}$ *until* $m_t = \bar{m}$.

Proof. Note that $p^p_t z^p = \frac{\partial y(k^p_t, q^p_t)}{\partial q^p_t}$. When $\tau_t = \frac{\mu_t}{u'(c_t)}$, we thus have

$$p^p_t z^p - G\tau_t = \frac{\partial y(k^p_t, q^p_t)}{\partial q^p_t} - G\frac{\mu_t}{u'(c_t)} = \nu_t$$

which is the same condition as 11. □

Thus, just as in the central planner problem, we will have stranded assets when

$$\frac{\partial y(k^p_t, k^p_t)}{\partial q^p_t} < G\tau_t.$$

2.2 Decentralized equilibrium with a subsidy on clean capital

We now show that we can obtain the same relative allocation of clean and polluting capital using a subsidy σ^c_t on clean capital.

The problem of the clean firm now becomes

$$V(k_t^c) = \max_{k_{t+1}^c} \left\{ d_t^c + \frac{V(k_{t+1}^c)}{1 + r_{t+1}^c} \right\} \quad \text{s.t.} \quad x_t^c = z^c k_t^c$$

$$d_t^c = p_t^c x_t^c - k_{t+1}^c + (1-\delta)k_t^c + \sigma_t^c k_t^c.$$

The first-order condition of the clean firm now becomes

$$1 + r_{t+1}^c = p_{t+1}^c z^c + \sigma_{t+1}^c + 1 - \delta.$$

Using the Euler equations from the household, we thus have

$$\frac{\partial y(k_{t+1}^c, q_{t+1,p})}{\partial y_{t+1}^c} + \sigma_{t+1}^c = \frac{\partial f(k_{t+1}^c, q_{t+1,p})}{\partial q_{t+1,p}} - \ell_{t+1}$$

which is the same relative allocation of clean and polluting capital if the clean capital subsidy is set to the level of the social cost of carbon adjusted for the carbon intensity of the polluting capital $\sigma_{t+1} = \frac{\mu_{t+1} G}{u'(c_t)}$.

However, the main difference between the decentralized economy with a subsidy and the decentralized economy with a carbon tax is that, in the first case, there can be no stranded assets as the government has no 'punitive' tool to limit the use of polluting capital in the short run. The economy will thus use all of the installed capacity at each period. This, in turn, implies that this allocation is feasible only if the level of installed capital is small enough so that the total level of emissions when using the whole capital stock until its total depreciation will be inferior to the remaining carbon budget.

This result is important because, according to recent studies on committed emissions, the level of polluting capital today already exceeds the remaining carbon budget (Pfeiffer et al. 2016, 2018). A carbon tax will thus be necessary to limit global warming to 2°C or less.

We summarize and prove those facts in the two following propositions.

Proposition 8. *In the decentralized equilibrium with a clean capital subsidy, the economy will never feature stranded assets.*

Proposition 9. *The climate constraint can be met with a subsidy on clean capital only if*

$$\bar{m} \geq \frac{k_0 G}{\delta} + m_0.$$

Proof. See appendix. □

2.3 Constrained equilibrium with compensation

We now want to account for the main controversial point behind stranded assets: the compensation of owners of polluting capital. Thus, we assume that the government implements an optimal carbon tax τ_t similar to the first decentralized economy, but also want to compensate owners of polluting capital for their losses through a subsidy σ_t^p.

The problem of the polluting firm now becomes

$$V(k_t^p) = \max_{q_t^p, k_{t+1}^p} \left\{ d_t^p + \frac{V(k_{t+1}^p)}{1 + r_{t+1}^p} \right\} \quad \text{s.t.} \quad \begin{aligned} x_t^p &= z^p q_t^p \\ d_t^p &= p_t^p x_t^p - k_{t+1}^p + (1-\delta)k_t^p - q_t^p \tau_t + \sigma_t^p k_t^p \\ k_{t+1}^p &\geq (1-\delta)k_t^p \\ k_t^p &\geq q_t^p \end{aligned}$$

It is important to note that the firm pays a tax on the amount of polluting capital that it uses but gets a subsidy on the level of capital that it owns. This setup corresponds to the incentive structure set up by the German government regarding its lignite coal industry and described by Sen & von Schickfus (2019). The German government planned to pay the lignite industry to keep some power plants off the electricity grid while implementing a higher carbon tax on electricity producers.

The first-order conditions are

$$p_t^c z_p - \tau_t = \nu_t,$$
$$(1 + r_{t+1}^p)(1 - \psi_t) = \nu_{t+1} + \sigma_{t+1}^p + (1 - \psi_{t+1})(1 - \delta).$$

Proposition 10. *The emission path in the constrained equilibrium with compensation will follow the same path as in the benchmark case if* $\tau_t = \frac{\mu_t}{u'(c_t)}$.

Proposition 11. *In the constrained equilibrium with compensation, the optimal level of polluting capital k_t^p can be above the actual use level of polluting capital q_t^p.*

Proof. Assume we have stranded assets so that $\nu_t = 0$. We can rewrite the Euler equation of the polluting firm as

$$\frac{\partial f(k_t^c, q_t^p)}{\partial q_t^p} = \sigma_t - \ell_t > 0$$

using equation 2.3. We see that if $\sigma_t > 0$, then ℓ_t can take any value such that $\ell_t < \sigma_t$, including $\ell_t = 0$, and the Inada conditions will still be met. Thus, this economy can feature stranded assets while the irreversibility condition is not binding if σ_t is large enough. □

In this economy, we can thus have no legacy costs $\ell_{t+1} = 0$ and still stranded assets, which means that the existence of stranded assets doesn't necessarily imply that the stock of polluting capital will decrease and converge to $q_t^p = k_t^p$. The government can thus adjust σ_t so that the irreversibility constraint is never binding and that the representative entrepreneur will never have to bear the legacy cost due to its excessive investment in polluting capital.

3 Stochastic transition with tax and compensation

We now introduce uncertainty in the model. We assume the economy is in the laissez-faire equilibrium without tax or subsidy. At each period, there is a probability ρ to transit to a new state, called 2, where the government imposes an optimal carbon tax τ that might create stranded assets, as in the benchmark case. With probability η, the economy moves to another state, called 3, where the government imposes a carbon tax but compensates the owner of polluting capital at a rate σ. With probability $1 - \rho - \eta$, the economy remains in the stochastic state in state 1. We assume the government is credible because there is no probability of moving to another state once a policy is imposed. We can summarize the probability space as such

This model thus features two kinds of uncertainty: one related to the timing of the policy (i.e. when the uncertainty will be resolved), and one related to the political preferences of

State	1	2	3
1	$1-\rho-\eta$	ρ	η
2	0	1	0
3	0	0	1

Table 1: State-dependent probabilities

the government regarding the potential bailout of owners of polluting capital (i.e. whether the economy transit to state 2 or state 3.

Households

The problem of the households now write

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbb{E}[u(c_t)]$$

subject to

$$c_t + v_t^c s_{t+1}^c + v_t^p s_{t+1}^p = s_t^c(v_t^c + d_t^c) + s_t^p(v_t^p + d_t^p).$$

The associated Euler equations are

$$v_t^c c_t^{-\chi} = \beta \mathbb{E}[c_{t+1}^{-\chi}(d_{t+1}^c + v_{t+1}^c)], \tag{14}$$

$$v_t^p c_t^{-\chi} = \beta \mathbb{E}[c_{t+1}^{-\chi}(d_{t+1}^p + v_{t+1}^p)]. \tag{15}$$

Firms

The problem of the firms now takes into account the policy uncertainty. For simplicity, we mention only the first-order conditions of the optimal decisions of the polluting firm

$$(1-\psi_t)(1+r_{t+1}^p) = \mathbb{E}[p_{t+1}^p z^p - \psi_{t+1}(1-\delta)].$$

Proposition 12. *During the transition period, the economy never features stranded assets.*

Proof. Same as the proof for the laissez-faire equilibrium. □

In this stochastic equilibrium, the level of polluting capital and of CO_2 emissions will thus depend on the relative size of τ_t, σ_t, η and ρ. If investors expect a large bailout in the future, emissions can increase compared to the laissez-faire equilibrium and the discovery of the climate constraint can thus be coherent with a temporary increase in emissions. We further discuss the implications of this model in the next part.

3.1 Computational algorithm

Although our model is stylized, it's important to note that it is still challenging to solve. It is a highly non-linear two-asset model with four state variables (polluting and clean capital, carbon stock in the atmosphere, and the policy state), three occasionally binding constraints, and permanent shocks. We first simplify the model by assuming that taxes and subsidies are constant, and not implied by an optimal policy function derived from the carbon budget. This strong assumption allows us to get rid of a state variable and might be relaxed in further work.

We then use a modified version of Rendahl (2016) time iteration algorithm with an occasionally binding constraint. This global approximation method allows us to take into account all the non-linearities of the model and the risk implied by the policy shocks. We then compute policy announcements as MIT shocks on the probabilities to go to different climate policies. This means that households are rational with respect to a future climate policy, but they are unaware that the *probabilities themselves* of going to a different policy state might change over time.

3.2 Calibration

Our calibration follows the work of Fried et al. (2019) on US data.

To determine the share of clean and polluting capital z^p and z^c, we follow the computations of Fried et al. (2019) and set $z^p = 3$ and $z^c = 1$. This calibration reflects two main factors: it follows the capital share of the oil and coal sector in the US, to which we add the more carbon-intensive capital from other less polluting sectors, such as cars, heating systems, etc. However, it should be noted that this distinction between clean and polluting capital is mostly theoretical as, in practice, no infrastructure exists without associated carbon emissions in a life-cycle analysis.

ρ is set to 0.15 as in Fried et al. (2019), who estimate this parameter using data from internal carbon prices in large US firms. Due to a lack of data about investors' expectations of a global bailout, η is set to 0.05.

Parameters	Calibration
Household	
Discount rate: β	0.95
CRRA coefficient: χ	2
Production function	
Capital share: α	1/3
Polluting capital efficiency: z^p	3
Polluting capital share: z^c	1
Depreciation rate: δ	0.05
Policy	
Probability of carbon tax: ρ	0.10
Probability of compensation: η	0.05
Size of carbon tax: τ	0.2
Size of compensation: σ_0	0.1

Table 2: Calibration of the parameters of the model

3.3 Simulations

In this section, we study how the economy reacts to (1.) a climate policy shock, depending on the prior expectations of households and firms, and (2.) a shock on the expectations of households and firms regarding the future climate policy.

3.3.1 Climate policy shocks

Figures 3 and 5 show the impact of imposing a carbon tax, without a bailout, when coming from a state where investors expected only a carbon tax (Figure 3), or also a bailout (Figure 5).

Given our calibration, we see that if investors expect a carbon tax in the future, the transition can avoid stranded assets and the irreversibility of capital is binding for only a few periods, and the output cost is 18%. If investors expected instead a bailout of stranded assets, the stock of polluting capital needs to adjust by 80%, and output diminishes by 20% compared to the initial steady state. Expectations about the type of future climate policy can thus have a large impact on the cost of implementing a carbon tax.

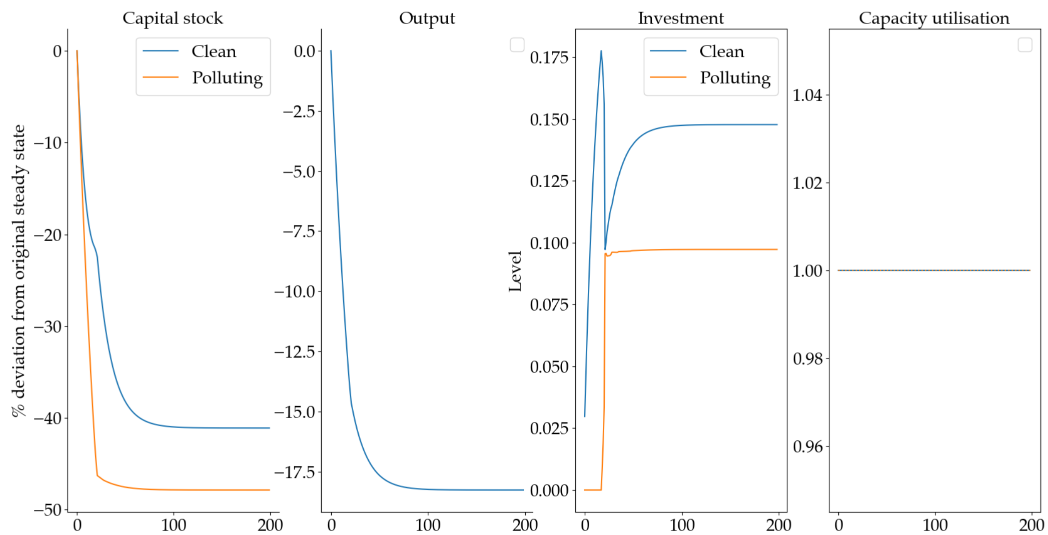

Figure 3: Impact of imposing a carbon tax without subsidy when investors expect only a carbon tax

The transition in a world where firms expected a bailout of polluting capital also features stranded assets and a longer investment period in which the irreversibility constraint on polluting capital is binding. Expectations of a bailout thus make not only the transition costlier but also longer to achieve. This, in turn, has a large impact on the financial valuations of firms. The dashed-line line Figure 4 display the % change in the average Tobin's Q of the polluting firm in the transition, after a carbon tax is imposed, when firms expected a bailout. The model predicts that the valuations of polluting firms will overreact to the implementation of the carbon tax, with the average Tobin's Q collapsing by almost 80%. This is due to the fact that, for the first initial periods of the transition where assets are stranded, a large part of the stock of physical capital is useless, decreasing the profitability and hence the valuation of the firm. This over-reaction of the price of firms is corrected over the long term, as the stock of physical capital adjusts and the capacity utilization rate

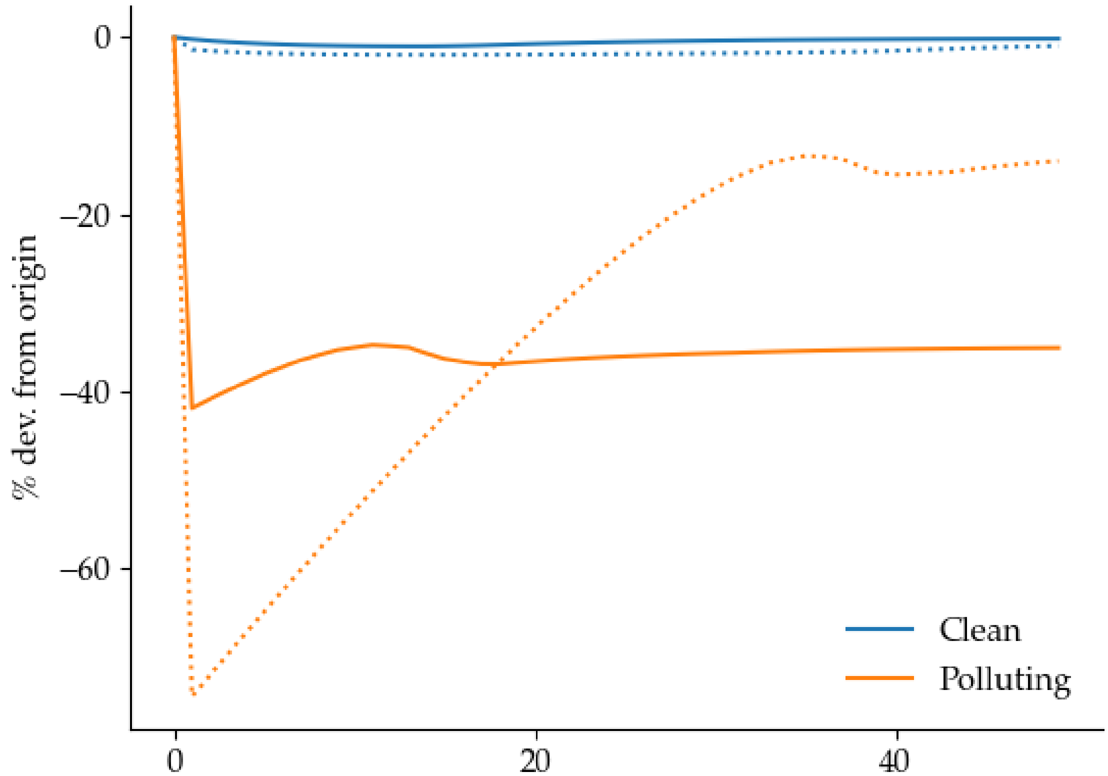

Figure 4: Tobin's Q following a carbon tax without a bailout

Note: The thick lines show the average Tobin's Q, measured as the price of the firm divided by its quantity of physical capital, after a carbon tax is imposed by the government, when investors expected only a carbon tax. The dashed-line shows the evolution of the average Tobin's Q if investors expected a bailout instead.

increases again.

In our model, this over-reaction of the valuations of firms does not have a feedback effect on output, investment, or consumption, since there is no financial friction that could connect the financial sphere to the real sphere. However, we can conjecture that, in a model with a financial accelerator à la Bernanke et al. (1996), this would trigger a large decrease in loans, decreasing aggregate demand, and hence output.

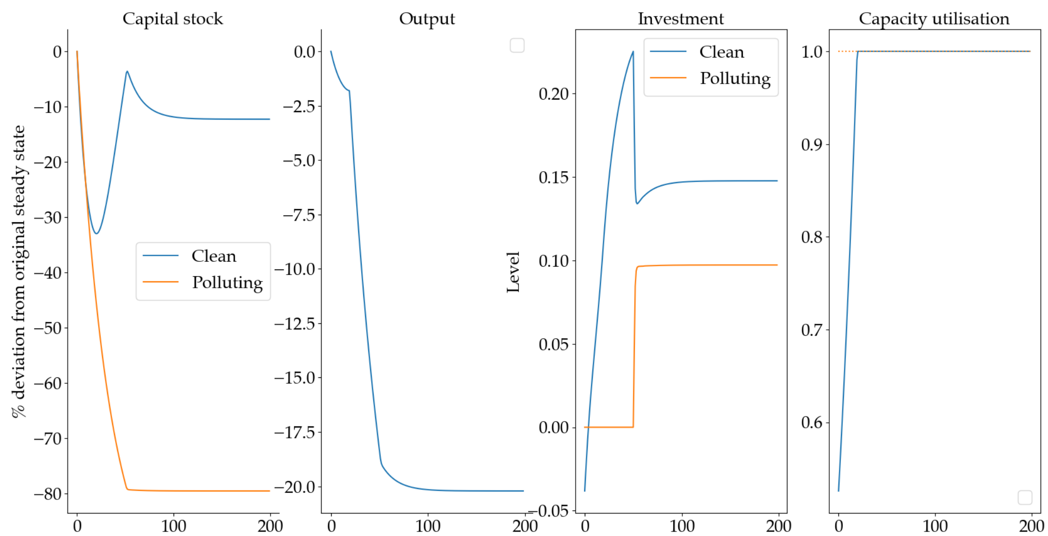

Figure 5: Impact of imposing a carbon tax without subsidy when investors expect a bailout of polluting capital

3.3.2 Shocks to the expectations about future climate policy

We now turn to the impact of a government committing to a future climate policy. Figures 6 and 7 show the impact of a government committing to a carbon tax in the future (Figure 6) or a bailout (Figure 7), without actually implementing it. Numerically, this implies computing a MIT shock where the economy moves from a state where there is a positive probability of a future bailout ($\rho > 0$ and $\eta = 0$) to one where there is no probability of a future bailout ($\rho = 0$ and $\eta > 0$).

We see that committing to a carbon tax (i.e., excluding a bailout) increases the stock of clean capital and decreases the stock of polluting capital. Output is reduced by 17%, but assets are never stranded, which is coherent with our previous propositions. Thus, some of the cost of transitioning to a clean economy is paid today, but the cost of a transition will be lower in the future, as shown by the previous figures.

At the opposite, committing to a bailout of polluting capital creates an investment boom in polluting capital that increases output by almost 20% compared to a state where firms expected no bailout, at the cost of a longer transition once a carbon tax is imposed (Figure 7).

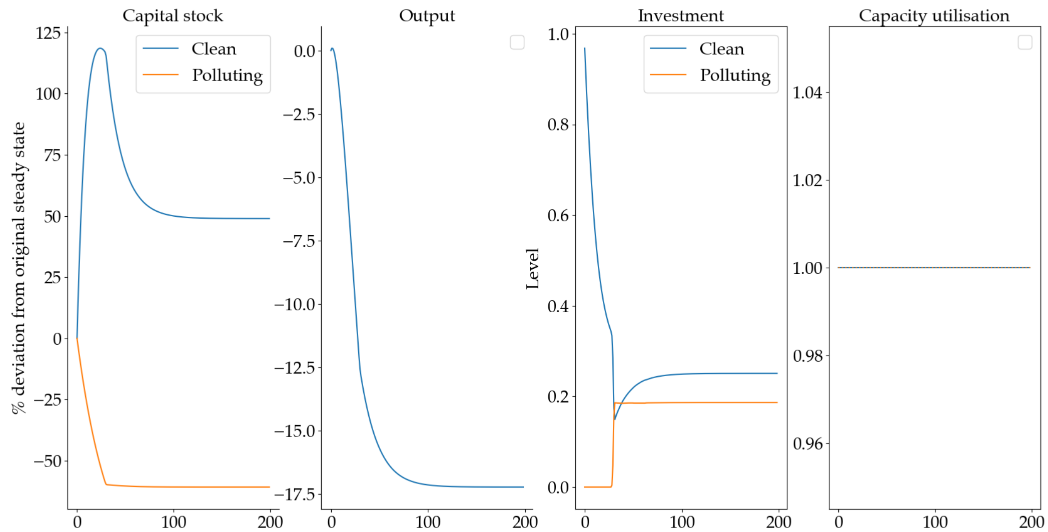

Figure 6: Impact of a government committing to a carbon tax in the future

Those policy commitments are enough to create large changes in the valuations of both the clean and the polluting firms, as shown in Figure 8. This is coherent with the empirical findings from Sen & von Schickfus (2019), which we mentioned earlier, that the price of polluting firms might react a lot to changes in expected climate policies, such as committing to never bailing them out.

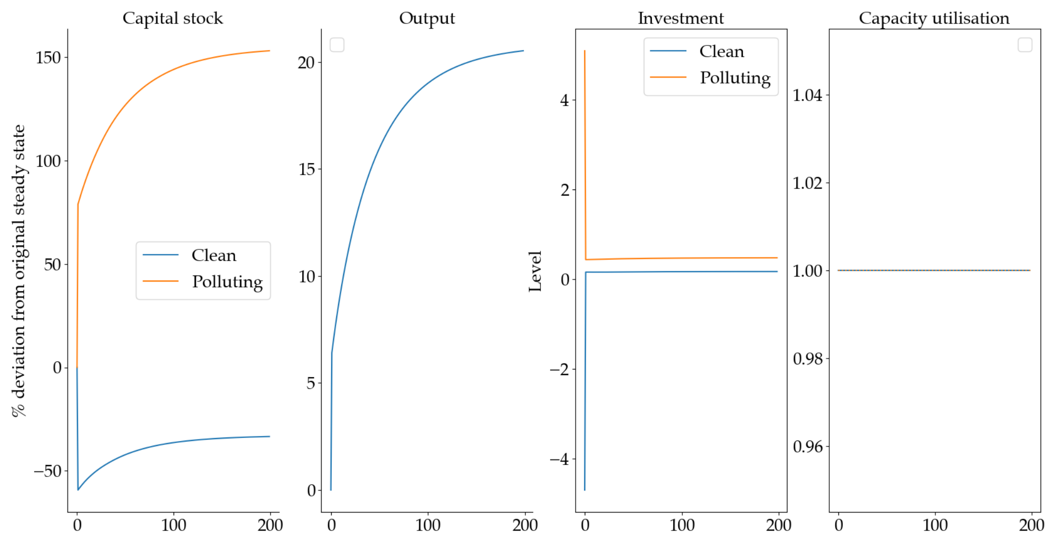

Figure 7: Impact of a government committing to a bailout in the future

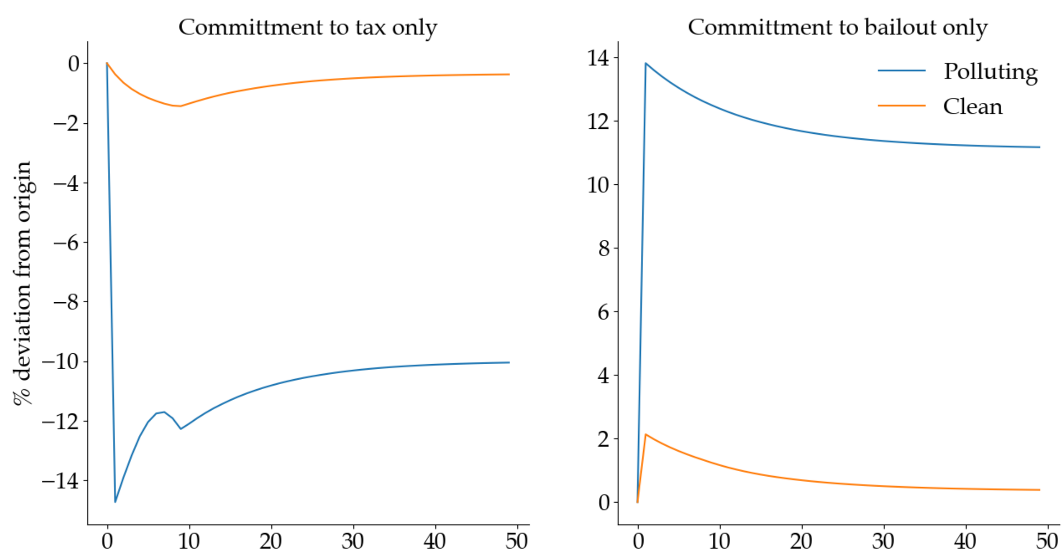

Figure 8: Average Tobin's Q of the clean and polluting firms after committing to a carbon tax or a bailout

4 Conclusion

Our model shows that investment in polluting capital and CO_2 emissions can increase even after the climate constraint has been discovered, if investors expect that a carbon tax will be accompanied by a bailout. This behavior can have an important impact on the cost of implementing a carbon tax or the length of the energetic transition. This reveals the essential role of announcing a credible climate policy for the government: committing not to bail out future stranded assets will reduce the current level of polluting capital and make the transition toward a green economy less painful. However, there is also an incentive for a shortsighted government to increase current production and consumption by announcing a future bailout of stranded assets, which would significantly increase the cost of the transition and decrease the remaining carbon budget. This difficult choice of committing to a "hard" transition is necessary: another conclusion of our model is that it is too late for a strictly "non-punitive" climate policy. Given that the committed emissions implied by the current size of polluting capital already exceeds the remaining carbon budget, a subsidy on clean capital will not be enough to meet a 2°C global warming target.

Our analysis could be further developed in several ways. First, the transition between the stochastic state and the state with a carbon tax could be analyzed further, showing how wrong expectations by investors could increase the level of stranded assets in the future period. Secondly, we could include the financial aspect of stranded assets and some game-theoretical components. In our model, there is no benefit for society of a bailout. In practice, bailing out polluting capital could be a way to limit the financial risks associated with a stringent climate policy. There could thus be a space for strategic interactions between the government and "too-big-to-fail" owners of polluting capital, that could force a bailout by continuing to invest in polluting capital and putting their solvency at risk in case of a high carbon tax. Finally, our model could be enriched by including uncertainty about the future productivity of clean capital and some “learning by doing” effects.

References

Abel, A. B. (1983), 'Optimal investment under uncertainty', *The American Economic Review* **73**(1), 228.

Abel, A. B. & Eberly, J. C. (1993), A unified model of investment under uncertainty, Technical report, National Bureau of Economic Research.

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. & Meinshausen, N. (2009), 'Warming caused by cumulative carbon emissions towards the trillionth tonne', *Nature* **458**(7242), 1163–1166.

Andersson, M. & Baccianti, C. (2020), 'Climate change and the macro economy', *ECB Occasional Paper* (2020243).

Arrow, K. J. & Kurz, M. (1970), 'Optimal Growth with Irreversible Investment in a Ramsey Model', *Econometrica* **38**(2), 331–344.

Batten, S. (2018), 'Climate change and the macro-economy: A critical review'.

Batten, S., Sowerbutts, R. & Tanaka, M. (2016), 'Let's talk about the weather: The impact of climate change on central banks'.

Bernanke, B., Gertler, M. & Gilchrist, S. (1996), 'The Financial Accelerator and the Flight to Quality', p. 16.

Bolton, P. & Kacperczyk, M. T. (2019), 'Do Investors Care about Carbon Risk', *Available at SSRN 3398441* .

Byrd, J. & Cooperman, E. S. (2018), 'Investors and stranded asset risk: Evidence from shareholder responses to carbon capture and sequestration (CCS) events', *Journal of Sustainable Finance & Investment* **8**(2), 185–202.

Carney, M. (2016), 'Resolving the climate paradox'.

Davis, S. J. & Socolow, R. H. (2014), 'Commitment accounting of CO 2 emissions', *Environmental Research Letters* **9**(8), 084018.

Dixit, A. (1995), 'Irreversible investment with uncertainty and scale economies', *Journal of Economic Dynamics and Control* **19**(1), 327–350.

Dixit, A. K., Dixit, R. K. & Pindyck, R. S. (1994), *Investment Under Uncertainty*, Princeton University Press.

ECB (2019), *Financial Stability Review (May)*.

Fisch-Romito, V., Guivarch, C., Creutzig, F., Minx, J. C. & Callaghan, M. W. (2020), 'Systematic map of the literature on carbon lock-in induced by long-lived capital', *Environmental Research Letters* .

Fried, S., Novan, K. & Peterman, W. (2019), 'The Macro Effects of Anticipating Climate Policy'.

Lucia, A., Ossola, E. & Panzica, R. (2019), 'The Greenium Matters: Evidence on the Pricing of Climate Risk', *University of Milan Bicocca Department of Economics, Management and Statistics Working Paper* (418).

Matthews, H. D. (2016), 'Quantifying historical carbon and climate debts among nations', *Nature Climate Change* **6**(1), 60–64.

McGlade, C. & Ekins, P. (2015), 'The geographical distribution of fossil fuels unused when limiting global warming to 2 °C', *Nature* **517**(7533), 187–190.

Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. (2018), 'Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement', *Environmental Research Letters* **13**(5), 054019.

Pfeiffer, A., Millar, R., Hepburn, C. & Beinhocker, E. (2016), 'The '2 C capital stock'for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy', *Applied Energy* **179**, 1395–1408.

Rendahl, P. (2016), 'Fiscal Policy in an Unemployment Crisis', *The Review of Economic Studies* **83**(3), 1189–1224.

Rozenberg, J., Vogt-Schilb, A. & Hallegatte, S. (2018), 'Instrument choice and stranded assets in the transition to clean capital', *Journal of Environmental Economics and Management* **7**(1), 99–113.

Sen, S. & von Schickfus, M.-T. (2019), 'Climate policy, stranded assets, and investors' expectations', *Journal of Environmental Economics and Management* p. 102277.

Sinn, H.-W. (2012), *The Green Paradox: A Supply-Side Approach to Global Warming*, MIT press.

van der Ploeg, F. & Rezai, A. (2018), *Climate Policy and Stranded Carbon Assets: A Financial Perspective*, OxCarre.

van der Ploeg, F. & Rezai, A. (2019), 'Simple rules for climate policy and integrated assessment', *Environmental and resource economics* **72**(1), 77–108.

van der Ploeg, F. & Rezai, A. (2020), 'The risk of policy tipping and stranded carbon assets', *Journal of Environmental Economics and Management* **100**, 102258.