Large Firms, Common Ownership, and Incentives to Decarbonize and Innovate*

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We study a model of carbon emissions and green innovation which features both an environmental externality in the form of damages due to the stock of carbon and a technological externality in green innovation. When two Pigouvian instruments, carbon taxes and green innovation subsidies, are available, the social optimum can be efficiently decentralized without binding commitments by firms. However, when the level of carbon taxes and innovation subsidies are constrained, it can be optimal for large firms or coalitions of firms held by large institutional investors (common ownership) to make commitments to invest in green technologies, even if these firms and investors are purely profit-maximizing. Acting as Stackelberg leaders, their commitments spur more innovation by other firms, which ultimately reduces their own cost of decarbonization. Firm commitments also increase the credibility of government commitments to incentivize transition. We provide preliminary evidence that large firms and common ownership are associated with greater and earlier Net Zero commitments.

Keywords: Climate Change, Emissions, Carbon Taxes, Net Zero, Cap and Trade, Abatement, Green/Clean Technology, Renewables

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1 Introduction

The Paris Accord of 2015, agreed at the COP21 (21^{st} annual United Nations climate meeting), represented many milestones in climate negotiations but a central feature was that almost 200 nations agreed to focus on a quantity ("net zero") target for greenhouse gas emissions and temperature increases almost a half century away. At the recently concluded COP28 meeting, countries agreed on the need to "transition away from fossil fuels in energy systems." On the one hand, countries – especially richer countries – are expected to move away from coal, oil and gas more, but no specific timescale was agreed upon. On the other hand, the agreement includes global targets to triple the capacity of renewable energy and double the rate of energy efficiency improvements, by the year 2030.

Nevertheless, these agreements do not compel countries to take specific actions. There are many explanations for this, both political and economic, but a significant implication is that it has induced the policy research agenda to focus not only on government efforts to achieve transition but also to understand implications of corporate commitments to these quantity targets. In particular, given the inevitable lack of full government commitments to transition, what role can firm commitments play? Figure 1, using data from the Science Based Targets initiative (SBTi), shows that from no firm commitments in year 2015, just under 1500 firms globally had made net-zero commitments by 2022. What are the incentives of these firms and their investors to make such commitments, and how are government-provided incentives to decarbonize and innovate in cleaner ("green") technologies affected by these firm commitments?

We try to answer these important questions by considering a model of an economy with firms choosing their production, carbon emissions and investments in green innovation. The model allows for both an environmental externality in the form of a social cost due to the stock of carbon and a technological externality in the form of a social benefit from the stock of green innovation: the returns to green innovation are higher when there is more green innovation in the economy. Our main result is that when government commitments to employ carbon taxes or subsidize green innovation are constrained or incomplete, large firms and common ownership (effectively, coalitions of firms held by large institutional investors) can play a crucial role in accelerating the green transition. Crucially, this is so even when these firms and investors are entirely profit-maximizing rather than being altruistic.

Consider first the case with only an environmental externality. Assuming that carbon emissions by firms can be measured and Pigouvian taxes designed and implemented around

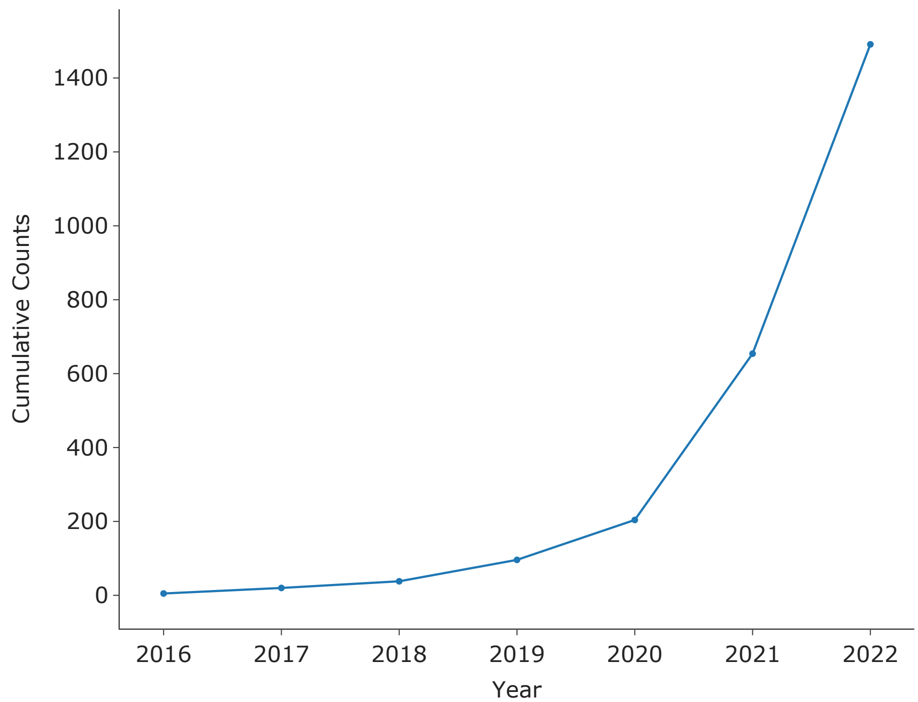


Figure 1: Total Net Zero Firm Commitments (full SBTi sample and fossil fuel firms).

them, the planner can achieve a socially optimal transition to the first-best allocation simply through a judicious design of these taxes. In particular, there is no need for commitments by the government (the entity that can implement these taxes) or the firms, in that commitments do not serve any purpose over and above the efficacy of these taxes. The private sector is forward-looking in our model and anticipates that future governments will have to set high carbon taxes if emissions remain high. This rational expectation is sufficient on its own not only to induce the optimal production plans but also the right incentives to innovate. Introducing a technological externality in innovation to the basic setup does not necessarily alter this insight. In particular, as in the seminal work of Acemoglu et al. (2012), if two separate Pigouvian instruments such as carbon taxes and green innovation subsidies are available to address the two respective externalities, then again the socially optimal transition can be decentralized without any commitment by individual governments or firms.

This benchmark result on the irrelevance of commitments then helps understand why net-zero commitments might matter in practice. The assumption that the space of policy instruments is rich enough to address the multitude of externalities in managing climate change can be considered a mere theoretical possibility. Different countries may face different constraints. For instance, the policy at present in Europe is focused more on measuring carbon emissions and taxing them, rather than measuring green innovation and incentivizing it; the opposite holds in the U.S. These are two extreme cases, and in practice every country may face some positive, but asymmetric, constraint on each instrument.

In the second-best environment featuring constrained public policies, we examine the role of commitments by the private sector in fostering efficient decarbonization. Firm commitments are defined as "over-investments" in green innovation relative to a standard decentralized equilibrium, as innovation is the only credible way firms can ensure reaching low emissions. If firms are all small (i.e., atomistic), then no individual firm will make such commitments. Commitments are only value-enhancing if they can change the firm's equilibrium payoff, and small firms cannot affect the equilibrium.

However, if some firms can coordinate their efforts towards emission reduction, then these firms recognize that if they can act as "Stackelberg leaders" and provide binding commitments to net-zero, then it would imply a transition path that would also incentivize all other firms to innovate. This would in turn produce in equilibrium a macroeconomic outcome with lower carbon tax bills for all firms, and in particular for those making the commitments in the first place. This description makes clear that the firms making commitments must be acting non-atomistically, in the sense that they realize their actions can shift the equilibrium. This can take the form of commitments by "large" firms, but also by "common ownership", i.e., coalitions of firms owned by common large institutional investors, taking into account positive spillovers in green innovation at the portfolio level.

We provide preliminary evidence (in Section 2) that this is indeed the case. Large firms in both the US and elsewhere have made (earlier) Net Zero commitments. Similarly, firms in the US owned more by large institutional investors (as reported in 13F SEC filings) have also made (earlier) Net Zero commitments. While the literature on common ownership (summarized below) has mostly emphasized potential social costs due to anti-competitive behavior, our model highlights a bright side of common ownership in the presence of externalities in green innovation.[1] In this sense, large firms and institutional investors play a role in climate change management that resembles the role of the government (or the social planner) in internalizing the benefits from technological spillovers. In the limit of a very large coalition of firm committers, the private sector can replicate the first-best allocation

[1]Recently, there have also been subpoenas issued to large investors in the US to this effect. See, for example, https://www.cnbc.com/2023/12/11/house-panel-subpoenas-vanguard-arjuna-in-esg-collusion-probe.html

as firm commitments fully substitute for the lack of green innovation subsidies.

Importantly, we always assume that the firms making commitments are *purely profit-maximizing* and do not value emission reduction per se (e.g., through investors' environmental mandates or worker preferences). The only reason these firms commit is to ultimately reduce their carbon tax burden. This carbon tax-saving motive also highlights an important asymmetry in terms of constrained public policies. We show that firm commitments have large welfare benefits in countries with carbon taxes but constrained innovation subsidies, because taxes are where firms stand to save the most by committing. By contrast, firm commitments do not improve welfare when innovation subsidies are available unconstrained but carbon taxes are constrained.

We then turn to government commitments and how they interact with firm commitments. In the case of governments, we define commitments as announcements of future carbon taxes. The reason governments may want to make strong commitments is that the anticipation of a carbon tax above and beyond the social cost of carbon stimulates ex-ante green innovation by firms seeking to reduce their future carbon tax bill. Therefore promising a high carbon tax acts as an imperfect substitute for any missing green innovation subsidy. However, a carbon tax exceeding the social cost of carbon will turn out to be time-inconsistent ex post, once green technology investments have been sunk, and the government will be tempted to lower the carbon tax back to the social cost of carbon.

We model the credibility of the government by introducing some limited commitment ability. We find that in general, when green innovation subsidies are constrained, governments will optimally promise a carbon tax above the social cost of carbon, and promise higher carbon taxes as their commitment ability increases. The key result is that *firm commitments improve government credibility*. The reason governments make commitments is to provide ex-ante incentives for green innovation when the private sector fails to internalize technological externalities. Firm commitments perform the same function, and therefore stronger firm commitments (for instance, when firms are large or institutional investors own a large fraction of firms) reduce the need of the government to promise high future carbon taxes, thereby making the government's promises more credible.

Related literature

The seminal paper of Weitzman (1974) gave the first analysis of the relationship between pricing carbon and setting emissions caps. He pointed out that in a stochastic world, setting prices would make the quantity uncertain and by setting quantities, the price becomes uncertain. Hybrid policies which have regulation of some sectors, cap and trade in others and net-zero targets in still others are much harder to analyze. While the overall literature on carbon taxes and caps and trade policies is now large, Adrian, Bolton and Kleinnijenhuis (2022) have recently provided quantitative estimates of gains to the world GDP from phasing out coal as the "great carbon arbitrage" strategy for climate change in a framework that factors in several attendant effects.

Another strand of literature focuses on setting carbon prices in a multiperiod problem given the critically important observation that climate change and its managements are inherently very long-horizon issues. Models such as the DICE model of Nordhaus (2017) – and more recent IAMs – and the model of Daniel, Litterman and Wagner (2019) calculate a dynamic version of carbon prices taking into account costs of adjustment in some cases and risk aversion in others (often reaching startlingly different conclusions). Towards the end of the paper, we too draw out some conclusions for dynamics of transition and commitments in our setup.

Turning to green innovation and its undertakers, recent empirical work sheds some light even though technological spillovers first theorized in Acemoglu et al. (2012) and Acemoglu et al. (2016) are yet to be understood fully. Cohen, Gurun and Nguyen (2020) infer that innovation subsidies could be efficient for innovation incentives given that such innovations are typically associated with firms that have lower ESG governance scores. Bolton, Kacperczyk and Wiedemann (2023) find and suggest, however, that green technical progress in itself does not lead to reduction of emissions by innovating and other firms, in the short term or in the medium term, suggesting a necessary role for carbon taxes.

Our model is consistent with this literature in requiring *both* carbon taxes and innovation subsidies for efficiency, but assumes there are policy limitations in its attainment and focuses in such a setting on the role of firm commitments. Besley and Persson (2023) study how lack of government commitment can prevent or slow down the green transition; we study how firm commitments alleviate the government's burden in this context. Acemoglu and Rafey (2023) argue that under lack of government commitment, the anticipation of geoengineering breakthroughs and lower future carbon taxes undermines incentives to switch to green technology. Biais and Landier (2022) show that lack of government commitment to future carbon taxes (or equivalently caps) and strategic complementarities between firms arising from technological externalities can lead to equilibrium multiplicity. Pedersen (2023) studies a unified model of carbon pricing and green investing affecting firms' cost of capital as a function of their emissions. One key result that emerges is that when carbon taxes are suboptimal (below the social cost of carbon), green investing provides a useful alternative but requires firms to credibly commit to reducing emissions in order to obtain a lower cost of capital. Our focus instead is on the role of large firms and common ownership in spurring green transition taking as given their ability to make credible commitments.

In this regard, López and Vives (2019) show theoretically that common ownership can lead to internalization of rivals' profits by firms, which leads to more efficient investments in cost-reducing R&D investments when innovation spillovers are sufficiently high. Antón et al. (2021) also posit such a potentially bright side to common ownership, and verify empirically that it is beneficial to innovation outcomes (measured as increase in citation-weighted patents) when technological spillovers (proximity in patent space) across firms are stronger relative to product-market spillovers (proximity in product market space).

In the legal scholarship and closer to the climate-change application, Condon (2020) argues conceptually, as we derive theoretically, that (diversified) common-owner investors should rationally be motivated to internalize intra-portfolio negative externalities, and that this portfolio perspective can explain the increasing climate-change related activism of institutional investors. Relatedly, Gasparini, Haanaes and Tufano (2022) also explain how dealing with carbon emissions effectively requires cooperation amongst companies across industries, but that in several jurisdictions "law might get in the way" by considering this as a form of anti-trust violation. Similarly, Miazad (2023) argues that Investor Climate Alliances (ICAs) provide a novel and necessary mechanism for climate governance via large, diversified investors ("universal owners"), rather than being an anti-trust concern.

More broadly, a growing empirical (e.g., Dimson, Karakas and Li 2015, Krueger et al. 2020) and theoretical (e.g., Broccardo, Hart and Zingales 2022, Oehmke and Opp 2022) literature on investor activism compares the impact of shareholder engagement mechanisms, i.e., "voice", with divestment or "exit" policies.

Finally, our results on the interaction of firm and government commitments are consistent with the empirical findings of Bolton and Kacperczyk (2021). Firm and government commitments are substitutable as they document. However, our model also shows that they are complementary in terms of credibility. Firm commitments in our model make government commitments more credible, even though the government reduces its commitment; in fact, it is exactly because the government does not need to commit to such a high carbon tax when firms take on a larger share of the job that the government becomes more credible. To the best of our knowledge, this form of complementarity between firm and government commitments has not yet been tested in data.

2 Motivating Evidence

In November 2016, the Paris Agreement marked a pivotal moment in global efforts to combat climate change. A significant aspect of this accord was the commitment made by numerous countries, and in turn, by their firms, to strive for Net-Zero emissions by 2050. We provide preliminary evidence below of factors influencing firms' decisions to join this Net-Zero commitment.

We collect the data from Science Based Targets initiative (SBTi) and Net Zero Tracker to analyze firm commitment dynamics. SBTi provides a dashboard on the website with firms' status on the way to Net Zero, which is updated weekly to reflect the new changes. We downloaded the data of firms making SBTi net-zero commitments from the website on 11 November, 2022. As of this date, 1491 firms had already made net-zero commitments in the full sample dataset. In addition, we collect data of fossil fuel firms from Net Zero Tracker since SBTi does not include any fossil fuel firms. Together, these add up to 1562 firms. We then merge the firm sample with Compustat (Global & North America) datasets by firms' ISINs to get information about their firm sizes. For firms with missing or wrong ISINs, fuzzy match was conducted based on their name, location, and region. As a result, we have 679 firms that that can be merged with the Compustat dataset.

We use to measure the size of a firm its market capitalization (market cap), calculated as the product of the close price of the day for the security (prccd) and shares outstanding (cshoc) in the year the firm joined the SBTi net-zero commitment. For firms with missing market cap during that year, we use the market cap of the year closest to the firm commitment year within the 2015–2022 period. Based on the market cap, firms are further divided into four size categories: large ($10 billion or more), medium ($2 billion to $10 billion), small ($250 million to $2 billion), and micro-small ($250 million or less). We also categorize firms into 10 industries following the Global Industry Classification Standards (GICS) 2-digit sectors. The largest three industries in the full sample are Industrials (33.87%), Consumer Discretionary(20.52%), and Consumer Staples (11.60%), while the largest three industries in the matched sample, as shown in Appendix A.1, are Industrials (22.3%), Consumer Discretionary (19.47%), and Information Technology (13.14%). Appendix B.1 provides summary statistics of outcome and explanatory variables in our analysis of the matched sample.

2.1 Effect of Firm Size

First, we investigate the relationship between firm size and net-zero commitments.

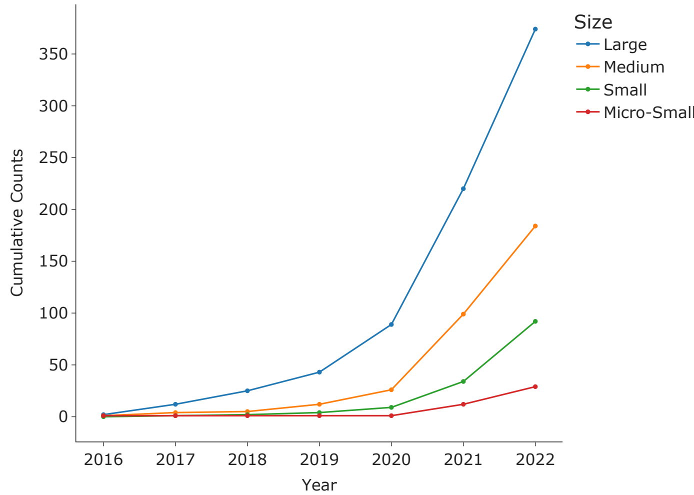


Figure 2: Cumulative Number of Firms Joining Net-Zero commitments by Firm Size (full SBTi sample). Firm size is measured by market cap: Large ($10 billion or more), medium ($2 billion to $10 billion), small ($250 million to $2 billion), and micro-small ($250 million or less).

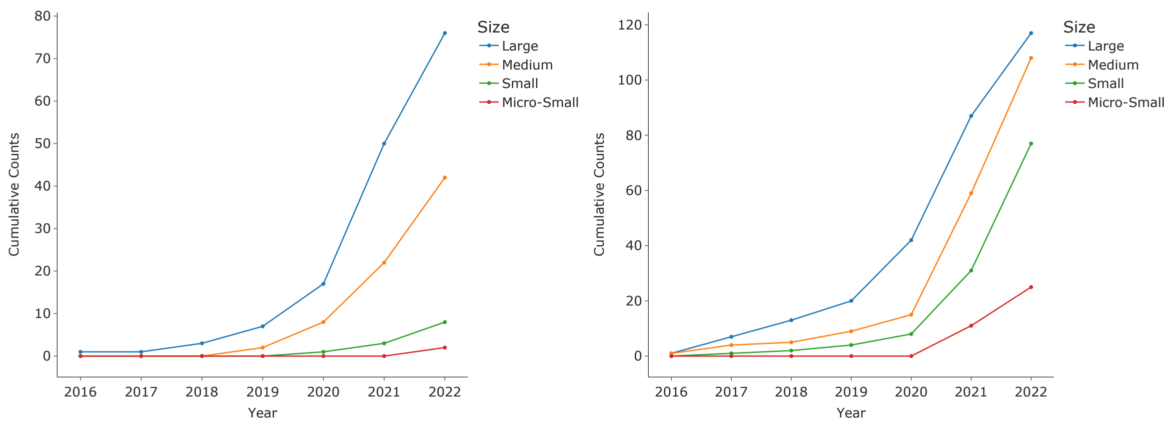


Figure 3: Cumulative Number of Firms Joining Net-Zero commitments by Firm Size (North America vs Europe). Left: North America; Right: Europe.

Figures 2 and 3 show that between 2016 and 2022, larger firms consistently outpaced their smaller peers in terms of joining the commitment early, respectively in the global sample as well as samples restricted to North America and Europe. The lines representing the commitment trajectory of firms in each size group, measured as the number of firms that have already commited to Net Zero, exhibit steeper inclines for larger firms most of the time, underscoring their more pronounced dedication to Net-Zero goals. These patterns are similar for the top three industries in our sample, viz., Industrials, Consumer Discretionary, and Information Technology, as shown in Appendix A.2.

Table 1 verifies this relationship econometrically by showing that firm size, employed as an explanatory variable as logarithm of market cap or within-sample cardinal rank of market cap, has a significant impact on firm's decision to make the Net-Zero commitment, including in the presence of industry fixed effects. In Columns (1)–(3), we employ the dependent variable calculated as one or zero based on commitment at any point in the sample period. In Columns (4)–(6), we instead employ the dependent variable calculated as the number of years since commitment by the firm, measured in 2023 (e.g., if the firm entered the commitment in 2017, then the variable is 6; in 2022, it is 1).[2]

2.2 Effect of Common Ownership

Next, we investigate the role of common ownership by examiming firm stock holdings by large institutional investors. Common ownership is defined as percentage of shares held by all 13F investors (as per their SEC 13F filings), who are institutional investment managers with over $100 million investment discretion. Table 2 shows that common ownership held by 13F investors captures cross-sectional variation in firm's net-zero commitment, both whether to enter the commitment and whether to be an early mover, including in the presence of industry fixed effects and controlling for the weighted average size of investors of a firm (weighted by percentages held of the firm).

Note that some firms have larger than 100% shares held by 13F investors. The main reason for the inflated ownership is that SEC 13F filings don't include short positions, leading to double counting issues. In addition, some brokers may report their positions as their holdings. Therefore, to ensure the robustness of our result, the firms with larger than 120% shares were dropped for all regression analysis. After restricting the sample further to the

[2]While we estimate the relationships in ordinary least squares regression, it is robust to estimating logit or probit model in columns (1)–(3) and as ordered logit or probit in columns (4)–(6) (results available upon request).

Table 1: Effect of Firm Size

	Net-Zero (1/0)			Net-Zero Time		
	(1)	(2)	(3)	(4)	(5)	(6)
Firm Size (log(mktcap))	0.228***	0.228***		0.510***	0.505***	
	(13.88)	(13.71)		(13.25)	(12.93)	
Firm Size (rank(mktcap))			0.405***			0.870***
			(12.72)			(11.64)
Constant	0.046***	0.046***	-0.029***	0.093***	0.093***	-0.068***
	(13.66)	(13.70)	(-4.23)	(11.76)	(11.81)	(-4.23)
Industry FE	No	Yes	Yes	No	Yes	Yes
Observations	3,708	3,708	3,708	3,708	3,708	3,708
Adj R^2	0.049	0.058	0.052	0.045	0.056	0.048

Notes: Table 1 shows the relation between firm size and firm's decision to enter the Net-Zero commitment. Log and rank form of firm's market cap are used as proxies for the firm size. Two dependent variables are: (1) a dummy variable indicating whether the firm enters the commitment; (2) the number of years since commitment until 2023 (if the firm entered the commitment in 2017, $Y = 6$; in 2022, $Y = 1$). Investor size is computed as the logarithm of the total equity (AUM) of each investor. Independent variables are measured as of Sep 30, 2017. We control for industry fixed effects as indicated.

Table 2: Effect of Common Ownership

	Net-Zero (1/0)			Net-Zero Time		
	(1)	(2)	(3)	(4)	(5)	(6)
Pct Shares by 13F Investors	0.054***	0.052***	0.048***	0.102***	0.095***	0.091***
	(4.73)	(4.45)	(3.87)	(3.77)	(3.50)	(3.11)
Investor Size (log(aum))			0.029			0.037
			(0.81)			(0.43)
Constant	0.012	0.013	-0.001	0.029	0.033*	0.015
	(1.44)	(1.63)	(-0.05)	(1.53)	(1.73)	(0.33)
Industry FE	No	Yes	Yes	No	Yes	Yes
Observations	3,708	3,708	3,708	3,708	3,708	3,708
Adj R^2	0.006	0.016	0.016	0.004	0.017	0.016

Notes: Table 2 shows the relation between common ownership held by 13F investors, investor size and firm's decision to enter the Net-Zero commitment. Common ownership dataset from Backus et al (2017) and total shares outstanding from CRSP are used to construct the dataset. Two dependent variables are: (1) a dummy variable indicating whether the firm enters the commitment; (2) the number of years since commitment until 2023 (if the firm entered the commitment in 2017, $Y = 6$; in 2022, $Y = 1$). Investor size for a firm is computed as the logarithm of the total equity (AUM) of each investor and then weighted by the percentages held by each investor of the firm. Independent variables are measured as of Sep 30, 2017. We control for industry fixed effects as indicated. See more descriptive details about the ownership data in Appendix B.1 and B.2 (Figure 18).

Table 3: Effect of Common Ownership (Sample of Bottom 90% Percentage Shares)

	Net-Zero (1/0)			Net-Zero Time		
	(1)	(2)	(3)	(4)	(5)	(6)
Pct Shares by 13F Investors	0.083***	0.082***	0.080***	0.156***	0.154***	0.152***
	(6.33)	(6.20)	(5.64)	(5.06)	(4.97)	(4.59)
Investor Size (log(aum))			0.014			0.010
			(0.37)			(0.12)
Constant	-0.000	0.000	-0.006	0.006	0.008	0.003
	(-0.04)	(0.05)	(-0.32)	(0.32)	(0.38)	(0.06)
Industry FE	No	Yes	Yes	No	Yes	Yes
Observations	3,338	3,338	3,338	3,338	3,338	3,338
Adj R^2	0.012	0.024	0.024	0.007	0.023	0.023

firms with the bottom 90% percentage shares, results in Table 3 are consistent, and in fact, with stronger effects (coefficients are to 1.5 to 2 times larger). This can also be verified visually. Appendix B.2 (Figure 18) shows that the cumulative count of net-zero committing firms by common ownership is robust within quartiles 2-4 (roughly below 90% of percentage shares owned by 13F investors), but quartile 1 does not fit the pattern. Note also that Appendix B.3 shows that our firm size and common ownership variables are correlated, so we do not employ a horse-race between them in explaining firm commitment; this would require instruments for each to do it well, which is beyond the scope of this mostly theoretical paper.

3 Model: Decarbonization and Technological Transition

Motivated by the evidence presented, we seek to build a model of firms' net-zero commitments. To start with, we lay out the simple building block featuring a model of decarbonization and green innovation that we will then use to study policies such as carbon taxes, green innovation subsidies, and Net Zero commitments. We start with a static, one-period, model, and discuss dynamics in Section 8.

3.1 Setup

Production. Consider an economy with one good, used for both consumption and investment. There is a unit mass of firms indexed by i. Firm i can transform k_i units of the good into y_i units according to the technology

$$y_i = f(k_i)$$

where f is increasing, concave, and differentiable.

Emissions and environmental externality. Production generates carbon emissions e_i as a by-product, assumed proportional to investment

$$e_i = \theta_i k_i$$

where θ_i denotes the emission intensity of firm i.

Emissions generate an environmental externality that depends on the total stock of carbon dioxide, or more generally greenhouse gases. The carbon stock depends on emissions through

$$Z = Z_0 + E$$

where Z_0 is the initial carbon stock and

$$E = \int_i e_i di = \int_i \theta_i k_i di$$

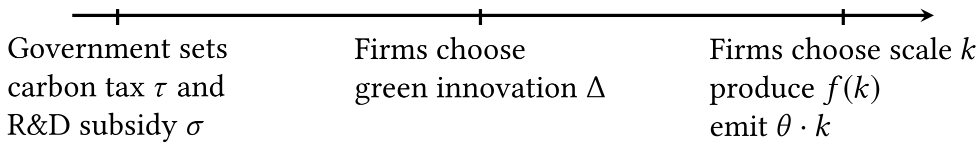
denote total emissions. Environmental externalities are captured by a flow damage function that depending on the current carbon stock. Since we take Z_0 as given in the static model we can rewrite damages as a function of emissions $\mathcal{L}(E)$. Damages are increasing and weakly convex in aggregate emissions, that is $\mathcal{L}' \geq 0, \mathcal{L}'' \geq 0$. For simplicity we assume damages are additive, in the sense that $\mathcal{L}$ does not depend on output. It is useful to define the marginal externality γ:

$$\gamma = \mathcal{L}'(Z), \tag{1}$$

also known as the social cost of carbon (SCC).

Green innovation and technological externality. Starting from an initial level θ_0, firms can adjust their emission intensity before undertaking production. Each firm chooses a level of innovation or clean technology adoption Δ such that the new emission intensity

Figure 4: Baseline timing.



is

$$\theta = \theta_0 - \Delta - \chi \bar{\Delta}$$

at a cost $C(\Delta)$ that is increasing and convex in $\Delta \geq 0$. The impact of green innovation on emission intensity θ can also be viewed as capturing the choice between alternative production technologies. In Appendix D we show how our model can be mapped to a model in which firms have a choice between two technologies, brown and green, such that the brown technology has a higher productivity but higher emission intensity.

The baseline timing is described in Figure 4; later on we augment this timeline with potential firm and government commitments.

As in Acemoglu et al. (2012), Aghion et al. (2016) and the literature that followed, we emphasize the presence of two interacting externalities. In addition to the environmental externality, there is a technological externality in the adoption of green technology. The parameter $\chi \geq 0$ captures how the economy's average innovation or adoption

$$\bar{\Delta} = \int_i \Delta_i di,$$

where the integral is over all the firms i in the economy, also lowers emission intensity through technological externalities or innovation spillovers. More green innovation increases the returns to green innovation (in terms of reduction in emission intensity θ). As we shall see, the dual externality is crucial in creating a role for public and private commitments.

Remark. Our formulation is equivalent to letting firms choose their new emission intensity θ at a cost $C(\theta_0 - \theta - \chi \bar{\Delta})$ so that the technological externality acts as a reduction in the cost required to reach emission intensity θ instead of a higher return to green innovation.

3.2 Functional forms

We make the following assumptions on the functions f, C and $\mathcal{L}$ to obtain transparent closed form solutions and analytical results. Firms have a quadratic production technology

$$f(k) = (1 + a)k - \frac{k^2}{2}, \quad k \in [0, 1 + a]$$

with $a > 0$, and a quadratic innovation cost

$$C(\Delta) = c\frac{\Delta^2}{2}.$$

The damage function is linear

$$\mathcal{L}(Z) = \gamma Z$$

hence the social cost of carbon γ is independent of the level of emissions, which can be viewed as a first-order approximation around some baseline level. In Section 8 we discuss interesting implications of a convex damage function.

4 First-Best Allocation and Pigouvian Benchmark

Social welfare is defined as net production minus environmental damages:

$$W = \int_i [f(k_i) - k_i - C(\Delta_i)]\, di - \mathcal{L}\left(\int_i (\theta_{i0} - \Delta_i - \chi\bar{\Delta})k_i di\right). \tag{2}$$

The first term captures production net of costs and investments in green technology. The second term captures the damages from emissions.

With symmetric firms, the first best allocation (in which the social planner can choose all variables, i.e., production and innovation) maximizes (2) taking into account that $\bar{\Delta} = \Delta_i$ hence solving:

$$\max_{\{k,\Delta\}} f\,(k) - k - C\,(\Delta) - \mathcal{L}([\theta_0 - \Delta(1 + \chi)]\,k)$$

Throughout the paper we make the following assumptions on parameters:

Assumption 1. *The cost of green innovation is high enough:*

$$c > \gamma^2(1 + \chi)^2, \tag{3}$$

and the initial emission intensity is low enough:

$$a > \gamma\theta_0. \tag{4}$$

Condition (3) ensures that green innovation remains finite under the first-best ($\Delta < \infty$) while (4) ensures that there is positive production under the first-best (otherwise "full degrowth" $k = 0$ would be optimal).

Proposition 2 (First Best)**.** *The first-best allocation is*

$$k^{FB} = \frac{a - \gamma\theta_0}{1 - \gamma^2(1+\chi)^2/c},$$
$$\Delta^{FB} = \frac{\gamma(1+\chi)(a - \gamma\theta_0)}{c - \gamma^2(1+\chi)^2}.$$

In the expression for k^{FB} the numerator $a - \gamma\theta_0$ shows the optimal production in a "no-innovation" benchmark $c \to \infty$, such that green innovation is unavailable and thus the only way to limit emissions is to restrict production. In general a higher SCC γ has two effects on the optimal production scale k^{FB}. It reduces the numerator $a - \gamma\theta_0$, but the positive effect on the denominator shows that a higher γ implies more innovation (higher Δ) which allows to increase production relative to the "no-innovation" benchmark $c \to \infty$.

The expression for Δ^{FB} reflects that the optimal innovation increases with the strength of innovation externalities χ, which in turns allows to increase production.

4.1 Implementation: Carbon Taxes and Green Innovation Subsidies

The first-best allocation can be implemented in a decentralized equilibrium using two fiscal instruments. A carbon tax τ implies that a firm must pay τ per unit of emissions, i.e., $\tau\theta k$ if its emission intensity is θ and it invests k. A clean or green innovation subsidy σ—also known as research and development (R&D) subsidy—means that a firm earns σ per unit of clean R&D expenditure, i.e., the firm receives $\sigma\Delta$ if it decreases its emission intensity by Δ. Since Δ can be mapped to a choice of green technology as explained above, the subsidies we consider also encompass green investment tax credits as in the United States' Inflation Reduction Act.

A firm facing a carbon tax τ and an innovation subsidy σ maximizes profits by solving

$$\max_{k,\Delta} f(k) - k - \tau(\theta_0 - \Delta - \chi\bar{\Delta})k - C(\Delta) + \sigma\Delta$$

taking the average innovation $\bar{\Delta}$ as given. Examining the private first-order optimality conditions with respect to k and Δ, respectively:

$$
\begin{aligned}
f'(k) &= 1 + \tau(\theta_0 - \Delta - \chi\bar{\Delta}) \\
C'(\Delta) &= \tau k + \sigma
\end{aligned}
$$

and imposing $\bar{\Delta} = \Delta$ in equilibrium, we obtain the following implementation of the first-best allocation:

Proposition 3. *The first best allocation can be implemented in a competitive equilibrium with taxes and subsidies using a carbon tax $\tau^{FB} = \gamma$ and a clean innovation subsidy $\sigma^{FB} = \chi\gamma k^{FB}$.*

The optimal carbon tax simply equals the social cost of carbon γ. The optimal innovation subsidy is proportional to the strength of the technological externality χ and the social cost of carbon γ, since the technological externality only matters to reduce emissions. The point of the subsidy is to make firms internalize the effect of their individual innovation on the average innovation $\bar{\Delta}$, which helps towards reducing emissions without sacrificing production; this is why σ^{FB} also depends on k^{FB}.

4.2 Time-Consistency

The production stage happens after firms have chosen their innovation and thus taking emission intensities as given. At the innovation stage, firms' decisions are affected both by the innovation subsidy σ they currently face and the carbon tax τ they expect in the future. At the production stage, however, the only policy tool left to curb emissions is the carbon tax τ.

Definition 4. A policy requires commitment if at the ex-post stage, once emission intensities are fixed, the government can improve welfare by setting a different tax τ. A policy is time-consistent if it does not require commitment.

Corollary 5. *The optimal policy (τ^{FB}, σ^{FB}) does not require commitment.*

For any given emission intensity, the ex-post optimal carbon tax is equal to the social cost of carbon γ. Since $\tau^{FB} = \gamma$ the government has no incentive to deviate ex-post to a different carbon tax. The joint optimal policy is time-consistent because there is no point in using the future expected carbon tax to affect ex-ante innovation decisions when innovation can already be steered through subsidies. This echoes results in the literature on macroprudential regulation and bailouts (e.g., Jeanne and Korinek, 2020).

In particular, if there are no technological externalities, $\chi = 0$, then $\sigma^{FB} = 0$ and the first best can be achieved with a single instrument, a carbon tax set without commitment.

5 Constrained Policies and Second-Best Analysis

The presence of two externalities requires the use of two unconstrained Pigouvian instruments to achieve the first best. In the rest of the paper we will consider constraints on these two instruments of the form

$$\tau \leq \bar{\tau}, \quad \sigma \leq \bar{\sigma}$$

that, when binding, make the first best unattainable. Different countries face different constraints, and to understand the range of outcomes obtained in the second best we focus on two extreme cases. We interpret broadly the case of a carbon tax with no subsidies ($\bar{\tau}$ high, $\bar{\sigma}$ low) as the "European" case, and case of unconstrained subsidies but a stringent constraint on the politically feasible level of the carbon tax ($\bar{\tau}$ low, $\bar{\sigma}$ high) as the "U.S." case.

In addition the potential upper bounds on fiscal instruments $\bar{\tau}$ and $\bar{\sigma}$, we consider various assumptions on the commitment abilities of firms and governments. We first analyze optimal policies absent any firm and government commitments.

5.1 Constrained Innovation Subsidies

Suppose firms choose Δ anticipating a tax τ^{nc}, and τ^{nc} is then set ex post without commitment to maximize welfare once innovation Δ is already sunk. Moreover the government does not have access to an innovation subsidy. Thus the government sets its only tool τ to solve

$$\begin{aligned} &\max_{k,\tau} f(k) - k - \mathcal{L}\left(\left(\theta_0 - \Delta(1+\chi)\right) k\right) \\ &\text{s.t. } f'(k) = 1 + \tau(\theta_0 - \Delta(1+\chi)) \end{aligned}$$

which leads to the Pigouvian result

$$\tau^{nc} = \gamma.$$

The ex-post optimal tax is the same as the first-best tax, equal to the social cost of carbon.

However, the equilibrium without innovation subsidies departs substantially from the first best allocation in the presence of technological externalities. Ex ante, firms invest in green technology Δ given an expected carbon tax τ^{nc} at the production stage, thus they solve:

$$\max_{\Delta,k} f(k) - k(1 + \tau^{nc}(\theta_0 - \Delta - \chi\bar{\Delta})) - C(\Delta)$$

taking the average innovation $\bar{\Delta}$ as given. Equating $\bar{\Delta} = \Delta$ in equilibrium, firms' optimality conditions can be rewritten as

$$\begin{aligned} f'(k) &= 1 + \tau^{nc}(\theta_0 - \Delta(1 + \chi)) \\ C'(\Delta) &= k\tau^{nc} \end{aligned}$$

Therefore we can characterize the no-commitment equilibrium as follows:

Proposition 6. *The no-commitment equilibrium without subsidies is*

$$\begin{aligned} k^{nc} &= \frac{a - \gamma\theta_0}{1 - \gamma^2(1 + \chi)/c} \\ \Delta^{nc} &= \frac{\gamma k^{nc}}{c} \end{aligned}$$

If $\chi > 0$ then the no-commitment equilibrium features suboptimal innovation and production

$$\Delta^{nc} < \Delta^{FB}, \quad k^{nc} < k^{FB}.$$

The lack of innovation subsidy leads to under-investment green innovation relative to the first-best. Each firm fails to internalize that increasing its own innovation would lead to a larger decrease in emission intensity for all firms, which would lower their carbon tax bill for a given production scale k, and therefore allow them to increase their scale. As a result, firms end up under-producing as well.

In the next sections we show that the technological externality creates a motive for firms to coordinate and increase innovation through firm commitments, and for governments to commit to a carbon tax exceeding the first-best tax, $\tau > \gamma$, in order to partially substitute for the lack of innovation subsidy.

5.2 Constrained Carbon Taxes

Consider the opposite case: there are unconstrained subsidies σ, but the carbon tax is set at an exogenous and inefficiently low level $\bar{\tau} \leq \gamma$. This configuration can be interpreted as the case of the U.S., in which carbon taxes are much less feasible than innovation subsidies politically.

Firms' first-order conditions given a carbon tax $\bar{\tau}$ and an innovation subsidy σ are

$$\begin{aligned} f'(k) &= 1 + (\theta_0 - \Delta(1+\chi))\bar{\tau} \\ C'(\Delta) &= \bar{\tau}k + \sigma, \end{aligned}$$

showing that any level of innovation Δ can be implemented by setting a sufficiently high subsidy σ. We can thus rewrite the problem of the government as choosing k and Δ subject to a constraint tying k and $\bar{\tau}$:

$$\begin{aligned} &\max_{k,\Delta} f(k) - k - C(\Delta) - \mathcal{L}([\theta_0 - \Delta(1+\chi)]\, k) \\ &\text{s.t. } f'(k) = 1 + \bar{\tau}[\theta_0 - \Delta(1+\chi)] \end{aligned}$$

This leads to the following alternative second-best policy:

Proposition 7. *The optimal innovation subsidy given a carbon tax $\bar{\tau} \leq \gamma$ is*

$$\sigma^*(\bar{\tau}) = \chi k(\bar{\tau})\gamma + (\gamma - \bar{\tau})\left\{k(\bar{\tau})(1 + 1/a) - 1\right\}$$

where

$$k(\bar{\tau}) = \frac{a - \bar{\tau}\theta_0 - \frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{c}}{1 - \frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{ac} - \frac{\bar{\tau}\gamma}{c}(1+\chi)^2}.$$

In particular when $\bar{\tau} = 0$,

$$\begin{aligned} k(0) &= a, \\ \sigma^*(0) &= (1+\chi)\gamma a. \end{aligned}$$

If $\bar{\tau} = \gamma$ then we recover the first-best innovation subsidy $\sigma^{FB} = \chi\gamma k^{FB}$. In the first best the only reason to subsidize innovation is to take advantage of the technological externality. When the carbon tax is constrained, $\bar{\tau} < \gamma$, it is optimal to subsidize green innovation even more relative to the first best, in order to partially offset the inefficiently low carbon tax. This is, however, a highly inefficient way to reduce emissions since it targets emission intensity while letting production relatively undistorted if $\bar{\tau}$ is low, whereas the first best would require both innovation and a reduction in k.

A particularly simple case is when there is no technological externality, $\chi = 0$. In that case there would be no innovation subsidy in the first best ($\sigma^{FB} = 0$) but the optimal subsidy absent a carbon tax ($\bar{\tau} = 0$) is $\sigma = \gamma a$.

Another benchmark is the case without feasible green innovation, i.e., the cost c goes to infinity. Then $\Delta \to 0$ and emission intensity remains at its initial level θ_0 and innovation subsidies have no effect, leaving emissions without carbon taxes at $E = \theta_0 a$, whereas the optimal carbon tax would reduce emissions to $E^{FB} = \theta_0(a - \gamma\theta_0)$.

6 Firm Commitments

We now study the recent rise of *corporate* commitments, as documented in, e.g., Bolton and Kacperczyk (2021). What are private firms' incentives to commit, and what is the impact of their commitments on social welfare? Our main result is that the technological externality creates a motive for firms to coordinate and increase innovation, even if they are purely profit-maximizing and not concerned about environmental damages. Firm commitments are good substitutes for innovation subsidies, but we also show that they cannot substitute for suboptimal carbon taxes, as in our model the only reason for firms to commit credibly is to ultimately reduce their carbon tax bill.

We model this interaction as a game in which the government acts first by announcing policies, then a subset of firms commit by choosing Δ, then other non-committing firms choose Δ, and finally firms produce. Figure 5 shows the timeline with firm commitments, with the node in red highlighting the difference with Figure 4.

In our model, firms can reduce emissions by either reducing their emission intensity θ or scaling down production k. The only way for firms to credibly "commit" to reducing emissions is to invest in Δ and reduce their emission intensity, as ex post they can be expected to choose the optimal production scale k given their outstanding emission intensity. Investments in green technology Δ are also the only source of benefits from firm commitments in our model, as any firm's ex-post production decision k is irrelevant for other firms, whereas investments Δ have the potential to affect other firms' decisions through the technological externalities.

6.1 Stackelberg Equilibrium in Green Innovation

We now turn to a setup in which some firms may find it optimal to commit to "overinvest" in green innovation in the sense of choosing Δ above the ex-post optimal level.

Figure 5: Timing with firm commitments.

Suppose that the economy is populated by large and small firms; for simplicity we consider one large firm of "size" $\mu \in [0, 1]$ and a measure $1-\mu$ of small firms. "Large" means that individual actions by this single firm can affect the equilibrium, *and the firm internalizes this.* A large firm is thus somewhere between small firms and the government we analyzed earlier. Relative to the government, it still lacks the power to tax other firms: it can only choose its own policies $\left\{k^l, \Delta^l\right\}$. Yet the large firm can potentially find it optimal to credibly commit to policies that would be ex post suboptimal, if the commitment is able to steer the equilibrium in a direction it likes.

In this section we take the carbon tax τ as given; we will later let the government optimize τ taking into account the private sector's response, including through commitments. There is a mass $1-\mu$ of small (atomistic) firms and a large firm with size μ. The limit $\mu \to 0$ corresponds to the model with only small firms, in which no firm is willing to commit.

An alternative interpretation is that the large firm captures a *coalition* of a mass μ of small firms that can coordinate their actions, for instance because they are all owned by a large institutional investor. Most of the literature on common ownership has emphasized anti-competitive effects in product markets, although recent work has highlighted that in the presence of innovation spillovers, common ownership may have a bright side, e.g., López and Vives (2019) and Antón et al. (2021). Our model also emphasizes the potential benefits of common ownership for the green transition.

Non-Committers. For given emission intensity Θ by the large firm, and other emission intensities θ by other small firms, hence average intensity $\bar{\Delta} = \mu\Delta^l + (1-\mu)\Delta^s$, a small firm with initial emission intensity θ_0 solves the following problem:

$$\max_{\Delta, k} \quad f(k) - C(\Delta) - k - \tau(\theta_0^s - \Delta - \chi\left[\mu\Delta^l + (1-\mu)\Delta^s\right])k + \sigma\Delta.$$

Hence firms only care about their carbon bill, not directly about reducing damages. As a result the only large firm commitment that matters for small firms (conditional on τ) is Θ.

The fixed point to this problem gives reaction functions for small firms as a function of the large firm's commitments

$$\left\{k(\Delta^l, \tau, \sigma), \Delta^s(\Delta^l, \tau, \sigma)\right\}$$

solving the following system

$$\begin{aligned} f'(k^s) &= 1 + \tau(\theta_0^s - \Delta^s - \chi \left[\mu\Delta^l + (1-\mu)\Delta^s\right]) \\ c\Delta^s &= \tau k + \sigma \end{aligned}$$

With our functional forms we can obtain closed-form solutions for the small firms' policy functions for investment

$$k^s(\tau, \sigma, \Delta^l) = a - \tau(\theta_0^s - \Delta^s - \chi \left[\mu\Delta^l + (1-\mu)\Delta^s\right]$$

and innovation

$$\Delta^s(\tau, \sigma, \Delta^l) = \frac{\tau\left(a - \tau\theta_0^s\right) + \sigma}{c - \tau^2(1 + \chi(1-\mu))} + \frac{\chi\tau^2\mu}{c - \tau^2(1 + \chi(1-\mu))}\Delta^l. \tag{5}$$

Assume that the technological externality is not too strong

$$c > \tau^2(1 + \chi(1-\mu))$$

to get a finite solution. Equation (5) gives small firms' best-response innovation Δ^s given firm commitments Δ^l by firms in the coalition and government policies τ and σ.

A key derivative that enters the large firm's Stackelberg leader problem is the slope of reaction of small firms' innovation, and thus θ, to the large firm's innovation:

$$\frac{\partial\Delta^s}{\partial\Delta^l} = \frac{\tau^2\chi\mu}{c - \tau^2(1 + \chi(1-\mu))} > 0.$$

Naturally, the larger μ, the stronger the innovation externalities $\chi\bar{\Delta}$ and in turn the more each individual small firm outside the coalition responds. The mechanism driving the positive spillovers $\frac{\partial\Delta^s}{\partial\Delta^l} > 0$ is that when firm commitments are stronger (larger Δ^l), small firms outside the coalition are able to increase production k^s, and given this higher scale the returns to their own green innovation are also higher. For this reason the effect of firm commitments on green innovation by outside firms is also increasing in τ: a higher tax makes outside firms more responsive to firm commitments, because the innovation externality has a stronger impact on scale k^s when carbon taxes are higher. Conversely in a country with low carbon taxes, production scale becomes decoupled from green innovation and thus there are no spillovers from large firms' commitments to outside small firms.

Committers. In our setting, the only way some firms can make a commitment that affects the equilibrium is through their ex-ante choice of green innovation Δ. The large firm or coalition of firms making a commitment acts as Stackelberg leader, and solves

$$\max_{\Delta,k} f(k) - C(\Delta) - k - \tau(\theta_0^l - \Delta(1+\chi\mu) - (1-\mu)\chi\Delta^s(\Delta))k + \sigma\Delta$$

taking as given government policies and the reaction function of outside firms.

We can describe the full Stackelberg equilibrium in closed form as follows:

Proposition 8 (Equilibrium with Firm Commitments)**.** *Given government policies (τ, σ), equilibrium firm policies are given by:*

$$\Delta^l(\tau,\sigma) = \frac{c(\tau(\mu\chi+1)(a-\theta_0\tau)+\sigma) + \tau^2(\tau(\chi+1)(\theta_0\tau - a) + \sigma(-((\mu-1)\chi(\mu\chi-1))-1))}{c^2 - c\tau^2\left(\chi\left(\mu^2\chi+2\right)+2\right) + \tau^4(\chi+1)^2}$$

and

$$\begin{aligned}
k^l(\tau,\sigma) &= \frac{c}{\tau\left[1+\chi\left(\mu+(1-\mu)\frac{\tau^2\chi\mu}{c-\tau^2(1+\chi(1-\mu))}\right)\right]}\Delta^l(\tau,\sigma) \\
\Delta^s(\tau,\sigma) &= \frac{\tau\left(a-\tau\theta_0^s\right)+\sigma}{c-\tau^2(1+\chi(1-\mu))} + \frac{\tau^2\chi\mu}{c-\tau^2(1+\chi(1-\mu))}\Delta^l(\tau,\sigma) \\
k^s(\tau,\sigma) &= \frac{c\left(a-\tau\theta_0^s\right)+\tau\sigma(1+\chi(1-\mu))}{c-\tau^2(1+\chi(1-\mu))} + \frac{c\tau\chi\mu}{c-\tau^2(1+\chi(1-\mu))}\Delta^l(\tau,\sigma)
\end{aligned}$$

With a Pigouvian carbon tax $\tau = \gamma$ and no innovation subsidy $\sigma = 0$, in the extreme cases $\mu \to 1$ and $\mu \to 0$ we recover the first-best allocation and no-commitment equilibrium, respectively:

$$\begin{aligned}
\lim_{\mu\to 1}\Delta^l &= \gamma(1+\chi)\frac{a-\gamma\theta_0^l}{c-\gamma^2(1+\chi)^2} = \Delta^{FB} \\
\lim_{\mu\to 0}\Delta^l &= \gamma\cdot\frac{(a-\gamma\theta_0^l)}{c-\gamma^2(1+\chi)} = \Delta^{nc}
\end{aligned}$$

A large share of the effect comes from the direct externalities *within* the coalition μ of firm committers, in addition to the positive spillover effects on the mass $1-\mu$ of small firms outside the coalition characterized by (5). When μ is small, firm commitments only have a small effect on outsiders, hence it is not optimal for committers to act strongly. When μ is large, firm commitments have a large effect on outsiders but there are not many outsiders and most of the adjustment comes directly from committers. Spillover effects are maximal for intermediate values of μ.

6.2 Welfare Implications of Firm Commitments

We now study how firm commitments impact welfare and how this depends on government policies. Denote

$$W(\tau, \sigma, \mu)$$

the welfare, defined as net output minus environmental damages as in (2), under a carbon tax τ, an innovation subsidy σ, and optimal firm commitments by a coalition of size μ as described in Proposition 8.

Irrelevance of Firm Commitments with Optimal Innovation Subsidies. We first show a simple irrelevance result: in the presence of unconstrained green innovation subsidies, firm commitments (that is, $\mu > 0$) cannot increase welfare relative to an equilibrium without commitments ($\mu = 0$).

To see this, suppose that $\mu = 1$ hence the entire private sector acts as a single coalition. In this case the optimal firm commitment solves

$$\max_{\Delta,k} f(k) - k - C(\Delta) + \sigma\Delta - \bar{\tau}\left[\theta_0 - (1+\chi)\Delta\right]k.$$

The two optimality conditions are

$$f'(k) = 1 + \bar{\tau}\left[\theta_0 - (1+\chi)\Delta\right], \tag{6}$$

$$C'(\Delta) = \sigma + \bar{\tau}(1+\chi)k. \tag{7}$$

Notice that relative to the case of no firm commitments ($\mu = 0$) studied in Section 5.2, the only difference is that the optimality condition with respect to Δ is (7) instead of

$$C'(\Delta) = \sigma + \bar{\tau}k.$$

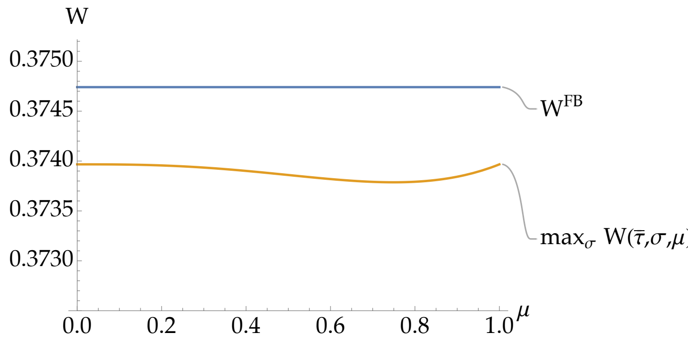


Figure 6: Welfare as a function of the size of the firm commitment coalition μ with constrained carbon tax $\bar{\tau} < \gamma$ and optimal innovation subsidy, compared to First Best.

However, once we allow the government to optimize freely over the innovation subsidy σ, the distinction becomes irrelevant: by increasing σ the government can always replicate what would be achieved by firm commitments. As a result

$$\max_{\sigma} W(\bar{\tau}, \sigma, 1) = \max_{\sigma} W\left(\bar{\tau}, \sigma, 0\right).$$

The same argument shows that for any coalition size $\mu \in [0, 1]$, the solution to a fictitious relaxed problem that allows the government to set different innovation subsidies for committers and non-committers is also equal to $\max_{\sigma} W(\bar{\tau}, \sigma, 0)$. Therefore the maximum welfare when the same innovation subsidy cannot differ across firms is weakly lower. As a result we have:

Proposition 9. *Firm commitments cannot improve welfare if the government can set an optimal innovation subsidy:*

$$\max_{\sigma} W(\bar{\tau}, \sigma, \mu) \leq \max_{\sigma} W(\bar{\tau}, \sigma, 0) \quad \forall \mu \in [0, 1].$$

In particular, firm commitments can never achieve the first-best welfare W^{FB} if the carbon tax is below the social cost of carbon, $\bar{\tau} < \gamma$, even as $\mu \longrightarrow 1$.

This result, illustrated in Figure 6, embodies an important lesson: in our model firm commitments are good substitutes for innovation subsidies but they cannot substitute for carbon taxes. They are thus most useful when a carbon tax is available, as in the case of Europe, and, as we discussed previously, they also make carbon taxation more credible by lowering the required tax towards the Pigouvian level.

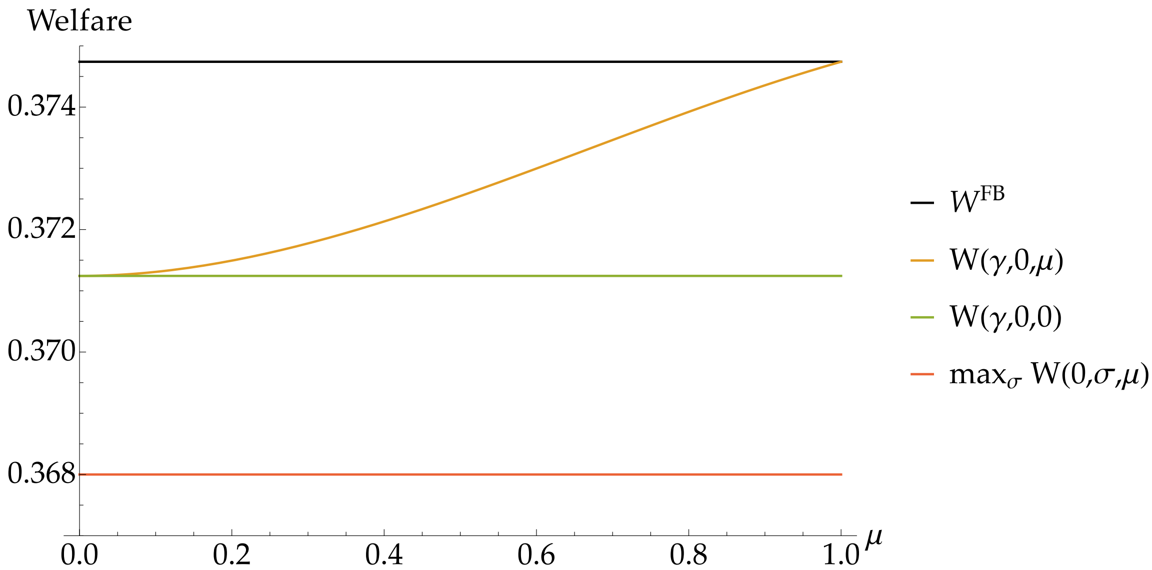


Figure 7: Welfare as a function of the size of the firm commitment coalition μ, compared to three benchmarks: first best ($\mu = 1$), Pigouvian carbon tax without innovation subsidies ($\tau = \gamma$, $\mu = 0$), and no carbon taxes but optimal subsidies ($\bar{\tau} = 0$).

Welfare Comparisons. Our main normative result compares welfare under different configurations of government policies and firm commitments:

Proposition 10 (Welfare ranking)**.** *Suppose that technological externalities are not too large:*

$$\chi \leq \frac{1}{2\gamma^2}\left\{c + \sqrt{c\left(\sqrt{c}-\gamma\right)\left(3\gamma + \sqrt{c} - 4\gamma^2\theta_0/a\right)} + \gamma\sqrt{c}\right\} - 1, \tag{8}$$

where the right-hand side is always positive under Assumption 1. Then for any $\mu \in [0,1]$ we have the following welfare ranking:

$$\max_{\sigma} W(0,\sigma,\mu) \leq W(\gamma,0,0) \leq W(\gamma,0,\mu) \leq W(\gamma,0,1) = W^{FB}.$$

Proposition 10 shows a simple ranking. First, carbon taxes are essential, in the sense that the welfare without tax ($\bar{\tau} = 0$) is lowest even when optimal subsidies and firm commitments are available. Subsidies and firm commitments are mostly targeting green innovation, but this is never sufficient and scaling down production remains necessary. Without carbon tax the private sector always overproduces ($k = a$), which ends up generating too many emissions in spite of the lower emission intensity achieved thanks to green innovation.

Figure 7 illustrates the result by showing the different values of welfare, as a function of the strength of firm commitments measured by μ. In the case of a Pigouvian carbon tax $\tau = \gamma$, as μ increases towards 1, $W(\gamma, 0, \mu)$ converges to the first-best welfare. With optimal innovation subsidies but no carbon tax ($\bar{\tau} = 0$), welfare $\max_{\sigma} W(0, \sigma, \mu)$ is almost unaffected by the strength of firm commitments μ, consistent with Proposition 9 and Figure 6.

A central point is that firm commitments improve upon welfare and are optimal from the perspective of firms in the coalition even though we make the conservative assumption that *all firms are purely profit-maximizing* and do not take into account damages in their objective function. We thus abstract from any ESG-motives that may lead firms to invest in green technology and reduce emissions above and beyond the simple pecuniary benefits of reducing their expected carbon tax bill. These extrinsic preferences for emission reduction could be expressed, for instance, through ESG-investing making firms' cost of capital contingent on their emissions (Pastor et al., 2021; Pedersen, 2023). One of our main points is that even without such preferences there may be an economic rationale to "over-invest" in green technology from the perspective of large firms or institutional investors in the presence of technological externalities.

Our model provides a new perspective on the effect of common ownership on firm decisions. While the literature has focused on negative effects working through diminished competition between firms owned by the same institutional investors, we highlight a potential brightside of common ownership.[3] The mechanism is closely related since in both the cases of market power and our case with technological externalities, common ownership leads firms to internalize externalities on other firms. In the case studied by the literature they internalize the effect of their pricing and production decisions on other firms' profits and respond by increasing prices and weakening competition. In our case firms internalize the effect of their green technology adoption on other firms' ultimate emission intensity. In the next section we introduce an additional consideration which is the endogenous response of government policies (i.e., carbon taxes) to firms' commitments.

6.3 Incentives to Commit

Profits in the equilibrium with firm commitments are higher than in the equilibrium without firm commitments, for both the firms that commit ("committers") and the firms that do

[3] López and Vives (2019) and Antón et al. (2021) are two exceptions that also highlight the potential benefits of common ownership on general innovation that affects productivity. We focus on *green* technology that affects emission intensity, and the interaction with other frictions and policies, i.e., environmental externalities and carbon taxes.

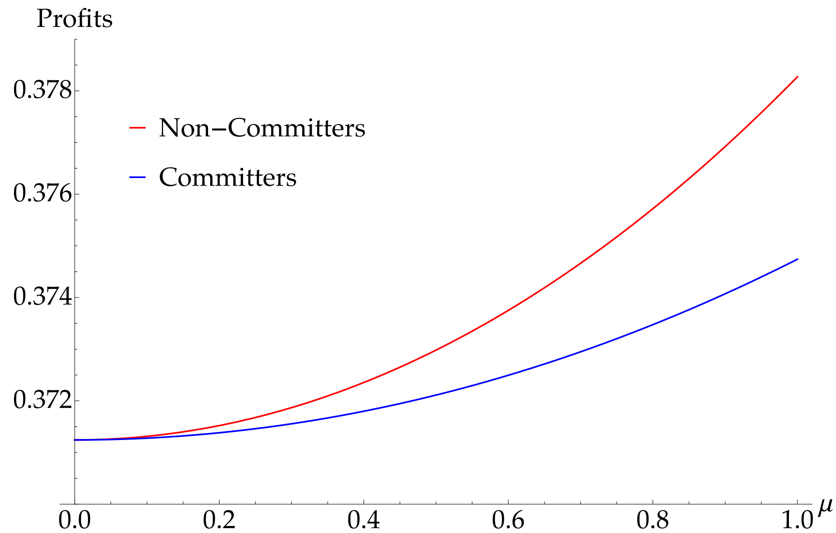


Figure 8: Equilibrium firm profits Π for committers and non-committers as a function of coalition size μ. Here $\bar{\tau} = \gamma$ and $\sigma = 0$.

not ("non-committers"). For both types of firms we can compute the increase in profits Π_i where

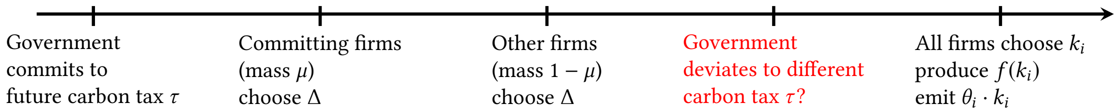
$$\Pi_i = f(k_i) - k_i - C(\Delta_i) - \bar{\tau}\left[\theta_0 - \Delta_i - \chi\bar{\Delta}\right] k_i + \sigma\Delta_i$$

resulting from a shift in the equilibrium from no firm commitments to commitments by a coalition of size μ. For now we hold policies fixed; in the next section we also allow policies to vary in response to firm commitments.

Figure 8 shows the profits for firms making commitments ("committers") and firms outside the coalition ("non-committers"). Profits are higher relative to the case $\mu = 0$ which corresponds to no firm commitments. The increase in profits for the committers shows the strength of their incentives to commit, that is, how much they gain by shifting the equilibrium thanks to technological externalities, even without any extrinsic preferences for lower emissions.

The non-committing firms (in mass $1-\mu$) obtain even higher profits than the committers, and the gap increases with μ. This implies that ex-post committers have an incentive to deviate and free-ride on the commitments of the coalition, as this would yield the positive externalities from the firm commitments without the cost of having to "over-invest" in the clean technology. In our interpretation, however, the firms in the coalition would not be able to deviate unilaterally, as they are owned by a large institutional investor acting as common owner.

Figure 9: Timing with firm and government commitments.



7 Government Commitments

We have seen that government policy is time-consistent if two unconstrained Pigouvian instruments, carbon taxes and green innovation subsidies, are available. In a second-best environment there is a role for government commitments to carbon taxes above the ex-post optimal level, in order to give the private sector stronger ex-ante incentives to reduce emission intensity.

We now extend the model to allow for both firm and government commitments and study their interactions. We focus on the case of constrained innovation subsidies, since this is the case that makes government and firm commitments relevant. Hence to simplify we assume $\sigma = 0$ throughout this section.

We model government commitments as promises to increase carbon taxes in the future. These promises may have limited credibility, hence we explicitly model governments' commitment ability and solve for the government's optimal response to firm commitments.

The main results in this section are two-fold. First, the government has an incentive to commit to a future carbon tax that exceeds the social cost of carbon and therefore the ex-post optimal Pigouvian level $\tau = \gamma$. Promising a tax $\tau > \gamma$ is an indirect way to strengthen the private sector's incentives to invest in green innovation and reduce emission intensity. However this government commitment policy is time-inconsistent and thus not always credible.

Our second main finding is that *firm commitments improve government credibility.* Stronger firm commitments (i.e., a larger μ) have a positive impact on the government's ability to commit because they take away part of the burden from the government and reduce the need for an abnormally high carbon tax to stimulate innovation. With strong firm commitments, the government can optimally promise a lower carbon tax. The temptation to lower the carbon tax ex post is weaker, which makes the initial commitment more credible.

Figure 9 shows the timeline with both firm and government commitments, with the node in red highlighting the difference with Figure 5.

7.1 Full Government Commitment

We have seen that with two unrestricted policy instruments, carbon taxes and innovation subsidies, the government can achieve the first best and does not face any time-inconsistency problem while doing so. Suppose now that the government can set a tax τ^c that differs from the ex post optimum level $\tau^{nc} = \gamma$ and has full commitment ability.

No Firm Commitments. The government takes into account that firms' choice of Δ depends on the carbon tax they expect at the production stage. Given a carbon tax commitment τ^c and no firm commitments (i.e., $\mu = 0$), firms solve

$$\max_{k,\Delta} f(k) - k\left[1 + \tau^c(\theta_0 - \Delta)\right] - C(\Delta)$$

hence their first-order optimality conditions are

$$f'(k) = 1 + \tau^c(\theta_0 - \Delta) \tag{9}$$

$$C'(\Delta) = k\tau^c \tag{10}$$

Conversely, the government can use τ^c to implement any pair (k, Δ) satisfying the implementability condition

$$f'(k) = 1 + \frac{C'(\Delta)}{k}(\theta_0 - \Delta). \tag{11}$$

Thus the optimal commitment maximizes social welfare

$$f(k) - k - C(\Delta) - \mathcal{L}([\theta_0 - \Delta(1+\chi)]\,k)$$

subject to (11). We obtain the following result:

Proposition 11. *Without innovation subsidies, the optimal carbon tax under full commitment $\kappa = \infty$ and no firm commitments is between γ and $\gamma(1+\chi)$.*

The first-best optimality conditions are $f'(k) = 1 + \gamma\theta$ for production, and $C'(\Delta) = \gamma(1+\chi)k$. Contrasting these conditions with (9)-(10) shows that it is impossible to satisfy both at the same time, but committing to a tax τ^c between γ and $\gamma(1+\chi)$ strikes a middle ground.

Figure 10 illustrates the result by showing the optimal tax as a function of the technological externality parameter χ. In the absence of innovation subsidies, the government

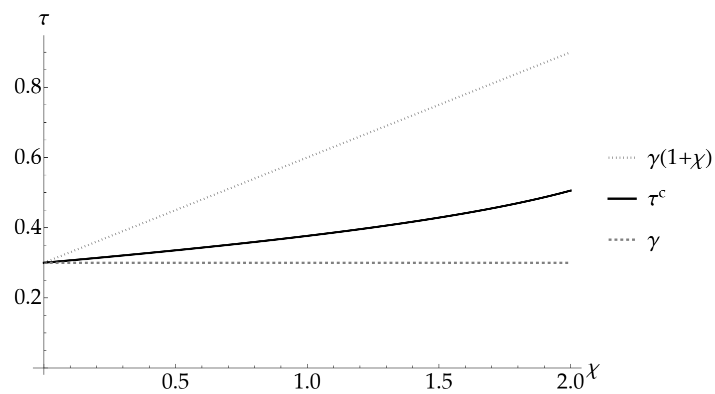


Figure 10: Optimal carbon tax under full commitment as a function of χ, without firm commitments ($\mu = 0$).

finds it optimal to commit to a carbon tax that is *above* the social cost of carbon, $\tau^c > \gamma$. By making carbon emissions privately more costly, the higher carbon tax stimulates innovation and thus allows to partly take advantage of technological externalities in emission reduction. The efficient way to stimulate innovation would be to use a "carrot" subsidy. Stimulating innovation through the carbon tax "stick" improves upon the no commitment outcome, but comes at the cost of lowering production much more than would be desirable in the first best. Proposition 11 shows again that without technological externalities ($\chi \to 0$) no commitment is needed and the Pigouvian carbon tax $\tau = \gamma$ is optimal both ex ante and ex post.

In the case of a constraint the carbon tax $\tau \leq \bar{\tau}$ but unconstrained innovation subsidies, the time-consistency constraint is only binding for carbon taxes and irrelevant for the choice of subsidies. This means that given a constrained carbon tax $\bar{\tau}$, the optimal innovation subsidy under commitment is the same as described in Section 5.2.

Firm Commitments. With firm commitments of size μ, the government solves a similar problem but now takes into account the private sector's response to the anticipated carbon tax τ by both committers and non-committers, captured by the reaction functions

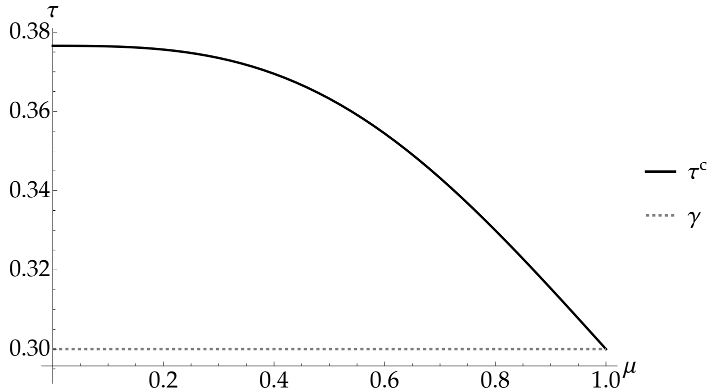


Figure 11: Optimal carbon tax under full commitment as a function of firm commitments μ.

$\Delta^i(\tau, \mu), k^i(\tau, \mu)$:

$$\max_{\tau} \quad \mu \left\{ f(k^l(\tau, \mu)) - k^l(\tau, \mu) - C(\Delta^l(\tau, \mu)) \right\} + (1-\mu) \left\{ f(k^s(\tau, \mu)) - k^s(\tau, \mu) - C(\Delta^s(\tau, \mu)) \right\}$$
$$- \gamma \left\{ \mu(\theta_0 - \Delta^l(\tau, \mu) - \chi\bar{\Delta}(\tau, \mu))k^l(\tau, \mu) + (1-\mu)(\theta_0 - \Delta^s(\tau, \mu) - \chi\bar{\Delta}(\tau, \mu))k^s(\tau, \mu) \right\} \tag{12}$$

Figure 11 shows the solution to this problem, i.e., the optimal government commitment τ^c as a function of μ. The optimal government commitment falls with the strength of firm commitments μ, and converges to the social cost of carbon γ when $\mu \to 1$ as firm commitments become sufficient to take full advantage of the technological externalities.

7.2 Limited Government Commitment

We now turn to the case of limited commitment ability. Our main finding is that firm commitments improve government credibility. When more firms commit (higher μ), the government's optimal commitment is less harsh, getting closer to its ex-post optimal tax γ, which makes the commitment more credible since the government gains relatively less ex-post from deviating.

Modeling Government Credibility. We model government commitments as promises about future carbon taxes. The objective of such promises is to provide stronger incentives for green innovation ex ante, but these promises may have limited credibility because they entail deviating from the ex-post optimum. We start with a simple model of governments' commitment ability, before solving from the government's optimal commitment and how it is affected by firm commitments.

The ex-post social welfare given a carbon tax τ, once innovation Δ^i has taken place for firms of type $i = l, s$, is

$$V(\Delta^l, \Delta^s, \tau, \mu) = \mu[f(k^l) - k^l] + (1-\mu)[f(k^s) - k^s] \\ - \gamma \left\{ \mu(\theta_0 - \Delta^l - \chi\bar{\Delta})k^l + (1-\mu)(\theta_0 - \Delta^s - \chi\bar{\Delta})k^s \right\}$$

where

$$f'(k^i) = 1 + \tau(\theta_0 - \Delta^i - \chi\bar{\Delta})k^i, \quad \text{for } i = l, s. \tag{13}$$

Equation (13) captures the fact that firms adjust their production according to the tax τ, which is why changing the tax may improve welfare. For instance, if the government promised a high carbon tax to incentivize green innovation ex ante, sticking to the promised tax implies a lower production than deviating to a lower tax.

Given linear damages, the ex-post optimal tax is extremely simple, always equal to γ. Therefore deviating from a commitment τ^c, given that firms chose Δ believing the tax would be τ^c, yields an ex-post welfare gain

$$\begin{aligned} \Delta V(\tau^c, \mu) &= \max_{\tau} V(\Delta^l(\tau^c, \mu), \Delta^s(\tau^c, \mu), \tau, \mu) - V(\Delta^l(\tau^c, \mu), \Delta^s(\tau^c, \mu), \tau^c, \mu) \\ &= V(\Delta^l(\tau^c, \mu), \Delta^s(\tau^c, \mu), \gamma, \mu) - V(\Delta^l(\tau^c, \mu), \Delta^s(\tau^c, \mu), \tau^c, \mu), \end{aligned}$$

where the firms' policy functions $\Delta^i(\tau^c, \mu)$ are given by Proposition 8 specialized to $\sigma = 0$.

We assume that the government has some limited commitment ability. The government faces some penalty $\kappa \geq 0$ if it deviates from its commitment.

Definition 12. A carbon tax τ is credible if and only if the following incentive compatibility (IC) constraint holds:

$$\Delta V(\tau, \mu) \leq \kappa \tag{14}$$

For a government commitment to be credible, the promised tax τ must not be too far away from the ex-post optimal tax γ, so that the ex-post welfare gain from deviating to $\tau = \gamma$ remains smaller than the parameter κ that captures, e.g., the loss in reputation. If $\kappa = 0$ then the government will always deviate to $\tau = \gamma$ so no commitment is possible. A higher κ means a stronger commitment ability. The limit $\kappa = \infty$ corresponds to a government with full commitment as in Section 7.1.

Optimal Government Commitment. The government should take its own capacity κ into account when setting an optimal commitment, and realize that it is allowed to depart somewhat from the ex-post optimum $\tau = \gamma$ if it can improve ex-ante incentives to innovate. Thus the optimal government commitment is the solution to a principal-agent problem of the ex-ante government with its future incarnation: given firm commitments of strength μ, the government chooses τ to maximize (12) subject to an additional incentive constraint (14). We denote the solution

$$\tau^c_{IC}(\mu, \kappa).$$

Therefore we have $\tau^c(\mu) = \lim_{\kappa\to\infty} \tau^c_{IC}(\mu, \kappa)$. In general this problem cannot be fully solved analytically, but we characterize the solution before showing numerical results in Figures 12 and 13.

The welfare wedge $\Delta V(\tau^c(\mu), \mu)$ decreases with μ and goes to zero as $\mu \to 1$, hence there exists a minimal firm coalition size $\underline{\mu}$ (decreasing in the government's commitment ability κ) such that the IC constraint (14) is slack for $\mu \geq \underline{\mu}$ but binding for $\mu < \underline{\mu}$. In the region $\mu \geq \underline{\mu}$ the government can simply commit to the optimal commitment $\tau^c(\mu)$ under $\kappa = \infty$ as studied in Section 7.1.

In the region $\mu < \underline{\mu}$ the government cannot commit to $\tau^c(\mu)$ as such a high tax would not be credible given its limited commitment capacity κ. The government then optimally commits to a lower, but credible, carbon tax $\tau^c_{IC}(\mu, \kappa) < \tau^c(\mu)$. The incentive-compatible tax τ^c_{IC} increases with commitment power κ and naturally converges to $\tau^c(\mu)$ as $\kappa \to \infty$. In this region the tax $\tau^c_{IC}(\mu, \kappa)$ can be found by solving for the tax τ that makes the IC constraint (14) bind:

$$\kappa = V(\Delta^l(\tau, \mu), \Delta^s(\tau, \mu), \gamma, \mu) - V(\Delta^l(\tau, \mu), \Delta^s(\tau, \mu), \tau, \mu).$$

In general, when μ is higher (more firm commitments), the optimal government commitment with infinite credibility, $\kappa = \infty$, $\tau^c(\mu)$ falls. But τ^c is not the actual commitment observed; the actual tax τ^c_{IC} is non-monotone in μ. In the region $\mu < \underline{\mu}$, the optimal credible commitment $\tau^c_{IC}(\mu, \kappa)$ is increasing in the strength of firm commitments μ, hence government and firm commitments are complements in strength; in the region of strong firm commitments $\mu \geq \underline{\mu}$, this dependence is reversed as the IC constraint (14) is slack and $\tau^c_{IC}(\mu, \kappa) = \tau^c(\mu)$, which is decreasing in the strength of firm commitments μ, as shown in Figure 12.

Firm commitments make government commitments more credible. The reason is that

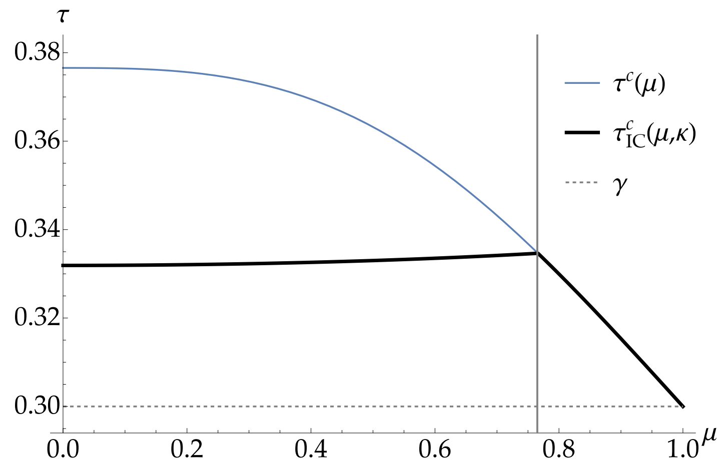


Figure 12: $\tau^c_{IC}(\mu, \kappa)$ as a function of μ. The vertical line denotes $\underline{\mu}$.

the government can weaken its commitment when firm commitments are strong, i.e., τ^c falls with μ. As a result, firm and government commitments are substitutes in terms of strength in the region $\mu \geq \underline{\mu}$, consistent with Bolton and Kacperczyk (2021). Yet our model highlights a different form of interaction, which is that firm and government commitments are complements in terms of credibility. It is exactly because the government does not need to commit to such a high carbon tax when firms take on a larger share of the job that the government becomes more credible.

Figure 13 shows welfare, as a deviation from the first-best welfare, as a function of the strength of firm commitments μ, for different values of the government's commitment ability κ. As firm commitments become stronger (μ increases), welfare increases faster with finite commitment ability κ than with infinite credibility $\kappa = \infty$: this reflects the positive effect of firm commitments on government credibility.

Incentives to Commit. We can revisit firms' and investors' incentives to commit, first discussed in Section 6.3, when government policies respond endogenously to the strength of firm commitments. Figure 14 shows the profits of committers and non-committers as a function of μ, taking into account the response of the optimal government commitment $\tau^c_{IC}(\mu, \kappa)$. The dashed lines show the extreme case of no government commitment $\kappa = 0$ and thus no response of the carbon tax (i.e., Figure 8). With some positive commitment ability κ, as in the solid lines, we see that incentives to commit can become much stronger in the region $\mu > \underline{\mu}$. We can interpret this result as saying that firm commitments may be limited at first, until they reach a critical mass $\underline{\mu}$ which spurs a strong complementarity

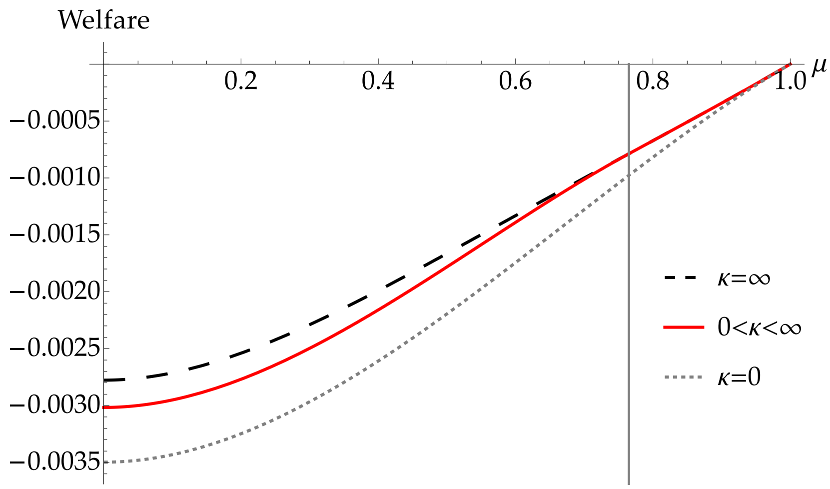


Figure 13: Ex-ante welfare (measured as deviation from first-best welfare) as a function of μ when varying firm and government commitment power. The vertical line denotes $\underline{\mu}$.

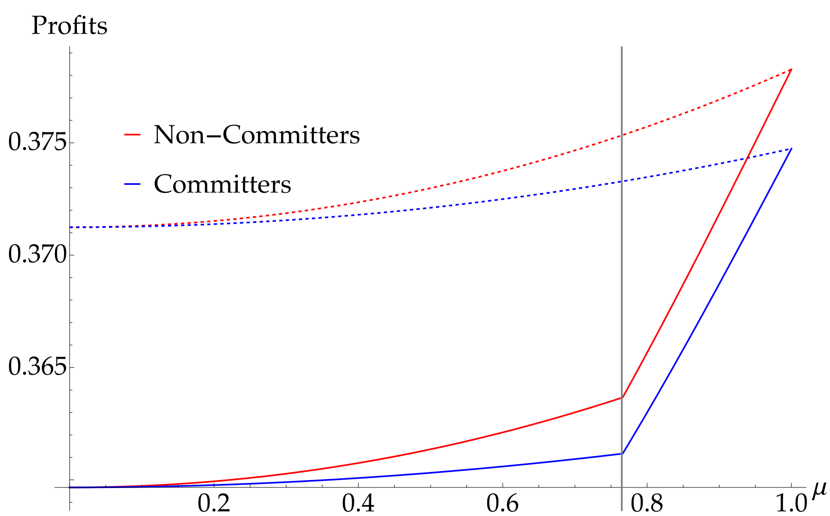


Figure 14: Equilibrium firm profits Π for committers and non-committers as a function of coalition size μ when the carbon tax is $\tau^c_{IC}(\mu, \kappa)$ with $\kappa > 0$. The dashed lines show the case without any government commitment, $\kappa = 0$, and thus $\tau = \gamma$.

with government policies that makes firm commitments even more profit-enhancing.

8 Extensions [TBC]

8.1 Nonlinear Damages

8.2 Dynamics

8.3 Price vs. Quantity Commitments

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A Net-Zero Firm Sample

A.1 Summary Statistics

Industry	Counts	Percentage
Industrials	134	22.30%
Consumer Discretionary	117	19.47%
Infomation Technology	79	13.14%
Consumer Staples	66	10.98%
Materials	60	9.98%
Financials	55	9.15%
Energy	38	6.32%
Communication Services	38	6.32%
Health Care	35	5.82%
Real Estate	29	4.83%
Utilities	28	4.66%
Total	679	100%

Table 4: Firm Distribution by Industry

A.2 Figures

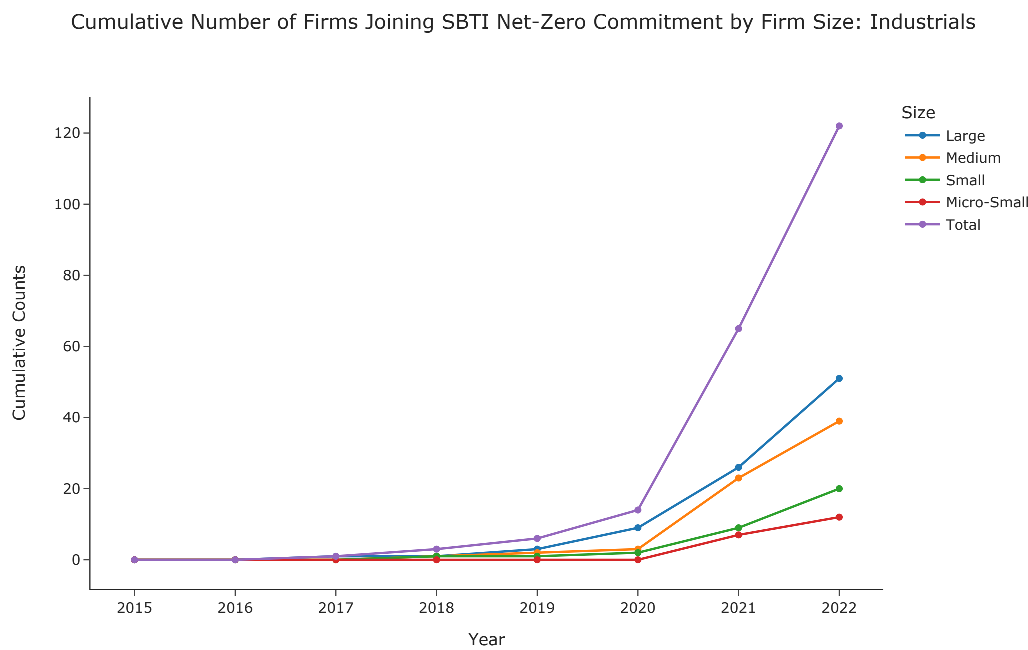

Figure 15: Net Zero commitments by firms across firm size groups in the "Industrials" industry. Firm size is measured by market cap: Large ($10 billion or more), medium ($2 billion to $10 billion), small ($250 million to $2 billion), and micro-small ($250 million or less).

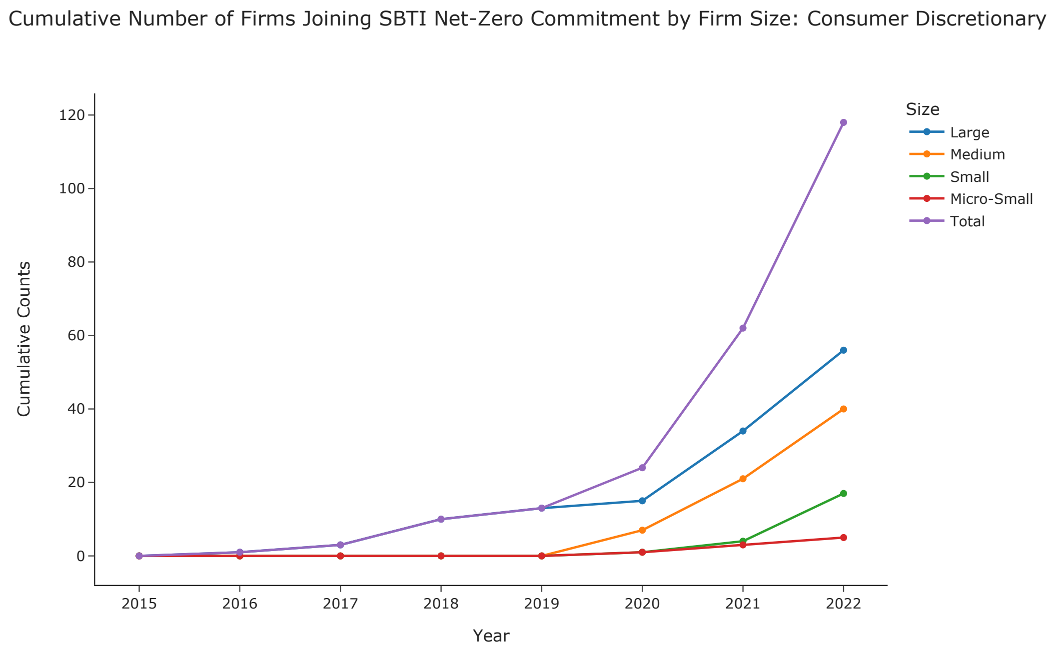

Figure 16: Net Zero commitments by firms across firm size groups in the "Consumer Discretionary" industry. Firm size is measured by market cap: Large ($10 billion or more), medium ($2 billion to $10 billion), small ($250 million to $2 billion), and micro-small ($250 million or less).

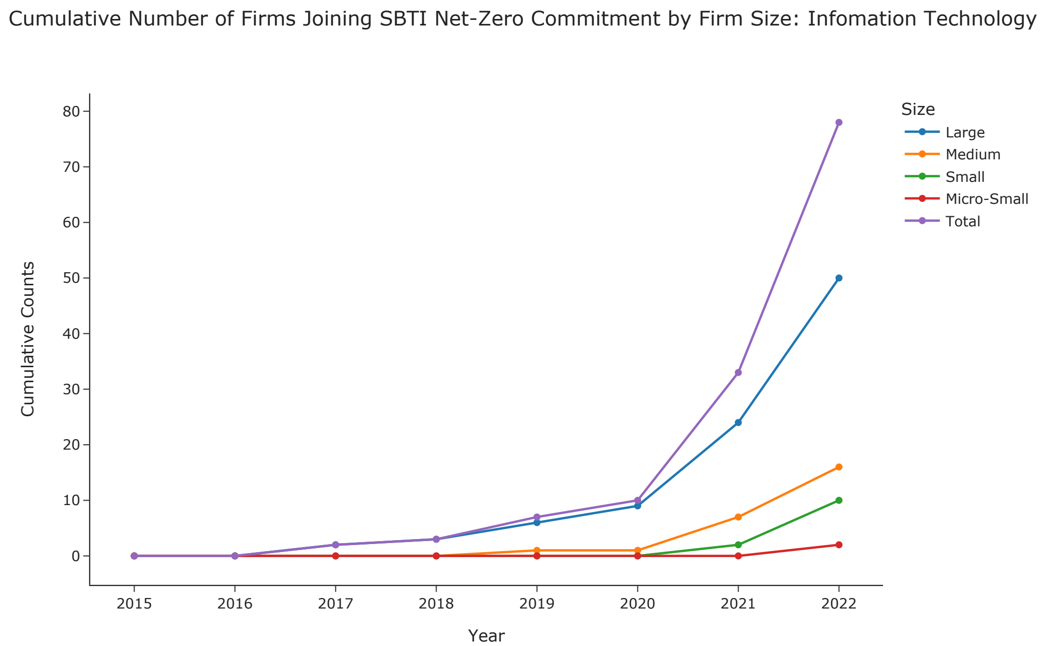

Figure 17: Net Zero commitments by firms across firm size groups in the "Information Technology" industry. Firm size is measured by market cap: Large ($10 billion or more), medium ($2 billion to $10 billion), small ($250 million to $2 billion), and micro-small ($250 million or less).

Variables	(1) N	(2) mean	(3) sd	(4) min	(5) max
Firm Market Cap (Billion)	3,708	7.69	30.2	0.00088	788
Pct Shares by 13F Investors	3,708	64.5	30.1	0.022	120
Investor Equity AUM (Billion)	3,708	418	216	0.0059	1,988
Firm (Net-Zero: 1/0)	3,708	0.047	0.21	0	1
Firm Commitment Time	3,708	0.095	0.50	0	6
Firm Assets (Billion)	3,708	19.3	124	0.00071	2,723
Firm Size (log(assets))	3,708	0.31	2.23	-7.24	7.91
Firm Size (rank(assets))	3,708	1,868	1,081	1	3,745
Investor Size (log(aum))	3,708	5.77	1.04	-5.14	7.59
Investor Size (rank(aum))	3,708	1,879	1,082	1	3,745

B Common Ownership Firm Sample

B.1 Summary Statistics

B.2 Figures

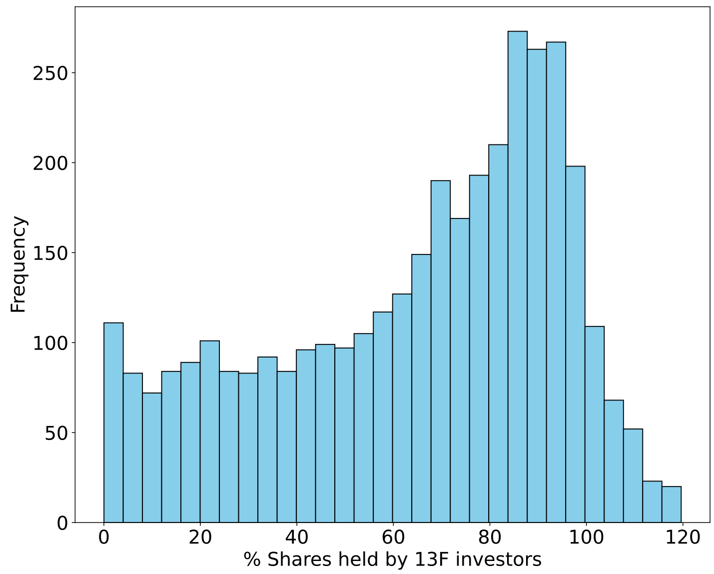

Figure 18: Distribution of Percentage Shares Held by 13F Investors.

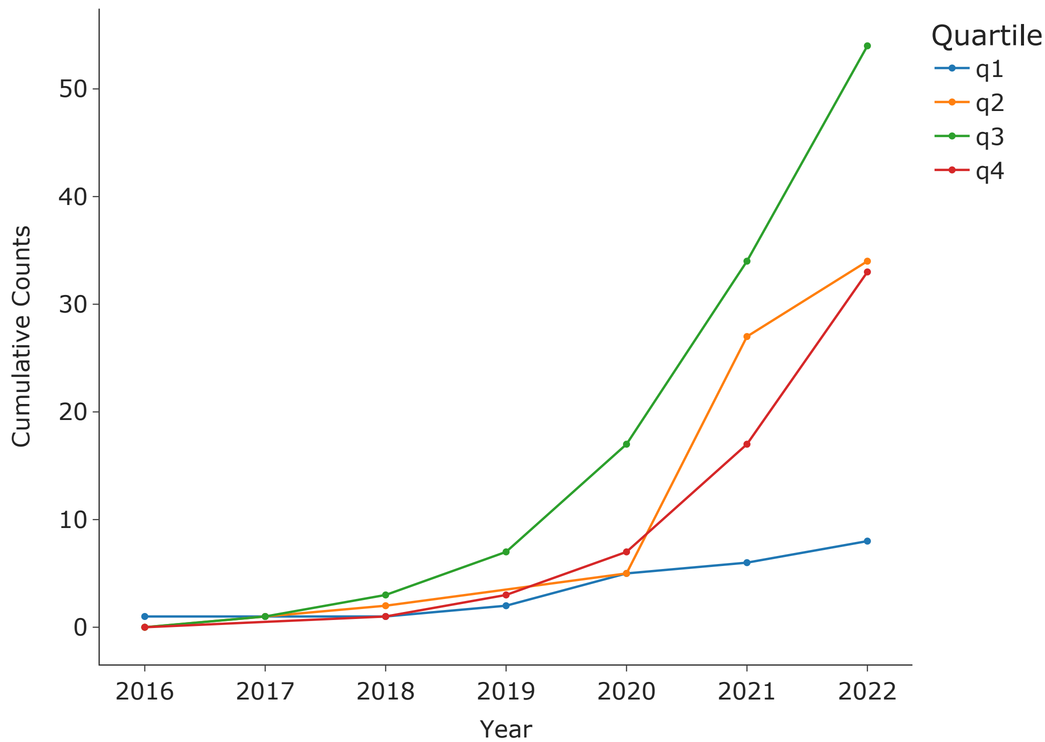

Figure 19: Cumulative Number of Firms Joining Net-Zero commitments by Ownership Size. Ownership size is measured by percentage shares held by all 13F investors: q1: bottom 25%; q2: 25% - 50%; q3: 50% - 75%; q4: top 25%.

B.3 Correlation Table

Table 5: Cross-correlation table

Variables	Pct Shares by 13F Investors	Firm Size (log(assets))	Firm Size (rank(assets))	Investor Size (log(aum))	Investor Size (rank(aum))
Pct Shares by 13F Investors	1.000				
Firm Size (log(assets))	0.466	1.000			
	(0.000)				
Firm Size (rank(assets))	0.469	0.974	1.000		
	(0.000)	(0.000)			
Investor Size (log(aum))	0.361	0.273	0.288	1.000	
	(0.000)	(0.000)	(0.000)		
Investor Size (rank(aum))	0.295	0.278	0.311	0.751	1.000
	(0.000)	(0.000)	(0.000)	(0.000)	

C Proofs

C.1 Proof of Proposition 7

The Lagrangian is

$$f(k) - k - C(\Delta) - \mathcal{L}(Z_0 + [\theta_0 - \Delta(1+\chi)]\,k) + \lambda\left\{1 + (\theta_0 - \Delta)\bar{\tau} - f'(k)\right\}$$

and the government's optimality conditions are

$$f'(k) = 1 + \gamma\theta + \lambda f''(k)$$

hence

$$-\lambda f''(k) = (\gamma - \bar{\tau})\theta$$

and if $\lambda > 0$

$$\begin{aligned} C'(\Delta) &= (1+\chi)k\gamma - \lambda\bar{\tau} \\ &= \bar{\tau}k + k(\gamma - \bar{\tau}) + \chi k\gamma + \frac{(\gamma - \bar{\tau})\theta}{f''(k)}\bar{\tau} \end{aligned}$$

The planner uses a subsidy

$$\sigma = \chi k\gamma + (\gamma - \bar{\tau})\left(k + \frac{\theta\bar{\tau}}{f''(k)}\right)$$

which combines the standard subsidy and an extra term (positive if $\bar{\tau}$ is low enough) that replaces the carbon tax.

With our functional forms,

$$\begin{aligned} c\Delta &= \bar{\tau}k + k(\gamma - \bar{\tau}) + \chi k\gamma - \frac{(\gamma - \bar{\tau})(\theta_0 - (1+\chi)\Delta)}{a}\bar{\tau} \\ k &= a - \bar{\tau}(\theta_0 - (1+\chi)\Delta) \end{aligned}$$

$\theta = \theta_0 - (1+\chi)\Delta$ and $\theta = \frac{a-k}{\bar{\tau}}$ hence

$$\frac{c}{1+\chi}(\theta_0 - \frac{a-k}{\bar{\tau}}) = \bar{\tau}k + k(\gamma - \bar{\tau}) + \chi k\gamma - \frac{(\gamma-\bar{\tau})}{a}(a-k)$$
$$\frac{c}{1+\chi}(\theta_0 - \frac{a}{\bar{\tau}}) + \gamma - \bar{\tau} = k\left\{\gamma(1+\chi) - \frac{c}{1+\chi}\frac{1}{\bar{\tau}} + \frac{(\gamma-\bar{\tau})}{a}\right\}$$

implies

$$k(\bar{\tau}) = \frac{a\left[1 - \frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{ac}\right] - \bar{\tau}\theta_0}{1 - \frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{ac} - \frac{\bar{\tau}\gamma}{c}(1+\chi)^2}.$$

Therefore

$$\sigma^*(\bar{\tau}) = \chi k(\bar{\tau})\gamma + (\gamma - \bar{\tau})\left(k(\bar{\tau}) - \frac{a-k(\bar{\tau})}{a}\right)$$

Note that if $\bar{\tau} = \gamma$ we recover the first-best level: $k = \frac{a-\theta_0\gamma}{1-\frac{\gamma^2}{c}(1+\chi)^2} = k^*$.

Then

$$\Delta = \frac{\theta_0 - \theta}{1+\chi} = \frac{\theta_0 - \frac{a-k}{\bar{\tau}}}{(1+\chi)}.$$

The emission intensity attained by this policy is

$$\theta = \frac{a - \frac{a\left[1-\frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{ac}\right]-\bar{\tau}\theta_0}{1-\frac{\bar{\tau}(\gamma-\bar{\tau})(1+\chi)}{ac}-\frac{\bar{\tau}\gamma}{c}(1+\chi)^2}}{\bar{\tau}}.$$

C.2 Proof of Proposition 8

With our functional forms,

$$c\Delta^l = \tau\left[a - \tau(\theta_0^l - \Delta^l(1+\chi\mu) - (1-\mu)\chi\frac{\tau\left(a - \tau\theta_0^s + \chi\tau\mu\Delta^l\right)}{c - \tau^2(1+\chi(1-\mu))})\right]\left[1 + \chi\left(\mu + \frac{\tau^2\chi\mu(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}\right)\right] \tag{15}$$

$$\left[\frac{c}{1+\chi\left(\mu+\frac{\tau^2\chi\mu(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}\right)}-\tau^2(1+\chi\mu)\right]\Delta^l=\tau\left[a-\tau(\theta_0^l-(1-\mu)\chi\frac{\tau\left(a-\tau\theta_0^s+\chi\tau\mu\Delta^l\right)}{c-\tau^2(1+\chi(1-\mu))})\right]$$

$$\Delta^l(\tau)=\tau\cdot\frac{a-\tau\theta_0^l+\tau^2(1-\mu)\chi\frac{a-\tau\theta_0^s}{c-\tau^2(1+\chi(1-\mu))}}{\frac{c}{1+\chi\mu\left(1+\frac{\tau^2\chi(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}\right)}-\tau^2(1+\chi\mu)+\frac{\tau^3\chi^2\mu(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}}$$

and therefore

$$\begin{aligned}k^l&=\frac{c\Delta^l}{\tau\left[1+\chi\left(\mu+(1-\mu)\frac{\partial\Delta^s}{\partial\Delta^l}\right)\right]}\\&=\frac{c\Delta^l}{\tau\left[1+\chi\left(\mu+(1-\mu)\frac{\tau^2\chi\mu}{c-\tau^2(1+\chi(1-\mu))}\right)\right]}\\&=\frac{c}{1+\chi\left(\mu+(1-\mu)\frac{\tau^2\chi\mu}{c-\tau^2(1+\chi(1-\mu))}\right)}\times\frac{a-\tau\theta_0^l+\tau^2(1-\mu)\chi\frac{a-\tau\theta_0^s}{c-\tau^2(1+\chi(1-\mu))}}{\frac{c}{1+\chi\left(\mu+\frac{\tau^2\chi\mu(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}\right)}-\tau^2(1+\chi\mu)+\frac{\tau^3\chi^2\mu(1-\mu)}{c-\tau^2(1+\chi(1-\mu))}}\end{aligned}$$

C.3 Proof of Proposition 10

We start with the first inequality

$$\max_{\sigma}W(0,\sigma,0)\leq W(\gamma,0,0).$$

Denote $\sigma^*(0)$ the optimal innovation subsidy with a zero carbon tax, that is, $\max_\sigma W(0,\sigma,0)=W(0,\sigma^*(0),0)$. Denote $\Delta(\sigma,\tau)$ the innovation given a subsidy σ and a carbon tax τ. Then the innovation $\Delta(\sigma^*(0),0)$ under the optimal subsidy but no tax solves

$$\begin{aligned}&\max_{\Delta}f(k)-k-C(\Delta)-\gamma(\theta_0-(1+\chi)\Delta)k\\&\text{s.t. } f'(k)=1\end{aligned}$$

or

$$C'(\Delta)=\gamma(1+\chi)f'^{-1}(1)$$

We have

$$\begin{aligned}
\max_\sigma W(0,\sigma,\mu) &= \max_\sigma W(0,\sigma,0) \\
&= \underbrace{f(a) - a - \gamma\theta_0 a}_{W(0,0,0)} + \frac{1}{2}(1+\chi)^2\,\frac{\gamma^2 a^2}{c} \\
&= \frac{a^2}{2} - \gamma\theta_0 a + \frac{1}{2}(1+\chi)^2\,\frac{\gamma^2 a^2}{c}
\end{aligned}$$

whereas given $k = (a-\gamma\theta_0)\frac{c}{c-\gamma^2(1+\chi)}$ and $\Delta = \frac{\gamma(a-\gamma\theta_0)}{c-\gamma^2(1+\chi)}$ we have

$$W(\gamma,0,0) = \frac{c\left(c-\gamma^2\right)(a-\gamma\theta_0)^2}{2\left(c-\gamma^2(1+\chi)\right)^2}.$$

Inequality (8) then follows from equalizing $\max_\sigma W(0,\sigma,0)$ and $W(\gamma,0,0)$ and noting that for $\chi = 0$ we always have

$$W(\gamma,0,0) = \frac{c(a-\gamma\theta_0)^2}{2\left(c-\gamma^2\right)} \geq \frac{a^2}{2} - \gamma\theta_0 a + \frac{1}{2}\frac{\gamma^2 a^2}{c} = \max_\sigma W(0,\sigma,0).$$

Then we know that

$$\begin{aligned}
W(0,\sigma^*(0),0) &\leq \max_k f(k) - k - C(\Delta(\sigma^*(0),0)) - \gamma(\theta_0 - (1+\chi)\Delta(\sigma^*(0),0))k \\
&\leq \max_k f(k) - k - C(\Delta(0,\gamma)) - \gamma(\theta_0 - (1+\chi)\Delta(0,\gamma))k \\
&\leq \max_k f(k) - k - C(\Delta^{FB}) - \gamma(\theta_0 - (1+\chi)\Delta^{FB})k
\end{aligned}$$

The second inequality in the Proposition

$$W(\gamma,0,0) \leq W(\gamma,0,\mu)$$

follows from the fact that firm commitments increase welfare since firms within the coalition could always choose the same k and Δ as under $\mu = 0$.

The third inequality in the Proposition

$$W(\gamma,0,\mu) \leq W(\gamma,0,1)$$

follows from the fact that when $\mu = 1$ firm commitments achieve the first best, i.e., $W(\gamma,0,1) =$

W^{FB}.

C.4 Proof of Proposition 11

The corresponding Lagrangian is

$$f(k) - k - C(\Delta) - \mathcal{L}(Z_0 + [\theta_0 - \Delta(1+\chi)]\,k) + \lambda\left\{1 + \frac{C'(\Delta)}{k}(\theta_0 - \Delta(1+\chi)) - f'(k)\right\}$$

hence the government's first-order optimality conditions are

$$\begin{aligned} f'(k) - 1 - \gamma\theta - \lambda\left[\frac{C'(\Delta)}{k^2}\theta + f''(k)\right] &= 0 \\ -C'(\Delta) + \gamma(1+\chi)k + \lambda\left[\frac{C''(\Delta)}{k}\theta - \frac{C'(\Delta)}{k}(1+\chi)\right] &= 0 \end{aligned}$$

which can be rewritten in terms of the tax $\tau^c = C'(\Delta)/k = \frac{1}{\theta}(f'(k) - 1)$ as

$$\begin{aligned} f'(k) &= 1 + \gamma\theta + \frac{\lambda}{k}\left[\theta\tau^c + kf''(k)\right] \\ \frac{\lambda}{k} &= \frac{1}{\frac{C''(\Delta)}{k}\theta - \tau^c(1+\chi)}\left(\tau^c - \gamma(1+\chi)\right) \end{aligned}$$

If $\chi = 0$ the solution is trivial: $\tau^c = \gamma$, $\lambda = 0$. This reiterates that commitments are not needed to achieve the first best when there are no innovation externalities.

With $\chi > 0$, our functional forms imply $f'(k) - 1 + kf''(k) = a$ hence

$$f'(k) = 1 + \gamma\theta + \frac{\lambda}{k}a$$

hence $\tau^c > \gamma$ if and only if $\lambda > 0$. The second FOC rewrites

$$\frac{\lambda}{k} = \frac{\tau^c - \gamma(1+\chi)}{\theta\frac{c}{k} - \tau^c(1+\chi)}$$

$$\begin{aligned} (\tau^c - \gamma)\theta &= a\frac{\tau^c - \gamma(1+\chi)}{\theta\frac{c}{k} - \tau^c(1+\chi)} \\ &= a\frac{\gamma(1+\chi) - \tau^c}{\tau^c(1+\chi) - \theta\frac{c}{k}} \end{aligned}$$

hence

$$f'(k) = 1 + \gamma\theta + a\frac{\tau^c - \gamma(1+\chi)}{\theta\frac{c}{k} - \tau^c(1+\chi)}$$
$$= 1 + \tau^c\theta$$

which leads to

$$\tau^c - \gamma = a\frac{\tau^c - \gamma(1+\chi)}{\theta\frac{c}{k} - \tau^c(1+\chi)}$$
$$a - k = \tau^c\theta$$

where $\Delta = \tau^c k/c$ and $\theta = \theta_0 - \Delta(1+\chi)$ hence

$$k = \frac{a - \tau^c\theta_0}{1 - \frac{(\tau^c)^2}{c}(1+\chi)}$$

$$\begin{aligned}\tau^c - \gamma &= a\tau^c\frac{\tau^c - \gamma(1+\chi)}{\theta\tau^c\frac{c}{k} - (\tau^c)^2(1+\chi)} \\ &= a\tau^c\frac{\tau^c - \gamma(1+\chi)}{(a-k)\frac{c}{k} - (\tau^c)^2(1+\chi)} \\ &= -a\tau^c\left[\frac{\tau^c - \gamma(1+\chi)}{c(\frac{a\frac{(\tau^c)^2}{c}(1+\chi)+\tau^c\theta_0}{a-\tau^c\theta_0}) + (\tau^c)^2(1+\chi)}\right]\end{aligned}$$

Since $\tau^c - \gamma$ and $\tau^c - \gamma(1+\chi)$ have opposite signs, the optimal commitment τ^c satisfies $\tau^c \in [\gamma, \gamma(1+\chi)]$.

D Green and Brown Technologies

We outline a mapping between our model and an alternative model, closer to some models in the literature such as Acemoglu et al. (2012), in which firms have a choice between two technologies, "green" and "brown", such that the brown technology has a higher productivity but also higher emission intensity. For simplicity we abstract from technological spillovers here, setting $\chi = 0$, but a similar mapping can be written with $\chi > 0$.

In our model we can rewrite production net of costs of innovation as

$$F(k,\Delta) \equiv f(k) - k - C(\Delta)\,. \tag{16}$$

If we interpret Δ as how green technology is, $F_\Delta < 0$ captures the effective productivity advantage of brown technology (i.e., it does not require the firm to pay the cost C). Firms subject to a tax τ and a subsidy σ maximize

$$F(k,\Delta) - \tau\left[\theta_0 - \Delta\right]k + \sigma\Delta$$

Consider now an alternative model with an explicit choice between green and brown technologies. Suppose there are two production functions for green and brown intermediate inputs:

$$y_g = A_g k_g$$
$$y_b = A_b k_b$$

with $A_g < A_b$. Production using brown technology emits $\theta_0 k_b$, whereas green technology emits $\theta_g k_g$ with $\theta_g < \theta_b$; we normalize $\theta_g = \theta_0 - 1$. The final good is given by aggregating the green and brown inputs using an aggregator G

$$Y = G(y_g, y_b)$$

which captures the substitutability between green and brown inputs; for instance, if they are perfectly substitutable then $\frac{\partial G}{\partial y_b} = \frac{\partial G}{\partial y_g}$. Firms subject to a carbon tax τ per unit of emissions and a subsidy to using the green technology $\sigma \cdot \frac{k_g}{k_g + k_b}$ solve

$$\max_{k_g, k_b} G(A_g k_g, A_b k_b) - \tau(\theta_g k_g + \theta_0 k_b) + \sigma \frac{k_g}{k_g + k_b}$$

We can change variables to rewrite this problem exactly as in our formulation (16):

$$\max_{k,\Delta}\ F(k,\Delta) - \tau\left(\theta_0 - \Delta\right)k + \sigma\Delta$$

where

$$
\begin{aligned}
k &\equiv k_b + k_g \\
\Delta &\equiv k_g / k \\
F(k, \Delta) &\equiv G(A_g \Delta \cdot k, A_b k(1 - \Delta))
\end{aligned}
$$

Now

$$
F_\Delta = -k \left[A_b \frac{\partial G}{\partial y_b} - A_g \frac{\partial G}{\partial y_g} \right]
$$

Therefore if the technologies are sufficiently substitutable (so $\frac{\partial G}{\partial y_b} \approx \frac{\partial G}{\partial y_g}$) and green technology is less productive ($A_g < A_b$) as we assumed, we obtain $F_\Delta < 0$ as before.