Emission caps and investment in green technologies

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Abstract:

We study the interaction between firms, which can invest in green technologies, and government, which can impose emission caps but has limited commitment power. Investment in green technologies generates innovation spillovers, reducing the cost of further investments. Spillovers generate strategic complementarities between firms and government, and equilibrium multiplicity. In a "green equilibrium", firms, anticipating caps, invest a lot in green technologies, which reduces the cost of further investment, making the government willing to cap emissions. In a "brown equilibrium", firms anticipating no caps invest only a little, so green technologies remain costly and the government gives up on emission caps.

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1 Introduction

To mitigate global warming, firms should reduce CO2 emissions. But CO2 emissions are externalities, which profit maximizing firms don't internalize. This calls for public intervention, such as carbon taxes and emission caps. Yet, if the government lacks political clout, it may not be in a position to implement such policies. To shed light on these issues, we offer a model of the interaction between firms' investments in green technologies and government's emission reduction policies. Our model takes on board the important stylized facts discussed below.[1]

The first important stylized fact incorporated in our model is that investments in green technologies bring about innovation, reducing the cost of further investments. Such spillovers in green technoogies have been documented by numerous empirical studies, see, e.g., Popp (2002), Aghion et al. (2016), Elia et al. (2021), Grafström and Lindman (2017), Zhou and Gu (2019). For example, Aghion et al. (2016), write (on page 3):

> "a firm's direction of innovation is affected by local knowledge spillovers. We measure this with the geographical location... a firm is more likely to innovate in clean technologies if its inventors are located in countries where other firms have been undertaking more clean innovation."

Similarly, Samadi (2016) writes, on the second page of his survey:

> "A large volume of empirical research indicates that specific costs decrease as the experience gained from the production and use of a particular technology increases. Initially, such learning was investigated at the the individual firm level but similar observations were

[1] Further empirical motivation for the assumptions of our model is provided in Section 2.

made at the industry level. These industry-level observations suggest that a significant share of the knowledge gained by individual companies and their customers through experience can ultimately be appropriated by other companies and customers (i.e. the spillover effect)."

Moreover, spillover effects are stronger for green technologies than for brown technologies, as found by Dechezleprêtre, Martin, and Mohnen (2017).[2] The interpretation offered by Dechezleprêtre, Martin, and Mohnen (2017) is that green innovations are more radical while brown innovations are more incremental. The magnitude of the spillover effects found by Dechezleprêtre, Martin, and Mohnen (2017) is so large that they write: "knowledge spillovers from clean technologies appear comparable to those in the IT sector, which has been behind the third industrial revolution."

The second important stylized fact incorporated in our model is that firms' investments in green technologies reflect their expectations about government's emission reduction policies. This is illustrated by firms' reactions to the Kyoto protocol, the Paris agreement, and the European Trading System. In 1997, the Kyoto protocol set targets for reduction in greenhouse gas emissions, but its complex and lengthy ratification process undermined its credibility. Because they were skeptical that governments would actually implement emission reduction policies, firms did not engage in large investments in green technologies. Learning from their mistakes, governments quickly ratified the 2015 Paris agreement just one year after its signature. This apparent determination and coordination of governments incentivized firms to invest in green technologies, as shown by Ramadorai and Zeni (2024). Ramadorai and Zeni (2024), document the link between i) firms' reported anticipations about future climate regulation

[2] For example, Dechezleprêtre, Martin, and Mohnen (2017) find that "clean" patents (in renewables, energy efficiency, etc.) are cited more frequently, and by more prominent patents, than comparable "dirty" technologies.

and ii) and abatement activities, i.e., costly actions that reduce CO2 emissions. They observe that

> "between 2011 and 2015, prior to the Paris announcement, all firms, on average, steadily downgraded their expectations over the impact of future regulation and progressively increased their actual carbon footprint... These patterns change dramatically in 2016, the year after the Paris announcement. In that year, all firms report upwardly revised beliefs over the impact of climate regulation, and sharply increase carbon abatement over the year from 2016 to 2017."

A related example of market behaviour reflecting expectations about public policies is offered by the European Union Emission Trading System (EU ETS). In its early phases, the EU ETS had very little bite and emission caps were hardly constraining. Correspondingly, the price of emission permits remained low (below 10 euros until 2018). Then, in the wake of the dynamics spurred by the Paris Agreement, the European Union took sterner measures and signaled its commitment. This led to a strong increase in the price of emission permits, which reached 100 euros in 2023 and is currently (April 2025) around 67 euros. As permits are storable, this increase in price reflects not only the current reduction in the supply of permits but also the expectation by the market that the supply of permits will continue to decline.

The third stylized fact is that causality also runs in the other direction. Government policies adjust to firms' actions, because the latter influence the cost of the former. The reaction of public policies to firms' actions is illustrated by the European electric car policy. In 2020, the European Commission announced that new thermic cars would be banned from 2035 on. Yet, only a small number of car manufacturers undertook significant investments to prepare for that change. Given that, overall, European car manufacturers undertook only limited investment, it would be very costly to implement the announced policy. In this context, the European Union is significantly weakening its electric car policy.

Our model takes on board these stylized facts. To model the dynamic interaction between firms and the government in the simplest possible manner, we consider two periods. In the first period, firms decide whether to invest in green technologies, while in the second period the government decides whether to cap emissions, constraining firms that have not yet invested in green technologies to do so in order to comply with the cap. When deciding whether to cap emissions or not, the government takes into account the cost of decarbonation for firms that did not previously invest. Because of spillovers, the larger the amount of time-1 investment in green technologies, the lower the cost of time-2 decarbonation. Therefore, when many firms invested in the first period the government is willing to cap emissions, while if very few firms invested in the first period the government is reluctant to cap emissions. So the actions of the firms at the first period and of the government at the second period are strategic complements. Because of strategic complementarity, there can be equilibrium multiplicity (see Vives (2005)). We study under which conditions there exists a "green equilibrium" in which firms anticipate emission caps at time 2 and react by investing a lot at time 1, which in turn implies the government finds it optimal to cap emissions. We also provide conditions for the existence of a "brown equilibrium" in which firms anticipate no caps invest only a little in green technologies at time 1, so that the government finds it optimal not to cap emissions at time 2. We show that under certain conditions the green and brown equilibria coexist for the same parameter values.

Strategic complementarity between firms' investment at time 1 and government policy at time 2 arises because of spillovers. If there was no spillover effect, then firms' investment at time 1 would not affect the cost of further investment at time 2, and thus would not affect government policy at time 2.

To assess the robustness of our analysis, we extend it to the case in which damages from global warming are strictly convex in cumulative emissions. We show that when the magnitude of spillovers is larger than that of damage convexity our qualitative results are unchanged. When damage convexity is the dominant force, however, our qualitative results are altered. When the convexity of the damage function is large, after low investment in green technologies (and correspondingly high emissions) at time 1, the marginal cost of further emissions at time 2 is very high, which prompts the government to cap emissions. So, instead of strategic complementarity, we have strategic substitutability: the lower firm's investment in green technologies at time 1, the larger the willingness of the government to cap emissions at time 2. While the finding that strategic complementarity or substitutability depends on the comparison between spillovers and damage convexity is theoretically interesting, we believe strategic complementarity is empirically more plausible. In our numerical illustration of the model, based on previous empirical evidence and calibration, there is indeed strategic complementarity.

We also consider another extension of our basic framework in which a fraction of the firms is held by a large fund. Under the assumption that the large fund can control the green technology investments of the firms it holds, we find that if the fund is large enough it can tilt the balance in favour of the green equilibrium. So the large fund has two impacts: a direct impact reflecting the decrease in emissions of the firms it holds, and an indirect impact reflecting the shift from a brown equilibrium to a green equilibrium. This impact generates an increase in welfare, which could possibly counterbalance the welfare costs of market power generated by common ownership (see Azar et al, 2018.) In practice, however, this effect can be undermined by the limited control large passive funds have over the green investments of the firms they hold.

The outline of the paper is the following. Section 2 briefly discusses the literature to which our paper is related. Section 3 provides empirical motivation for the main assumptions in our model: spillovers in green technologies and social cost of brown technologies. Section 4 presents our model. Section 5 analyzes the first-best allocation, prevailing when the government directly sets investment in green technologies at both periods, fully internalizing climate and spillover externalities. Section 6 presents equilibrium emission caps, when firms set early-stage investment and government then sets carbon taxes and emission caps. In that section we show how limits to government's commitment power impact equilibrium emissions. Section 7 discusses the robustness of our analysis in the case in which damages from global warming are convex in emissions. Section 8 concludes.

2 Literature

Our paper is mainly related to the literature analyzing greenhouse gas reductions and to the literature analyzing strategic complementarities in banking and finance.

2.1 Greenhouse Gas reduction

First, our paper contributes to the literature on firms' choices between adopting dirty versus clean technologies. For example, Broccardo, Hart, and Zingales (2022), Pedersen, Fitzgibbons, and Pomorski (2021), Pástor, Stambaugh, and Taylor (2021), Oehmke and Opp (2025), Landier and Lovo (2025), and Green and Roth (2021) analyze corporate decisions characterized by a trade-off between private profits and social externalities. These studies underscore the critical role of socially responsible investors, who internalize a fraction of the negative externalities generated by the firms in their portfolios. In this literature, welfare improvements can be initiated by private agents without government intervention. By contrast, in our analysis we consider atomistic profit maximizing firms who do not internalize externalities and we abstract from investors' social preferences, so that public policy is needed to reduce global warming.[3]

Inderst and Opp (2025) show that a taxonomy for sustainable investment products can mitigate greenwashing and thus complement environmental regulation. This result, however, relies on the assumption that firms face financial frictions, which are absent in our model.

Ramadorai and Zeni (2024) offer a model of firms' abatements in which a firm suffers reputation costs when it abates less than its competitors. We do not make such an assumption. In our analysis, the effect of firms' choices on other firms' profits goes through the optimal response of the government to past aggregate firms' choices.

Gersbach and Glazer (1999) analyze cap and trade policies. Under the assumption that the government can commit to a given number of emission permits, i.e., a given cap, Gersbach and Glazer (1999) give conditions for a unique equilibrium implementing the first best. In our analysis, in contrast, when the government cannot commit to a cap there can exist a brown equilibrium with excessive emissions relative to the first best.

Acemoglu and Rafey (2023) and Aghion et al. (2016) show that regulatory intervention, via carbon taxes and research subsidies, encourages innovation in green technologies. In line with this analysis, Calel and Dechezleprêtre (2016)

[3]While in our basic model firms are atomistic and competitive, and don't internalize externalities, we also consider an extension in which a fraction of firms are owned by a (profit-maximizing) large fund. This is a form of common ownership, whose importance was underscored by Azar, Schmalz, and Tecu (2018). While Azar, Schmalz, and Tecu (2018) find that common ownership has anti-competitive effects generating social cost, in our setting it can generate social benefits, because it encourages the large fund to induce a switch to the Pareto dominant equilibrium.

find evidence that the European Union Emission Trading Scheme fostered innovation in green technologies. We complement these analyses by showing causation also runs the opposite way: innovation in green technologies encourages governments to enforce CO2 emission caps.

2.2 Strategic complementarity

Two actions are complementary if the marginal value of one of the actions increases in the level of the other action (see Vives (2005)). As shown by Vives (1985) and Vives (1990), when actions are chosen by different agents, strategic complementarities between these agents can give rise to equilibrium multiplicity. Our analysis is grounded in that paradigm.

Strategic complementarities arise in models of bank runs à la Diamond and Dybvig (1983), such as, e.g, Goldstein and Pauzner (2005), Vives (2014), and Schilling (2023). In these models simultaneous actions taken by similar agents are strategic complements: for one depositor, the gain from running (relative to the gain from staying) increases in the mass of investors simultaneously running. In contrast, in our model strategic complementarities arise between sequential actions taken by different types of participants: the time-1 investment decisions of the entrepreneurs and the time-2 cap decision of the government are strategic complements. Moreover, strategic complementarity does not stem from exogenous technologies or preferences, but endogenously stems from the politico-economic interaction between the entrepreneurs and the government. Finally note that in our model, in contrast with bank run models, there is strategic substitutability between firms' simultaneous actions: for a given government policy, the larger the fraction of firms expected to invest at time-1, the lower the expected cost of investment at time 2, and thus the more attractive it is to delay investment until time 2.

In Farhi and Tirole (2012), there is strategic complementarity between the actions of banks and the reaction of the government: When banks anticipate the government will be lenient, they take risk, which implies many banks end up distressed, which compels the government to lower the interest rate to save banks. The economic mechanism in our model is different, since our key ingredient is spillovers, which are absent in Farhi and Tirole (2012). A key ingredient in their model is that government policy (the interest rate) must be the same for all banks. There is no such assumption in our model, in which firms with different investments pay different carbon taxes.

Besley and Persson (2023) consider a model in which consumers develop green preferences when there is ample supply of green goods, while firms find it optimal to supply green goods when consumers' preferences are green. This leads to strategic complementarity between consumers and firms. In this context, government failures may prevent or slow down a green transition in which consumers would develop greener and greener preferences and firms supply greener and greener goods. The key ingredient in this analysis (consumers' green preferences) differs from the key ingredient in our paper (spillovers).

Goldstein et al. (2022) analyze price formation in a noisy rational expectations model in which profit-maximizing investors coexist with investors valuing the ESG performance of the firm. Both types of investors observe private signals on the profits and the ESG performance of the firm. This gives rise to a form of strategic complementarity between investors: When a green investor expects the other green investors to trade intensively, he/she perceives the price of the stock to be more informative about the firm's ESG performance, and this reduction in uncertainty makes it more attractive for the green investor to trade the stock. This can generate equilibrium multiplicity. While strategic complementarities and equilibrium multiplicity are at play both in Goldstein et al. (2022) and in the present paper, their focus is different from ours: Goldstein et al. (2022) study equilibrium pricing of green stocks with private signals, while we study equilibrium investment in green technologies with spillovers.

3 Motivation

In this section, we provide motivation for two main assumptions in our model: spillovers in green technologies and social cost of brown technologies. To do so we rely on empirical and calibration analyses conducted in previous papers.

3.1 Spillovers in green technologies

Popp (2002), Aghion et al. (2016), Elia et al. (2021), Grafström and Lindman (2017), and Zhou and Gu (2019) offer empirical evidence of spillovers in green technologies.

As explained in Grafström and Lindman (2017) on page 182 of their study of wind power generation costs:

> "The simplest and, in energy studies, most commonly used form of the learning curve specification connects the cost of the technology to the cumulative capacity installed... It can be written as $c_{nt} = \delta_0 CC_{nt}^{\delta_L}$, where c_{nt} represents the real engineering cost per unit (kW) of installing a windmill... CC_{nt} is the level of total installed wind power capacity ... and this is used as a proxy for learning."

Grafström and Lindman (2017) estimate this specification at the country level, so C_{nt} and CC_{nt} is the cost in country n and CC_{nt} is the capacity in country n.

An intuitive way to interpret the value of δ_L is in terms of learning by doing rate (the acronym used in the energy literature is LBR) which is the percentage decrease in cost for each doubling of cumulative capacity. Denoting by γ the capacity and by $c(\gamma)$ the corresponding cost, the percentage decrease in cost for a doubling in capacity is

$$LBR = \frac{c(\gamma) - c(2\gamma)}{c(\gamma)} = \frac{\delta_0 \gamma^{\delta_L} - \delta_0 (2\gamma)^{\delta_L}}{\delta_0 \gamma^{\delta_L}} = 1 - 2^{\delta_L},$$

For the order of magnitude of the estimate in Grafström and Lindman (2017), the LBR is around 7%. A more recent paper, Zhou and Gu (2019), finds an LBR of 17.5% for windpower and photovoltaics. In its 2020 report (International Renewable Energy Agency (IRENA) (2020)), the International Renewable Energy Agency reports even larger learning rates estimated over the 2000-2020 period: 34% for utility scale solar PV (photovoltaic) and 32% for onshore wind.

To illustrate this discussion, Table 1 reports for the period 2010 - 2023 total photo-voltaic solar electricity production capacity in Giga Watt and the levelized cost of solar electricity in cents per kwh.[4] During this period, photo-voltaic solar electricity production capacity rose from 40. GW to 1406.7 GW, while the levelized cost of solar electricity declined from 46 cents per kWh to 4.4 cents per kWh.

To fit the power specification of Grafström and Lindman (2017) for the data in Table 1 we run a regression in logs

$$\ln(cost) = \ln(\delta_0) + \delta_1 \ln(capacity) + \epsilon.$$

This yields an estimate of δ_1 equal to -.7, with a corresponding learning rate (LBR) of 38.4 %, which is not too far apart from the estimates reported above. The observed levelized costs in Table 1 and their fitted counterparts are plotted in Figure 1. Of course we are not claiming causality, our goal is just to offer a

[4]Source: International Renewable Energy Agency (IRENA) (2024a) for capacity numbers and International Renewable Energy Agency (IRENA) (2024b) for LCOE numbers.

Table 1: Global solar-power deployment and costs, 2014–2023

Year	Capacity (GW)	LCOE (¢/kWh)
2010	40.1	46
2011	70.8	34.3
2012	99.9	25.6
2013	135.5	19.7
2014	174.5	17.7
2015	222.4	13.2
2016	294.2	11.6
2017	389.2	9.1
2018	484.5	7.7
2019	586.3	6.7
2020	717.2	6.0
2021	860.5	5.2
2022	1053.9	5.0
2023	1406.7	4.4

Notes: Capacity is total global installed photovoltaic solar-electricity capacity (in GigaWatts). LCOE is the global average levelized cost of solar PhotoVoltaic electricity in 2023 U.S. cents per kilowatt-hour. Source: International Renewable Energy Agency (IRENA) (2024a) for capacity numbers and International Renewable Energy Agency (IRENA) (2024b) for LCOE numbers.

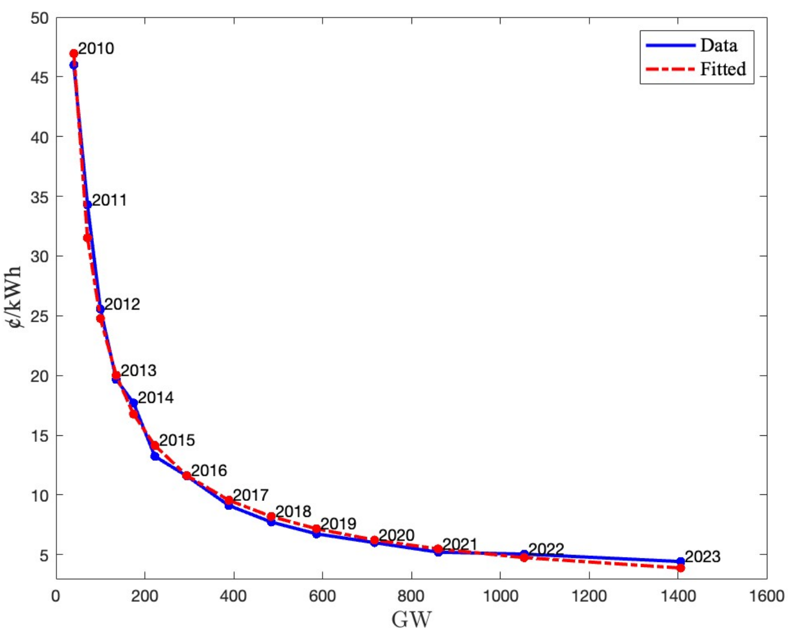

Figure 1: Numerical illustration of spillovers in the solar electricity sector. The plot shows the levelized cost of electricity (LCOE) versus total installed solar capacity, 2010–2023 (Table 1). A log–log learning-curve fit delivers an elasticity $\hat{\delta}_1 = -0.7$, implying a 38.4 % cost decline for each doubling of cumulative capacity—in line with strong spillover-driven cost reductions.

numerical illustration in line with stylized facts.

3.2 Social cost of carbon

Integrated Assessment Models (IAMs) offer a method to estimate the social cost of carbon, i.e., the present value of the stream of social disutility flows from emitting a given amount of carbon. William Nordhaus pioneered the use of these models, leading to the elaboration of the Dynamic Integrated Climate Economy model, whose acronym is DICE (see Nordhaus (1992, 1993, 2014, 2017)), and the Regional Integrated Climate Economy model, whose acronym is RICE (see Nordhaus and Yang (1996); Nordhaus (2011)).

Llavador, Roemer, and Stock (2022), relying on the Regional Integrated Model of Climate and the Economy (RICE), specify the yearly disutility flow from global warming as follows:

$$\alpha_1 \exp(\alpha_2 \Delta T),$$

where ΔT is the temperature change in degrees centigrades above pre-industrial levels, and disutility is measured in trillions of dollars per year. For positive parameters α_1 and α_2, the function is increasing and convex. Table 1 in Llavador, Roemer, and Stock (2022) provides estimates of the parameters α_1 and α_2: (.07, .8) for the US, (.09, .85) for Europe, (.1, 1) for China, (.1, .85) for India. The orders of magnitude are similar across these countries. Llavador, Roemer, and Stock (2022) then rely on the 2022 IPCC report to specify a linear relationship between cumulative global emissions and warming:

$$\Delta T = 0.45 * 10^{-3} * E^{cum},$$

where E^{cum} is cumulative anthropogenic emissions in GtCO2.

To offer an illustration of the order of magnitude of the disutility flow from global warming, Figure 2 plots yearly disutility flows per year in trillion dollars, evaluated with parameters $\alpha_0 = .1$ and $\alpha_1 = .8$, within the range given in Llavador, Roemer, and Stock (2022), against cumulative emissions in Gigatons CO2 between 2011 and 2023. Figure 2 shows that the function is almost linear.[5]

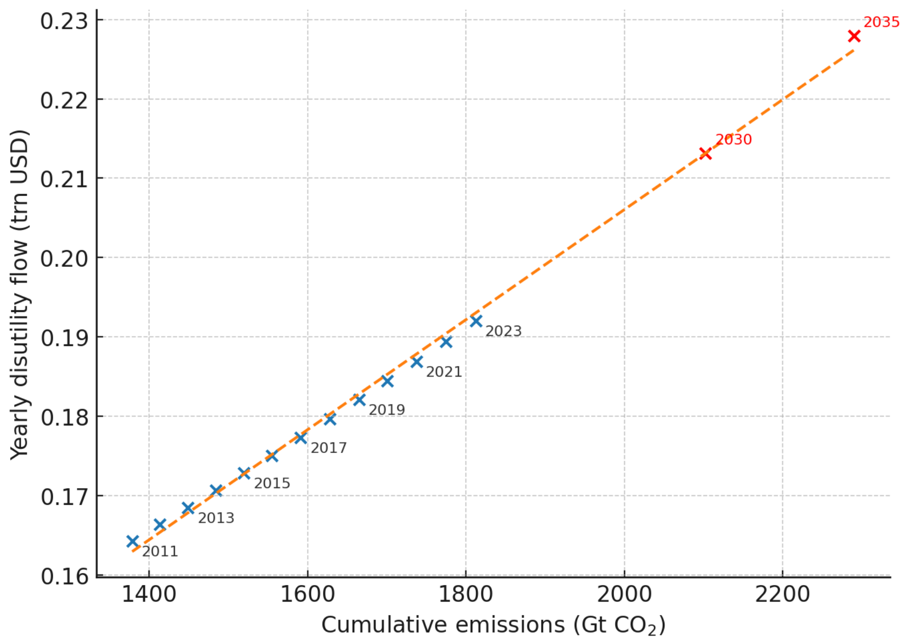

Figure 2: Climate-damage flow versus cumulative emissions. We plot the yearly disutility from global warming (trillion USD) against cumulative CO2 emissions (gigatons). Past observations (2011–2023), in blue, use the Global Carbon Project time-series processed by Our World in Data, while the prospective points (2030 and 2035, in red in the figure) are derived from the baseline trajectory in U.S. Energy Information Administration (EIA) (2023) (which assumes only green efforts that are already enacted and funded). Damages are calculated with the damage-function parameters of Llavador, Roemer, and Stock (2022), with $\alpha_0 = .1$ and $\alpha_1 = .8$. The observed and prospective observations lie almost exactly on a common regression line, indicating an approximately constant marginal disutility per additional gigaton of CO over this range.

[5]This is in line with Golosov et al. (2014), in which damages are linear in emissions.

4 Model

There is a mass-one population of ex-ante identical atomistic risk-neutral entrepreneurs, with discount factor β, each operating their own firm. Firms are indexed by $i \in [0,1]$. There are two periods, denoted by $t = 1$, and $t = 2$. At each period, each firm, if it operates, generates output Y. Firms can operate green or brown technologies. The carbon intensity of firms operating the brown technology is denoted by η, while for simplicity, that of firms operating the green technology is normalized to 0. That is, the emissions per period of firms operating brown technologies are equal to ηY, while the emissions of firms operating green technologies are 0.

A fraction $\gamma_0 < 1$ of firms is initially endowed with green technologies. γ_0 can be interpreted as the population of firms that have already invested in green technologies.[6] The other firms are endowed with brown technologies, but can invest to switch to green technologies. At time 1, firm $i \in [\gamma_0, 1]$ chooses $I_{i,1} \in \{0,1\}$, where $I_{i,1} = 1$ means firm i invests in green technologies at $t = 1$ and $I_{i,1} = 0$ means it does not.[7] Denote by γ_1 the fraction of firms that develop green technologies at time 1,

$$\gamma_1 = \int_{i=\gamma_0}^{1} I_{i,1} di. \tag{1}$$

For each firm, time-1 investment in green technologies costs $c(\gamma_0)Y$ and is irreversible.[8]

At time 2, firm $i \in [\gamma_0 + \gamma_1, 1]$ chooses $I_{i,2} \in \{0,1\}$, where $I_{i,2} = 1$ means

[6]It could reflect the impact of previous government policies, such as publicly funded early research in green technologies, or mandatory investment in industries in which such investment is observable by the government and can be directly regulated.

[7]Because agents have linear preferences and technologies, our analysis is unaffected when agents choose I_i in $[0,1]$.

[8]Since we analyze the timing of irreversible investments, there is a real option dimension to the problem we consider (see Pindyck (1991)). In contrast with real options models in which the state of the world is exogenous, in our analysis the state of the world (cost of investment and government policy at time 2) is endogenous.

firm i invests in green technologies at $t = 2$ and $I_{i,} = 0$ means it does not. Denote by γ_2 the fraction of firms that develop green technologies at time 2,

$$\gamma_2 = \int_{i=\gamma_0+\gamma_1}^{1} I_{i,2} di. \tag{2}$$

For each firm, time-2 investment in green technologies costs $c(\gamma_0 + \gamma_1)Y$.

In line with the empirical evidence discussed in the previous section, we assume the function $c(.)$ is decreasing and convex. That $c(.)$ is decreasing reflects the above discussed spillover effects. Our specification of the damage from emissions is also in line with the figures presented above. As shown in Figure 2, for the parametrization in Llavador, Roemer, and Stock (2022), damages are almost perfectly linear over the period 2011 to 2023, and the continuation of this damage function with prospective emissions in 2030 and 2035 also is almost perfectly linear. Thus we assume the social disutility, or damage, from emissions E_t at time t is linear in emissions, and we denote if by ϕE_t, $\forall t \in \{1, 2\}$. In Section 6, we study the robustness of our analysis in the case in which the damage function is convex.

The sequence of real decisions at each period $t \in \{1, 2\}$ is the following:

- At the beginning of period t, γ_t firms invest in green technologies, each at cost $c(\sum_{s=0}^{t-1} \gamma_s)$.
- At the end of period t, firms produce Y, aggregate emissions are: $E_t = \eta(1 - \sum_{s=0}^{t} \gamma_s)Y$ and they generate damage ϕE_t.

5 First best

We first consider the benchmark case in which the government directly sets γ_1 and γ_2 to maximize utilitarian welfare. Utilitarian welfare, which we denote by

w, is equal to the present value of consuming output, minus the cost of investing in green technologies and the damage from global warming. That is

$$w = Y - \gamma_1 c(\gamma_0)Y - \phi\eta(1 - \gamma_0 - \gamma_1)Y$$

$$+\beta\left(Y - \gamma_2 c(\gamma_0 + \gamma_1)Y - \phi\eta(1 - \gamma_0 - \gamma_1 - \gamma_2)Y\right),$$

where β is the discount factor between period 1 and period 2. Because of spillovers the cost of investment in green technologies is lower at time 2 than at time 1, i.e., $c(\gamma_0 + \gamma_1) \leq c(\gamma_0)$.

Utilitarian welfare maximization can be analyzed as a dynamic programming problem, solved by backward induction. Correspondingly, in the next subsection, we solve for the optimal value of γ_2 given γ_1. Then, in the following subsection, we solve for the optimal value of γ_1 taking into account the impact of γ_1 on γ_2.

5.1 Optimal policy at time 2

At time 2, the derivative of utilitarian welfare with respect to investment in green technologies is

$$\frac{\partial w}{\partial \gamma_2} = \eta Y \phi - c(\gamma_0 + \gamma_1)Y, \tag{3}$$

which is equal to the benefit of investment in green technologies (less global warming) minus the cost of investment.

Assume

$$c(1) < \eta\phi < c(\gamma_0), \tag{4}$$

that is, if there is no investment at time 1 then the cost of investment at time 2 is above its benefit, while if there is full investment at time 1 then the cost of investment at time 2 is below its benefit. Condition (4) is more likely to hold when $c(1)$ is much lower than $c(\gamma_0)$ which is the case if spillover effects are strong. We therefore hereafter refer to this condition as the "strong spillover assumption."

Given the estimates offered by the literature, the strong spillover assumption is likely to hold. The cost of switching to green technologies ranges between 10% and 1% of GDP (see for example, Nordhaus (2018) or Bistline, Mehrotra, and Wolfram (2023)). So a reasonable order of magnitude for the interval $[c(1), c(\gamma_0)]$ is $[1\%, 10\%.]$ On the other hand, for reasonable estimates of carbon intensity (around 2.5) and social cost of carbon (between 100 and 200 dollars per ton, see, e.g., Nordhaus (2018), Moore et al. (2024), Rennert et al. (2022) and Gollier (2024a)), the social cost of brown output $\eta\phi$ is between 2.5% and 5% of the dollar value of this output.[9]

Let $\bar{\gamma}$ denote the value of γ_1 such that, at time 2, the benefit of investment in green technologies is equal to its cost. That is

$$\eta\phi = c(\gamma_0 + \bar{\gamma}). \tag{5}$$

Under the strong spillover assumption we have

$$\bar{\gamma} \in [0, 1 - \gamma_0].$$

If $\gamma_1 \geq \bar{\gamma}$, then the derivative of the welfare function with respect to γ_2 in (3) is positive, so the optimal time 2 investment is

$$\gamma_2^* = 1 - \gamma_0 - \gamma_1.$$

[9]Note however that the above reported estimates of the social cost of carbon are conservative relative to some recent estimates , see, e.g., Tol (2023) and Bilal and Känzig (2024)

In contrast, if $\gamma_1 < \bar{\gamma}$, then the derivative of the welfare function with respect to γ_2 is negative, so the optimal time 2 investment is

$$\gamma_2^* = 0.$$

The above discussion is summarized in our first proposition:

Proposition 1 *Under the strong spillover assumption (4), there is a threshold $\bar{\gamma} \in (0, 1 - \gamma_0)$ characterized in (5) s.t., when $\gamma_1 \geq \bar{\gamma}$ it is optimal to fully invest at time 2 in green technologies, while if $\gamma_1 < \bar{\gamma}$ it is optimal not to invest in green technologies at time 2.*

Proposition 1 can be interpreted in terms of complementarity between time 1 and time 2 decisions: Investment at time 2 is large if investment at time 1 is large enough. Otherwise, if γ_1 is low, then $\gamma_2 = 0$.

Since c is decreasing, the threshold $\bar{\gamma}$ decreases in the marginal damage from global warming: The larger the damage from global warming, the more the government wants to reduce emissions, the larger the interval of values of γ_1 for which the government chooses full investment at time 2.

To offer a numerical illustration, we rely on the parameter values given above. We borrow the cost function from Grafström and Lindman (2017), and set its curvature parameter to $\delta_1 = -.7$, which as discussed above fits the decrease in cost between 2010 and 2023. We take a discount factor between the two periods of $\beta = .9$, in line with a discount rate of 2% and an interval between periods of 5 years.[10] We set δ_0 so that the level of of the cost of investment in green technologies is in line with the above discussed stylized facts. Carbon intensity η is set to 2.5 Gt CO2 / trillion dollars. The social cost of carbon, ϕ, is set to

[10] A discount of 2% is in line with discount rates used in the climate economics literature, see, e.g., Gollier (2024b)

200 dollars per ton. This yields damage from emissions $\eta\phi$ equal to 5% of GDP. We set the initial level of green technology γ_0 to 20%. These parameter values are reported in Table 2.

Table 2: Baseline parameter values used in the numerical illustration

Parameter	Assigned value
ϕ	200 US\$/tCO_2 (= 0.20 trn US\$/GtCO_2)
η	0.25 Gt CO_2/trn US\$
$\eta\phi$	5%
δ_0	3%
δ_1	−0.7
β	0.90
γ_0	20%

Notes: ϕ is the marginal damage per ton of CO_2; η is the carbon-intensity coefficient; $\eta\phi$ is the social cost of brown output; δ_0 and δ_1 are, respectively, the level and slope parameters of the learning-curve cost function; β is the inter-period discount factor; and γ_0 is the initial share of firms endowed with green technology.

For these parameter values the determination of $\bar{\gamma}$ is illustrated in Figure 3. It is equal, in this numerical example, to 28.2 %.

5.2 Optimal policy at time 1

Taking into account the above discussed impact of γ_1 on γ_2, we now turn to the optimal value of γ_1, which is given in the following proposition:

Proposition 2 *If the initial cost of investment in green technologies is low, so that*

$$\eta\phi + \beta c(1) > c(\gamma_0),$$

then it is optimal to fully invest at $t = 1$, i.e., $\gamma_1^* = 1 - \gamma_0$. If the initial cost of

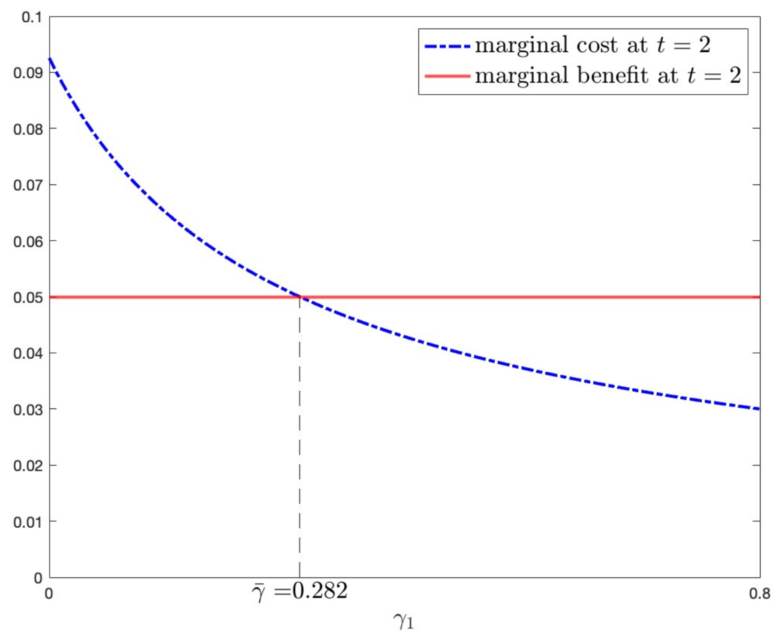

Figure 3: Determination of the threshold $\bar{\gamma}$. The figure plots the marginal cost of investing in green technologies at $t = 2$ (blue curve) and the marginal benefit of emission reduction (red curve) against the first-period green-investment share γ_1. The curves intersect at $\gamma_1 = \bar{\gamma} = 0.282$, the point beyond which the government finds it optimal to impose full decarbonization in the second period under the baseline parameters in Table 2.

investment in green technologies is intermediate, so that

$$(1+\beta)\eta\phi > c(\gamma_0) > \eta\phi + \beta c(1), \tag{6}$$

then, in the first best, there is an interior level of investment at $t = 1$, $\gamma_1^* \in (\bar{\gamma}, 1-\gamma_0)$ *such that*

$$c(\gamma_0) = \eta\phi + \beta c(\gamma_0 + \gamma_1^*) - \beta(1-\gamma_0-\gamma_1^*)c'(\gamma_0+\gamma_1^*), \tag{7}$$

and there is full investment at time 2. If the initial cost of investment in green technologies is large, so that

$$c(\gamma_0) > (1+\beta)\eta\phi,$$

the objective is not quasi-concave and the optimum is either $\gamma_1^* = 0$ *or* $\gamma_1^* \geq \bar{\gamma}$.

As the social cost of brown output $\eta\phi$ increases, the condition for full investment: $c(\gamma_0) < \eta\phi + \beta c(1)$ is relaxed, and the interior optimum γ_1^* goes up, since the right-hand side of

$$c(\gamma_0) = \eta\phi + \beta c(\gamma_0 + \gamma_1^*) - \beta(1-\gamma_0-\gamma_1^*)c'(\gamma_0+\gamma_1^*)$$

is decreasing in γ_1^*.

Equation (7) is the first order condition of the government in an interior equilibrium. The left-hand side is the cost of investment at $t = 1$. The right-hand side is the benefit of time-1 investment equal to the social cost of time-1 emissions, plus the reduction in time-2 investment for which time-1 investment has been substituted, plus the reduction in the unit cost of time-2 investment brought about by time-1 investment.

For the parameter values given in Table 2, condition (6) holds and utilitarian welfare is plotted in Figure 4. For values of γ_1 between 0 and $\bar{\gamma}$, welfare increases linearly with γ_1. For higher values of γ_1, welfare is concave. It reaches its maximum at an interior value: $\gamma_1^* = 52.8\%$. That is, in our numerical example, the optimal level of decarbonation at the first period is around 50%. This is way higher than the actual current level of decarbonation, suggesting there is a need to increase investment in green technologies.

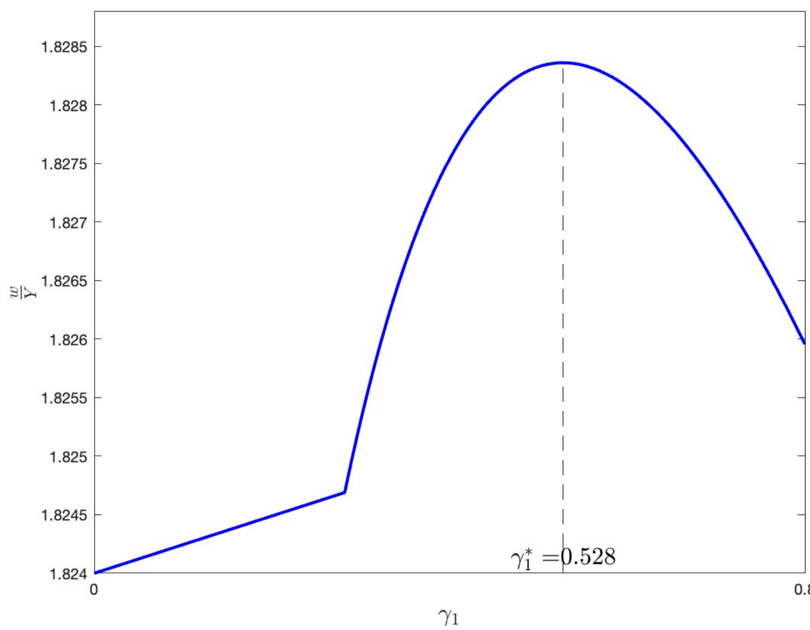

Figure 4: Utilitarian welfare vs. early investment. First-best social welfare (scaled by Y) as a function of the first-period green investment level γ_1, for the baseline parameters (stated in Table 2).

6 Equilibrium

We now step away from the first-best benchmark in which a benevolent government observes and sets investment at time 1 and time 2. As argued below, it is more plausible to assume time-1 investments are decided by firms, rather than by the government. In this section we study the equilibrium allocation arising in this context, and compare it to the first-best allocation.

The reason why government cannot directly set time-1 investment is that, at this point in time, investment in green technologies corresponds to early stage fundamental research. The industrial organization literature emphasizes that research effort at that early stage is hard to observe for outsiders. In their influential theoretical analyses, Akcigit, Hanley, and Stantcheva (2022) and Scotchmer (1999) assume it is privately observed by firm managers. In practice, claims on commitment to developing green technologies are sometimes viewed with caution, because of the risk of greenwashing.[11] When time-1 investment in green technologies are not directly observable and controllable, government can only indirectly influence them via incentive schemes. In our analysis, such incentives are provided by taxes and subsidies, contingent on emissions, which, in line with practice, we assume to be observable.

6.1 Equilibrium when the government has full commitment power

In this subsection, we assume the government can commit to its announced carbon tax and emission caps policy. We show that, in this case, the government can implement the first-best allocation as an equilibrium. We focus on the case in which (6) holds, so that the first best is interior, i.e., $\gamma_1^* \in [\bar{\gamma}, 1 - \gamma_0]$ and $\gamma_2^* = 1 - \gamma_0 - \gamma_1^*$. The sequence of actions is the following:

- At the beginning of period 1, the government announces the carbon tax and emission caps policy. Then, firms decide whether to invest, at cost

[11] For example, the PWC 2023 Global Investor survey reports that "94% of investors believe that corporate reporting on sustainability performance contains at least some unsupported claims." Another example is the finding by Shi et al. (2023) that after green bond issuance companies file patents which don't reflect inventions and have low citations rate.

$c(\gamma_0)$ or not.

- At the end of period 1, output is generated and emissions are observed. At that point, the government implements the announced carbon tax policy.
- At the beginning of period 2, the government implements the announced emission caps policy. If emissions are capped, firms that did not invest at time 1 must now do so, at cost $c(\gamma_0 + \gamma_1)$.[12]
- At the end of period 2, output is generated, emissions are observed, and the government implements the announced carbon tax policy.

Carbon taxes and green subsidies are designed to optimally set the incentives of the firms to invest at time 1. Carbon taxes make it costly for firms not to invest at time 1, and green subsidies make it more attractive for firms to invest at time 1.[13]

To strengthen incentives to invest at time 1, it is optimal to levy taxes and grant subsidies at both periods contingent on time 1 emissions. Firms investing at $t = 1$ receive green subsidies with present value $s(1 + \beta)Y$. The mass of firms receiving these subsidies is $\gamma_0 + \gamma_1$. Firms which don't invest at time 1 pay carbon taxes with present value $\tau(1+\beta)Y$. The mass of firms paying these taxes is $1 - \gamma_0 - \gamma_1$. So the government budget balance condition is

$$(\gamma_0 + \gamma_1)s = (1 - \gamma_0 - \gamma_1)\tau. \tag{8}$$

[12] Instead of explicit emission caps, the government can equivalently levy additional carbon taxes on firms emitting in period 2, such that firms which did not invest at time 1 are better of doing so at time 2.

[13] Such incentives could alternatively be provided by a cap and trade system, in which, at the end of time 1, brown firms would have to buy permits from green firms. The cost of buying permits provides incentives similar to those of carbon taxes, and the proceeds from selling permits provide incentives similar to those of green subsidies. Another aspect of the similarity between cap and trade and tax and subsidy schemes is that in the former market clearing implies the aggregate cost of buying permits is equal to the aggregate revenues from selling permits, while in the latter budget balance implies that, for the government, the aggregate revenue from carbon taxation is equal to the aggregate cost of green subsidies. Gersbach and Glazer (1999) offer an insightful theoretical analysis of the incentive role of cap and trade mechanisms.

Define $\tau(\gamma_1)$ as follows

$$\tau(\gamma_1) := \frac{\gamma_0 + \gamma_1}{1+\beta} \left(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1) \right). \tag{9}$$

As shown in the proof of Proposition 3, $\tau(\gamma_1)$ is the tax rate which makes each firm indifferent between investing at time 1 and investing at time 2, when it is expected that a fraction γ_1 of firms invest at time 1. Intuitively, the right-hand side of (9) reflects the cost of investing at time 1, which stems from the fact that the cost of investment in green technologies at time 1, $c(\gamma_0)$, is larger than the present value of the cost of investment in green technologies at time 2, $\beta c(\gamma_0 + \gamma_1)$. The left-hand side of (9) reflects the cost of delaying investment until time 2, which stems from the carbon tax. For $\gamma_1 > \bar{\gamma}$, taxing emissions at rate $\tau(\gamma_1)$ implements an equilibrium with time-1 investment equal to γ_1 and time-2 investment equal to $1 - \gamma_0 - \gamma_1$.

This leads to our next proposition:

Proposition 3 *When condition (6) holds, so that the first best is interior, and the government has full commitment power, the first best can be implemented as an equilibrium with emission caps at time 2, and budget-balanced carbon tax* $\tau(\gamma_1^*)$.

As noted in the discussion of Proposition 2, the larger the social cost of emissions, the larger the optimal initial investment in green technologies. Since the tax rate in (9) is increasing in the level of time-1 investment, Proposition 2 and Proposition 3 together imply that the larger the social cost of emissions, the larger the carbon tax needed to implement the first best.

6.2 Equilibrium when the government cannot commit to ex-post inefficient policies

We now relax the assumption that the government can fully commit to its policy, and assume the government cannot credibly commit ex-ante to policies that are ex-post inefficient. This is in the spirit of subgame perfection. This does not rule out carbon taxes and green subsidies, as long as they are purely redistributive and do not lead to inefficient real allocations, but it does rule out ex-post inefficient emission caps. As shown in the previous section, this implies that if at time 1 $\gamma_1 < \bar{\gamma}$, then at time 2 emissions are not capped, i.e., firms are not requested to invest in green technologies because this would be too costly.

6.2.1 Equilibrium multiplicity

In this context, the first-best allocation can still be implemented as an equilibrium. When the government announces $\tau(\gamma_1^*)$ and firms anticipate there will be caps, a fraction $\gamma_1^* > \bar{\gamma}$ of firms invest at time 1, so that it is optimal to cap emissions at time 2, confirming firms' expectations.

There can, however, also exist an equilibrium in which the government credibly announces $\tau(\gamma_1^*)$, but firms anticipate no caps and this belief is self-fulfilling. The condition for this to be an equilibrium is that firms be indifferent between investing at time 1 and not investing, which is

$$(1+\beta) - c(\gamma_0) + (1+\beta)s = (1+\beta) - (1+\beta)\tau(\gamma_1^*). \tag{10}$$

Substituting the budget balance condition (8) into the indifference condition (10), the latter simplifies to

$$\gamma_1 = \frac{1+\beta}{c(\gamma_0)}\tau(\gamma_1^*) - \gamma_0. \tag{11}$$

When this value of γ_1 is below $\bar{\gamma}$, then the anticipation that there would be no cap was rational. So we can state our next proposition:

Proposition 4 *Assume the government cannot commit ex-ante to ex-post inefficient policies, but can commit to purely redistributive policies, and the first best is interior, i.e., (6) holds. Then if*

$$\frac{1+\beta}{c(\gamma_0)}\tau(\gamma_1^*) < \gamma_0 + \bar{\gamma}. \quad (12)$$

the government can credibly announce it will levy carbon taxes at the first best level $\tau(\gamma_1^*)$, but there are two equilibria: A green equilibrium, implementing the first best allocation with $\gamma_1^* \geq \bar{\gamma}$ firms investing at time 1 and emission caps at time 2, and a brown equilibrium in which the mass of firms investing at time 1 is given by equation (11) and there are no caps at time 2.

The multiplicity of equilibria in Proposition 4 arises because of strategic complementarities between firms' investment at time 1 and government's cap policy at time 2. It is illustrated in Figure 5, for the parametrization given in Table 2. The figure depicts the level (or levels in the case of multiple equilibria) of time 1 investment γ_1 (on the vertical axis) corresponding to a given level of carbon tax τ (on the horizontal axis).

- The green curve corresponds to the green equilibrium, in which the link between γ_1 and τ is given by equation (9). It is defined only for tax rates τ that are high enough for the corresponding γ_1 to be above $\bar{\gamma}$. The lowest such tax rate is $\tau_G(\bar{\gamma})$, which we define to be the tax rate for which (9) holds for $\gamma_1 = \bar{\gamma}$. The green equilibrium implementing the first best is point $(\tau(\gamma_1^*), \gamma_1^*)$ on the green curve.

- The brown curve corresponds to the brown equilibrium, in which the link between γ_1 and τ is given by equation (11). It is defined only for tax rates τ that are low enough for the corresponding γ_1 to be below $\bar{\gamma}$. The highest such tax rate is $\tau_B(\bar{\gamma})$, which we define to be the tax rate for which (11) holds for $\gamma_1 = \bar{\gamma}$.

By construction, when (12) holds we have $\tau_G(\bar{\gamma}) \leq \tau_B(\bar{\gamma})$. Thus, for the different possible values of τ, the various possible equilibria are as follows.:

- For $\tau < \tau_G(\bar{\gamma})$, the only equilibrium is brown, i.e., in our setting, some carbon taxation is needed to induce investment at time 1.
- For τ between $\tau_G(\bar{\gamma})$ and $\tau_B(\bar{\gamma})$, there exists a brown equilibrium and a green one. For the parametrization given in Table 2, $\tau(\gamma_1^*) \in [\tau_G(\bar{\gamma}), \tau_B(\bar{\gamma})]$, so there are multiple equilibria at the level of carbon tax that can implement the first best.
- For $\tau > \tau_B(\bar{\gamma})$, the only equilibrium is green, i.e., in our setting, severe carbon taxation eliminates the bown equilibrium. As discussed below, however, carbon taxation is likely to be politically constrained.

6.2.2 Impact of γ_0

γ_0 can be interpreted as reflecting government-funded basic research and development in green technologies, or government mandated green investment in industries in which it is observable. To illustrate the impact of γ_0 on equilibrium outcome, Figure 6 plots relevant carbon tax rates as a function of γ_0. The blue line is the tax rate that implements the first best in the green equilibrium. It is first increasing, reflecting that γ_1 increases with γ_0, and then decreasing, reflecting that γ_1 increases with γ_0: Starting from an intermediate value of γ_0, any increase in γ_0, lowering the cost of time-1 investment, leads to an increase in γ_1^*, and correspondingly in $\tau(\gamma_1^*)$. Then, when γ_0 is large, the cost of time-

1 investment is low so that $\gamma_1^* = 1 - \gamma_0$. For tax rates above the green line, there exists a green equilibrium. For tax rates above the brown line, there does not exist a brown equilibrium. Figure 6 illustrates that, as γ_0 increases, the tax rate needed to eliminate the brown equilibrium decreases. Thus, publicly-funded early basic research in green technologies, by raising γ_0, helps achieving a green equilibrium and avoiding a brown equilibrium.

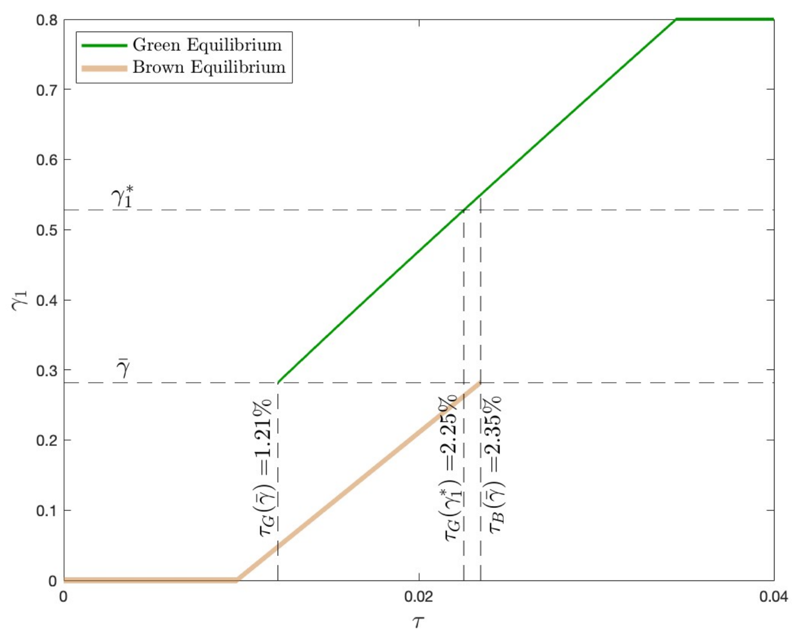

Figure 5: Green vs. brown equilibria. Equilibrium first-period investment γ_1 as a function of the carbon tax τ, showing the high-investment "green" equilibrium and low-investment "brown" equilibrium for the baseline parameters (Table 2). The upper (green) curve represents the green equilibrium (large γ_1), which only exists for sufficiently high carbon taxes (above a minimum τ that ensures $\gamma_1 \geq \bar{\gamma}$). The lower (brown) curve corresponds to the brown equilibrium (low γ_1), which vanishes once τ exceeds a certain threshold. For intermediate tax levels, both equilibria coexist.

6.2.3 Large investment fund

The brown equilibrium described in Proposition 4 reflects a coordination failure. All firms are better off in the green equilibrium, but if firms are pessimistic and expect the others not to invest at time 1 then the Pareto dominated brown equilibrium prevails. This coordination failure arises because firms are atomistic and don't internalize the consequences of their investments on future costs and government policy. As mentioned in Azar, Schmalz, and Tecu (2018), however, large investment funds own a large fraction of non-financial firms. While Azar, Schmalz, and Tecu (2018) note that this has anti-competitive effects, in our context it could have beneficial effects if large funds were able to drive coordination on the green equilibrium. This scenario seemed relevant as several large funds or banks announced their participation in coordinated decarbonization initiatives, such as the Net-Zero Banking Alliance or the Net-Zero Asset Managers alliance.

In this subsection we first articulate the theoretical possibility of coordination led by a large fund, and then discuss to which extent such coordination can be expected in practice.

To examine this point, we consider a variant of our model in which a fraction α of the firms is owned by a large fund. The shares of the fund are owned by the agents who owned these α firms in our basic model. The fund maximizes the utility of its shareholders. Suppose i) the fund can control the time-1 investments of the firms it owns and ii) $\alpha \geq \bar{\gamma}$. In that case consider what happens if the government credibly announces carbon taxation at rate $\tau(\gamma_1^*)$. If the fund instructs a mass of firms larger than $\bar{\gamma}$ to invest at $t = 1$ and this is known by the other firms in the economy, this rules out the brown equilibrium. Indeed, since all firms know the level of time-1 investment is at least as large as $\bar{\gamma}$, they know that emissions will be capped at time 2. With such expectations, and when the carbon tax rate is $\tau(\gamma_1^*)$, the green equilibrium prevails. In this case,

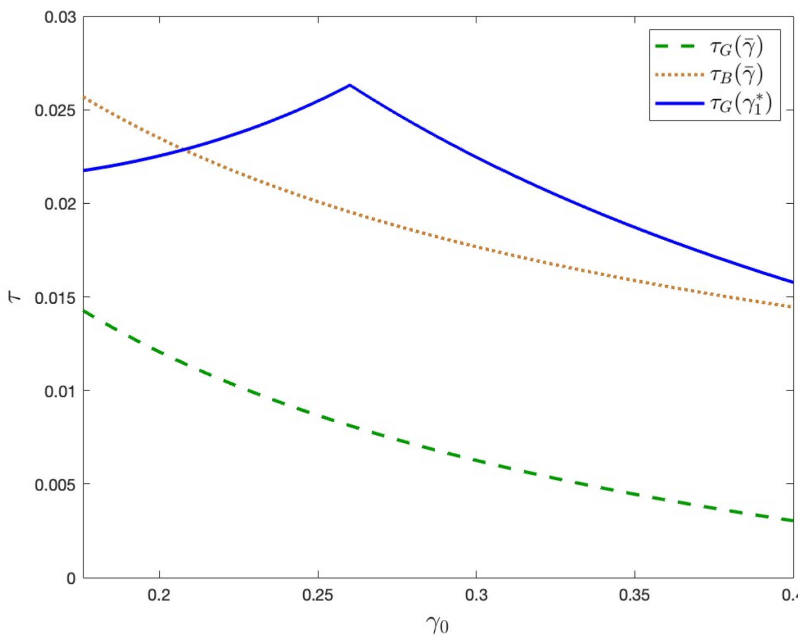

Figure 6: Impact of γ_0 on green and brown equilibria. This figure plots three carbon-tax thresholds as functions of the initial green-technology share γ_0 (baseline parameters in Table 2). *Blue curve*: tax that implements the first-best outcome (γ_1^*). *Green curve*: minimum tax that permits a green equilibrium. *Brown curve*: tax above which the brown equilibrium disappears. As γ_0 rises, both green-threshold and the brown-threshold taxes decline, suggesting that early public investment lowers the tax burden needed to rule out the brown equilibrium.

the shareholders of the fund obtain their first best utility, which is larger than their utility in the brown equilibrium. So the fund finds it optimal to follow this policy.[14]

Suppose that, without the large investor, with some probability, firms coordinate on the brown equilibrium. Then the presence of the large investor and its announced policy of investing in green technologies at time 1 tilt expectations towards the green equilibrium. This sheds new light on the notion of impact. The impact of an investor is typically defined through the notion of *additionality*: For instance, Brest and Born (2013) propose the following definition:

> "For an investment [...] to have impact, it must provide additionality; that is, it must increase the quantity or quality of the enterprise's social outcomes beyond what would otherwise have occurred."

In our model the large fund has impact, as it raises welfare from its brown equilibrium level to its green equilibrium level. In this context, the counterfactual to evaluate additionality is the brown equilibrium that would arise without the large investor.

When the large fund's policy leads to the selection of the green equilibrium, the financial performance of the firms it manages is exactly the same as that of the firms outside its portfolio. This is because the green equilibrium condition is that firms earn the same profits when they invest at time 1 and when they invest at time 2. So the large fund is "doing well by doing good."

While the above analysis suggests large funds could theoretically tilt the balance towards a green equilibrium, this might not obtain in practice. Indeed, the analysis above relies on a number of assumptions, that might fail to hold in practice:

[14]Thus, in our analysis the fund is not altruistic or ethical, but utilitarian. It maximizes the utility of its shareholders.

First, the analysis above relies on the assumption that, in contrast with the government, the large fund can observe and control the early stage research effort of the firms it owns. While this might be a realistic assumption for venture capitalists, closely monitoring the firms in which they invest, it is less realistic for funds investing in a large number of publicly traded firms. The managers of such funds have limited attention span and are subject to insider trading rules that restrict their information set to public information. Moreover, the above theoretical argument also relies on the assumption that other firms observe the time 1 investment of the firms owned by the fund. Again, this may not be the case in practice.

Second, the above analysis relies on the assumption that the large fund is indeed quite large, i.e., $\alpha \geq \bar{\gamma}$. In our numerical example above, realistic parameter values yield an estimate of $\bar{\gamma}$ in the ballpark of 25% to 30% of the firms in the economy. In practice, even the largest funds don't own that large a fraction of the firms. An alliance of investors, such as the Net-Zero Banking Alliance or the Net-Zero Asset Managers alliance, might reach a high threshold. But, the multiplicity of participants in the alliance rekindles the risk of coordination failures. In that context, defection by one of the members of a alliance may trigger a reversal to the brown equilibrium, especially if it brings the mass of the coalition below $\bar{\gamma}$. Defections observed in the recent period illustrate the fragility of investor coalitions: By the end of 2024, the major US banks (JPMorgan Chase, Goldman Sachs, Wells Fargo, Citigroup, Bank of America, and Morgan Stanley) had quit the Net-Zero Banking Alliance, while early 2025 Blackrock, the world's largest asset manager, announced its withdrawal from the Net Zero Asset Managers alliance.

6.3 Equilibrium when the government has limited taxation power

As mentioned above, another way to eliminate the brown equilibrium is to set a sufficiently high carbon tax rate $\tau > \tau_B(\bar{\gamma})$. But is it possible to levy such high taxes ? In practice, governments often had to give up on carbon taxes, or policies imposing costs on firms with large CO2 emissions. To name but a few examples: In 2014, the carbon tax announced in 2012 in Australia was repealed, because of the large cost it imposed on businesses. In 2018, Ontario withdrew its cap-and-trade program, due to concerns over costs to consumers and businesses. In 2020, the US withdrew from the Paris Climate Agreement, because of the cost to American businesses. After the US rejoined in 2021, they left again in 2025. Finally, in 2025 Europe reneged on its clean car policy, because of the cost it would have imposed on European car manufacturers that had not sufficiently invested in electric vehicle technology. These examples suggest that, in practice, when a carbon tax is announced it is not sure in advance whether it will be implemented. So, we hereafter assume that the carbon tax τ announced at the beginning of period 1 is only implemented with probability λ.

Also motivated by empirical observation, we impose an additional constraint on the government's ability to levy carbon taxes. When a country introduces a carbon tax on its industries, it runs the risk that domestic firms will relocate their brown production abroad, in countries without carbon tax. Li and Zhou (2017) offer an interesting analysis of such relocation within the US. They write that: "U.S. plants located in counties with greater institutional pressure for environmental performance offshore more." Coster, di Giovanni, and Mejean (2024) shed light on the offshoring behaviour of French firms. They find that: "French firms shifted their imports of dirty products to non-ETS country suppliers over time." To take on board this important constraint, we therefore hereafter assume the government cannot set the carbon tax τ above a threshold θ, which reflects the cost of offshoring. The larger that cost, the larger the carbon tax the government can levy without inducing offshoring.

In this version of our model, the sequence of moves is the following:

- At the beginning of period 1, the government announces its policy: the carbon tax rate τ, and whether emissions will be capped. Then firms invest, at cost $c(\gamma_0)$ or not.

- At the end of period 1, emissions are observed. With probability λ, the government has political clout and can levy carbon tax. If τ is above θ then firms offshore, while if $\tau \leq \theta$ firms remain in the country. On the other hand, with probability $1 - \lambda$ the government lacks political clout and emissions are not taxed.

- At the beginning of period 2, the government decides to cap emissions if this is efficient. If the government decides to cap emissions, then firms that did not invest at $t = 1$ must invest at $t = 2$, at cost $c(\gamma_0 + \gamma_1)$.

- Finally, at the end of period 2, emissions are observed, the government caps emissions if it is efficient to do so, and if it turned out that the government had political clout carbon taxes are levied.

When the government can perfectly commit to taxation (i.e., when $\lambda = 1$), to implement a green equilibrium with time 1 investment equal to γ_1 the government must set the tax rate to $\tau_{\lambda=1}(\gamma_1)$ s.t.

$$\tau_{\lambda=1}(\gamma_1) \geq \frac{\gamma_0 + \gamma_1}{1 + \beta}(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1)).$$

On the other hand, with limited commitment to taxation ($\lambda < 1$), to implement the same amount of time 1 investment the gov must set $\tau_{\lambda<1}(\gamma_1)$ s.t.

$$\lambda\tau_{\lambda<1}(\gamma_1) \geq \frac{\gamma_0+\gamma_1}{1+\beta}(c(\gamma_0)-\beta c(\gamma_0+\gamma_1)).$$

That is

$$\tau_{\lambda<1}(\gamma_1) = \tau_{\lambda=1}(\gamma_1)/\lambda.$$

Now, the condition under which there is no offshoring is that $\tau_{\lambda<1}(\gamma_1) < \theta$. So γ_1 can be implemented as a green equilibrium iff

$$\tau_{\lambda=1}(\gamma_1) \leq \lambda\theta. \tag{13}$$

This implies that a given level of time 1 investment, γ_1, can be implemented only if the probability λ that the government can enforce carbon taxes and the cost θ of offshoring are large enough. Of course, for the theoretical analysis we don't need to have two different parameters, λ and θ, since only their product matters, as can be seen in condition (13). However, for a realistic numerical application of the model, it is useful to specify both parameters.

For the parameter values of our numerical example given in Table 2, and for a cost of offshoring θ equal to 5%, if the probability λ that the government will implement the carbon tax is larger than 46.96% it is possible to set a tax rate large enough to eliminate the brown equilibrium. If λ is between 24.13% and 46.96%, for the tax rates that don't lead to offshoring, a green equilibrium and a brown equilibrium can coexist. Finally, when λ is lower than 24.13%, then the only equilibrium without offshoring is a brown equilibrium. Thus, if $\lambda\theta$ is low, the brown equilibrium cannot be eliminated by carbon taxation.

7 Convex damages

For simplicity, and because it is a good approximation for the parameter values obtained by Llavador, Roemer, and Stock (2022), the above analysis assumes that the damage flow at each period is linear in cumulative emissions. To assess the robustness of our findings to that assumption, we now consider the case in which the damage flow in each period is an increasing and convex function φ of cumulative emissions. We also assume $\varphi^{'''} > 0$, which is a regularity condition ensuring the uniqueness of the threshold $\bar{\gamma}$. The social disutility flow from global warming at time 1 is

$$\varphi(E_1) = \varphi((1 - \gamma_0 - \gamma_1)\eta Y),$$

while the social disutility flow from global warming at time 2 is

$$\varphi(E_1 + E_2) = \varphi((2(1 - \gamma_0 - \gamma_1) - \gamma_2)\eta Y).$$

In this context, utilitarian welfare is

$$Y - \gamma_1 c(\gamma_0)Y - \varphi((1 - \gamma_0 - \gamma_1)\eta Y)$$

$$+\beta \left(Y - \gamma_2 c(\gamma_0 + \gamma_1)Y - \varphi((2(1 - \gamma_0 - \gamma_1) - \gamma_2)\eta Y)\right). \qquad (14)$$

In this section we first analyze the optimal cap policy of the government at time 2. Then we analyze equilibria. For simplicity, we consider the case in which the government cannot levy carbon taxes, i.e., the last environment considered in the previous section, with λ set to 0. There are two cases: In the first case, spillovers dominate damage convexity and the results are qualitatively similar to those obtained in the linear damage case. In the second case, damage convexity dominates spillovers and the results are qualitatively different from those obtained in the linear damage case. This is because in the first case firms' investments and governments' cap are strategic complements, while in the second case they are strategic substitutes.

7.1 When spillovers dominate damage convexity

We first focus on the case in which

$$c(\gamma_0)Y > \eta\varphi'(2(1-\gamma_0)\eta Y) > \eta\varphi'((1-\gamma_0)\eta Y) > \eta\varphi'(0) > c(1)Y. \tag{15}$$

When φ is linear, condition (15) simplifies to (4).

At time 2, the derivative of the objective function of the government with respect to γ_2 is

$$\eta Y\varphi'((2(1-\gamma_0-\gamma_1)-\gamma_2)\eta Y) - c(\gamma_0+\gamma_1)Y, \tag{16}$$

which is equal to the social benefit from reducing global warming minus the cost of investment in green technologies. This derivative is positive (meaning that more investment at time 2 is optimal) as long as the marginal social disutility of emissions is larger than the marginal cost of investment. The second derivative of the objective function is negative. So, if there is an interior value of γ_2 for which the derivative is 0, then this is the optimum. There may also be corner solutions, however, with $\gamma_2 = 0$ or $\gamma_2 = 1-(\gamma_0+\gamma_1)$.

Denote by $\underline{\gamma}$, the amount of time 1 investment (γ_1) such that, if there is no investment at time 2 (i.e., $\gamma_2 = 0$), the marginal social value of investment at time 2 is equal to its marginal cost:

$$c(\gamma_0+\underline{\gamma})Y = \eta\varphi'(2(1-\gamma_0-\underline{\gamma})\eta Y). \tag{17}$$

Similarly, denote by $\bar{\gamma}$ the amount of time 1 investment such that after full investment at time 2 (i.e., $\gamma_2 = 1 - \gamma_0 - \gamma_1$), the marginal social benefit of investment at time 2 is equal to its marginal cost:

$$c(\gamma_0 + \bar{\gamma})Y = \eta\varphi'((1 - \gamma_0 - \bar{\gamma})\eta Y). \tag{18}$$

This is a new definition of $\bar{\gamma}$, but for linear damages it simplifies to the definition given above. Equations (17) and (18) imply that $\bar{\gamma} > \underline{\gamma}$.

Building on these observations, our next proposition spells out the optimal value of time 2 investment as a function of time 1 investment.

Proposition 5 *Under condition (15), the optimal time-2 policy is as follows*

- *if $\gamma_1 < \underline{\gamma}$, the optimal level of time 2 investment is 0,*
- *if $\gamma_1 \geq \bar{\gamma}$, the optimal level of time 2 investment is $1 - \gamma_0 - \gamma_1$,*
- *and if $\underline{\gamma} \leq \gamma_1 < \bar{\gamma}$, the optimal level of time 2 investment is interior and such that (16) equals 0.*

Proposition 5 is similar to its linear damage counterpart, Proposition 1. Like Proposition 1, Proposition 5 can be interpreted in terms of complementarity between first and second period investment, induced by spillovers: When first period investment is very low (below $\underline{\gamma}$), then, at the second period, the marginal cost of investment is high, so optimal second period investment is 0. In contrast, when first period investment is very large (above $\bar{\gamma}$), then at the second period the cost of investment is low, implying that optimal second period investment is large.

Next, we analyze equilibria. First note there is a brown equilibrium, with $\gamma_1 = \gamma_2 = 0$. To see this, consider the case in which firms anticipate no cap and there is no carbon tax. In that case firms prefer not to invest. In turn, this implies the government finds it optimal not to cap emissions at $t = 2$, implying that firms' initial expectations were rational. On the other hand, there is no green equilibrium. To see this, suppose firms anticipate caps. For this to be rational, it must be that firms anticipate $\gamma_1 \geq \bar{\gamma}$. In that case, however, the cost of investing at time 1, $c(\gamma_0)$, is strictly larger than the present value of the cost of investing at time 2, $\beta c(\gamma_0 + \gamma_1)$. So firms don't invest at time 1, which contradicts the initial expectation. This discussion is summarized in our next proposition:

Proposition 6 *Under condition (15), when the government cannot levy carbon taxes, the only equilibrium is a brown equilibrium, with no investment in green technologies at any of the two periods.*

Proposition 6 implies that, as long as spillovers dominate the convexity of damages, we get a similar result when φ is convex as when it is linear: If the government's ability to levy carbon taxes is very limited, there only exists a brown equilibrium, with no investment in green technologies. This result reflects that, when the convexity of the damage function is small relative to spillovers, there is strategic complementarity between firms' investments at time 1, and the cap policy of the government at time 2.

7.2 When damage convexity dominates spillovers

We now turn to the alternative case in which

$$\eta\varphi'(2(1-\gamma_0)\eta Y) > c(\gamma_0)Y > c(1)Y > \eta\varphi'((1-\gamma_0)\eta Y). \tag{19}$$

In this case the convexity of the damage function is very large. This implies that, as cumulative emissions grow, damages from global warming increase faster and faster. Under condition (19) this effect is stronger than that of spillovers, and we obtain our next proposition:

Proposition 7 *Under condition (19), if* $\gamma_1 \leq \underline{\gamma}$*, the optimal level of time* 2 *investment is positive and pinned down by the first order condition*

$$\eta\varphi'((2(1-\gamma_0-\gamma_1)-\gamma_2)\eta Y) = c(\gamma_0+\gamma_1)Y, \tag{20}$$

while if $\gamma_1 > \underline{\gamma}$*, the optimal level of time* 2 *investment is zero.*

The contrast between Proposition 5 and Proposition 7 reflects that an increase in γ_1 has two effects.

- On the one hand an increase in time 1 investment reduces the cost of time 2 investment. When this spillover effect is strong enough, this generates strategic complementarity between time 1 and time 2 investment, as in Proposition 5.
- On the other hand, an increase in time 1 investment also reduces the marginal disutility of emissions at time 2, which can bring this disutility below the cost of investment. When the convexity of the disutility of emissions is strong enough, this generates strategic substitutability between time 1 and time 2 investment, as in Proposition 7.

The first effect dominates when (15) holds, while the second effect dominates when (19) holds. In the latter case if there is no investment at time 1, the marginal disutility from emissions is so high at time 2 that it is socially optimal to invest. In the former case, if there is no investment at time 1 the cost of investment at time 2 is so high that it is optimal not to invest. But the mechanism is turned on its head after large initial investment. Under (19), if there is a lot of investment at time 1, the marginal disutility from emissions is low at time 2, so it is not socially optimal to invest. In contrast, under (15), if there is a lot of investment at time 1 the cost of investment at time 2 is so low that it is optimal to invest.

We now study equilibrium. As in the previous case without carbon taxes and green subsidies, there cannot exist an equilibrium with $\gamma_1 > 0$. This is, because for all values of γ_1, the cost of investing at time 1 is larger than the expected present value of the cost of time 2 investment, i.e.,

$$c(\gamma_0) > \beta c(\gamma_0 + \gamma_1) \Pr(\text{cap}), \forall \gamma_1,$$

where Pr(cap) is the probability of a cap at time 2. Yet, in contrast with the case in which spillovers were dominant, when damage convexity is dominant, lack of investment at time 1 does not rule out caps at time 2. Rather, the government can opt for a partial cap policy, in which at time 2 a mass γ_2 of firms are capped. By (16), the optimal cap policy is to set γ_2 such that:

$$\eta\varphi'((2(1-\gamma_0)-\gamma_2)\eta Y) = c(\gamma_0). \tag{21}$$

The right-hand side is the cost of investing in green technologies at time 2 after no investment at time 1. The left-hand side is the benefit of investment in green technologies at time 2. Because φ is convex, the left-hand side is decreasing in γ_2. For $\gamma_2 = 0$, by (19) the left-hand side of (21) is larger than the right-hand side, and for $\gamma_2 = 1 - \gamma_0$ it is lower. This implies that (21) has a unique root and this root is strictly between 0 and $1 - \gamma_0$. This is stated in our next proposition:

Proposition 8 *Under condition (19), when the government cannot levy carbon taxes there exists a unique equilibrium. It involves no investment in green technologies at time 1 but strictly positive investment at time 2:* γ_2 *solving (21).*

The equilibrium in Proposition 8 is “green” in the sense that there is some investment in green technologies at time 2. This contrasts with the brown equilibrium arising when spillovers dominate damage convexity in which there is no investment in brown technologies at time 2. The difference between the two cases reflects that when spillovers dominate there is strategic complementarity between time 1 investment and time 2 caps, while when damage convexity dominates there is strategic sustitutability between time 1 investment and time 2 caps. In line with the above discussion of Proposition 7, the intuition of the economic mechanism underlying Proposition 8 is the following: Without carbon taxation there is no investment in green technologies at time 1. This raises cumulative emissions at time 2. With strong damage convexity, such high cumulative emissions generate large costs from further emissions, making strictly positive investment in green technologies optimal.

8 Conclusion

This paper begins with the empirical observation that investment in green technologies generates spillovers. These spillovers imply complementarity between early and late investments in green technologies, as the former reduce the cost of the latter. As often the case for early-stage research and development, firms' early investments in green technologies are difficult to observe for the government. So, the government cannot directly control firms' early investments, but it can influence them via carbon taxes and emission caps. In this context, firms and government policy become strategic complements. The larger (resp. lower) firms' early investments in green technologies, the lower (resp. higher) the cost of further investment, the larger (resp. lower) the government ability to impose carbon taxes and emission caps. Because of strategic complementarities, there can be multiple equilibria. There can exist a green equilibrium, in which firms invest early in green technologies, enabling the government to implement emission caps later, and a brown equilibrium, characterized by low early investment and the absence of emission caps.

Previous literature has emphasized that it is good to invest early in green technologies and thus reduce emissions, because emissions have a quasi-permanent effect (Nordhaus, 2018); Our analysis suggests an additional reason: Early investment in green technologies reduces the cost of subsequent investments, making emission caps more politically acceptable. Our analysis also underlines the strategic complementarity among policy tools: Carbon taxes provide incentives for early investments in green technologies, which reduce the costs of further investments in green technologies and correspondingly the cost of emission caps.

Our analysis underscores the importance of anticipations about future regulations for the valuation of assets. This can help clarifying several legal and economic debates. First, there is the issue of "stranded assets" (assets tied to fossil fuels that will stop being economically profitable due to environmental regulations).[15] In our framework, the likelihood of assets becoming stranded is strongly dependent on beliefs about future regulations, and hence on the type of equilibrium that prevails. In the brown equilibrium, no assets are stranded, as future regulation does not force changes in production technologies. Second, our model provides a perspective on the emerging concept of "double materiality" which is used in framing the debate about environmental disclosure by companies. The European regulator draws a distinction between a company's disclosures that are relevant for estimating the financial value of the company ("financially material information") and disclosures that are useful for estimating the impact of the company on the environment ("environmental materi-

[15]For instance, the governor of the Bank of England, warned in 2015 about the "potentially huge" risk to investors from stranded assets, arguing that a large fraction of coal, oil and gas reserves could become "literally unburnable" and therefore deprived of financial value (Speech by Mr Mark Carney, Governor of the Bank of England and Chairman of the Financial Stability Board, at Lloyd's of London, London, 29 September 2015).

ality"). In her draft of guidelines for non-financial reporting[16], the European regulator acknowledges that these two categories overlap and might overlap even more as "public policies evolve in response to climate change". Our model shows how anticipations about *future* regulations by investors are essential in estimating the financial materiality of *current* corporate decisions, as corporate valuations take future profits into account. Moreover, it shows how these anticipations depend on information about the behavior of other companies regarding investments in decarbonation.

[16] European Commission, Guidelines on non-financial reporting: Supplement on reporting climate-related information (Official Journal of the European Union, 20.06.2019).

Proofs:

Proof of Proposition 2:

First consider the case in which $\gamma_1 < \bar{\gamma}$, so that $\gamma_2 = 0$. In that case utilitarian welfare is

$$(1 - \gamma_1 c(\gamma_0) - (1 - \gamma_0 - \gamma_1)\eta\phi)Y + \beta\,(1 - (1 - \gamma_0 - \gamma_1)\,\eta\phi)Y,$$

and its derivative with respect to γ_1 (divided by Y) is positive if $c(\gamma_0) < (1 + \beta)\eta\phi$. The left hand side of this inequality is the unit cost of time 1 decarbonization, while the right hand side is the benefit of decarbonization. Note that this condition does not depend on γ_1 except for the condition that $\gamma_1 < \bar{\gamma}$.

Second consider the case in which $\gamma_1 \geq \bar{\gamma}$, implying $\gamma_2 = 1 - \gamma_0 - \gamma_1$. In that case utilitarian welfare is

$$(1 - \gamma_1 c(\gamma_0) - (1 - \gamma_0 - \gamma_1)\eta\phi)Y + \beta(1 - (1 - \gamma_0 - \gamma_1)c(\gamma_0 + \gamma_1))Y,$$

and its derivative with respect to γ_1 (divided by Y) is

$$-c(\gamma_0) + \eta\phi + \beta c(\gamma_0 + \gamma_1) - \beta(1 - \gamma_0 - \gamma_1)c'(\gamma_0 + \gamma_1).$$

This derivative of welfare is negative at $\gamma_1 = 1 - \gamma_0 > \bar{\gamma}$ if $c(\gamma_0) > \eta\phi + \beta c(1)$. So we have an interior optimum if

$$(1 + \beta)\eta\phi > c(\gamma_0) > \eta\phi + \beta c(1).$$

This requires $\eta\phi > c(1)$, which is implied by the strong spillover assumption.

Note that, by construction welfare at $\bar{\gamma}^-$ and $\bar{\gamma}^+$ are equal. Moreover, the derivative of welfare with respect to γ_1 is positive at $\bar{\gamma}^+$ if

$$c(\gamma_0) < \eta\phi + \beta c(\gamma_0 + \bar{\gamma}) - \beta(1 - \gamma_0 - \bar{\gamma})c'(\gamma_0 + \bar{\gamma}).$$

Recall $c(\gamma_0 + \bar{\gamma}) = \eta\phi$. So the condition under which the derivative of welfare is positive $\bar{\gamma}^+$ at rewrites

$$(1 + \beta)\eta\phi - \beta(1 - \gamma_0 - \bar{\gamma})c'(\gamma_0 + \bar{\gamma}) > c(\gamma_0),$$

which is implied by $(1 + \beta)\eta\phi > c(\gamma_0)$.

Third, consider the case in which $c(\gamma_0) > (1 + \beta)\eta\phi$. In this case welfare is first decreasing, for $\gamma_1 < \bar{\gamma}$, and then concave. If the maximum of the concave part is larger than welfare estimated at $\gamma_1 = 0$, then optimal time-1 investment is $\gamma_1^* \geq \bar{\gamma}$. Otherwise, it is optimal not to invest at all.

QED

Proof of Proposition 3:

The budget balance condition rewrites

$$s = \left(\frac{1}{\gamma_0 + \gamma_1} - 1 \right) \tau.$$

In an equilibrium with $1 - \gamma_0 > \gamma_1 > \bar{\gamma}$, firms must be indifferent between investing at time 1 and at time 2. The present value of the gains of the firms investing at $t = 1$ is

$$\pi_1(\tau,_1 \gamma) := (1 + \beta)(1 + s) - c(\gamma_0) = (1 + \beta - c(\gamma_0)) + (1 + \beta) \left(\frac{1}{\gamma_0 + \gamma_1} - 1 \right) \tau,$$

which is increasing in τ. The present value of the gains of the firms that don't invest at time 1 is

$$\pi_2(\tau,\gamma_1) := (1+\beta)(1-\tau) - \beta c(\gamma_0+\gamma_1) = (1+\beta-\beta c(\gamma_0+\gamma_1)) - (1+\beta)\tau,$$

which is decreasing in τ.[17]

For $\tau = 0$, all firms prefer to wait if they anticipate $\gamma_1 \geq \bar{\gamma}$ firms will invest at $t = 1$ and $\gamma_2 = 1 - \gamma_0 - \gamma_1$ will have to invest at $t = 2$, i.e.,

$$\pi_1(\tau = 0, \gamma_1) = 1 + \beta - c(\gamma_0) < \pi_2(\tau = 0, \gamma_1) = 1 + \beta - \beta c(\gamma_0 + \gamma_1).$$

Moreover at $\tau = \bar{\tau}$, all firms prefer to invest immediately if they anticipate $\gamma_1 \geq \bar{\gamma}$ firms will invest at $t = 1$ and $\gamma_2 = 1 - \gamma_0 - \gamma_1$ will have to invest at $t = 2$, i.e.,

$$\pi_1(\tau = \bar{\tau}, \gamma_1) > 0 = \pi_2(\tau = \bar{\tau}, \gamma_1).$$

So for all $\gamma_1 \geq \bar{\gamma}$, there exists a unique $\tau(\gamma_1) \in (0, \bar{\tau})$ at which firms, anticipating that γ_1 firms will invest at $t = 1$ and emissions will be capped at $t = 2$, are indifferent between investing at time 1 and investing at time 2, i.e., $\pi_1(\tau, \gamma_1) = \pi_2(\tau, \gamma_1)$, that is

$$(1 + \beta - c(\gamma_0)) + (1+\beta)\left(\frac{1}{\gamma_0+\gamma_1} - 1\right)\tau$$

$$= (1 + \beta - \beta c(\gamma_0+\gamma_1)) - (1+\beta)\tau,$$

which yields

$$\tau = \frac{\gamma_0 + \gamma_1^*}{1+\beta}\left(c(\gamma_0) - \beta c(\gamma_0 + \gamma_1^*)\right)$$

QED

[17] Firms have limited liability which implies $\tau \leq 1 - \frac{\beta}{1+\beta}c(\gamma_0+\gamma_1) < 1$, but this constraint is not binding for reasonable parameter values, and in particular for the parameter values we use for our numerical illustration.

Proof of Proposition 5:

The derivative of the objective function given in (16) involves second period investment γ_2 only in the marginal benefit of time 2 investment, $\eta Y \varphi'((2(1 - \gamma_0 - \gamma_1) - \gamma_2)\eta Y)$, which is decreasing in γ_2. The maximum possible value of this marginal benefit corresponds to the case in which there is no investment at time 2, i.e., $\gamma_2 = 0$. In that case the marginal benefit is

$$\eta Y \varphi'((2(1 - \gamma_0 - \gamma_1)\eta Y)$$

The minimum possible value of this marginal benefit corresponds to the case in which there is full investment at time 2, i.e., $\gamma_2 = 1 - \gamma_0 - \gamma_1$. In that case the marginal benefit is

$$\eta Y \varphi'(((1 - \gamma_0 - \gamma_1)\eta Y).$$

So there are three possible cases:

- The first possible case is when

  $$\eta \varphi'((2(1 - \gamma_0 - \gamma_1)\eta Y) < c(\gamma_0 + \gamma_1)Y,$$

  implying that the optimal value of γ_2 is 0.

- The second possible case is when

  $$\eta \varphi'((1 - \gamma_0 - \gamma_1)\eta Y) > c(\gamma_0 + \gamma_1)Y,$$

  implying that the optimal value of γ_2 is $1 - \gamma_0 - \gamma_1$.

- The third possible case is when

  $$\eta \varphi'((1 - \gamma_0 - \gamma_1)\eta Y) \leq c(\gamma_0 + \gamma_1)Y \leq \eta \varphi'((2(1 - \gamma_0 - \gamma_1)\eta Y),$$

implying that the optimal value of γ_2 is interior.

We now characterize the values of γ_1 corresponding to each of these three cases.

- By the definition of $\underline{\gamma}$ given in equation (17),

$$\forall \gamma_1 < \underline{\gamma}, \eta \varphi'(2(1 - \gamma_0 - \gamma_1)\eta Y) < c(\gamma_0 + \gamma_1)Y,$$

  implying that we are in the first case, in which it is optimal to set $\gamma_2 = 0$.

- By the definition of $\bar{\gamma}$ given in equation (18),

$$\forall \gamma_1 > \bar{\gamma}, \eta \varphi'((1 - \gamma_0 - \gamma_1)\eta Y) > c(\gamma_0 + \gamma_1)Y,$$

  implying that we are in the second case, in which it is optimal to set $\gamma_2 = 1 - \gamma_0 - \gamma_1$.

- Finally, when

$$\bar{\gamma} > \gamma_1 > \underline{\gamma},$$

  we are in the third case, in which the optimal value of γ_2 is interior.

QED

Proof of Proposition 7:

As in the strong spillover case, it is useful to consider the maximum possible marginal benefit from investment at time 2, for a given γ_1, which occurs when $\gamma_2 = 0$. It is also useful to consider the minimum possible marginal benefit from investment at time 2, for a given γ_1, which occurs when $\gamma_2 = 1 - \gamma_0 - \gamma_1$.

Recall that $\underline{\gamma}$ is the value of γ_1 for which the maximum marginal benefit from investment at time 2 (occurring for $\gamma_2 = 0$) is equal to the marginal cost.

For values of γ_1 above $\underline{\gamma}$, the maximum possible benefit from investment at time 2 is below the marginal cost. So, when $\gamma_1 > \underline{\gamma}$ it is optimal to set $\gamma_2 = 0$. In contrast, for $\gamma_1 < \underline{\gamma}$, it is optimal to set $\gamma_2 > 0$. Note however that it is never optimal to fully decarbonize and set $\gamma_2 = 1 - \gamma_0 - \gamma_1$ since the marginal benefit of time 2 investment at $\gamma_2 = 1 - \gamma_0 - \gamma_1$ is always below the marginal cost. So, when $\gamma_1 < \underline{\gamma}$, the optimal time 2 investment is pinned down by the first order condition (20), which is obtained by setting the derivative of utilitarian welfare, (16), to zero.

QED

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