Financing Green Entrepreneurs under Limited Commitment*

Alain Bensoussan [†‡] Benoit Chevalier-Roignant [§]
Nam Nguyen [¶] Alejandro Rivera [‖]

Abstract

Risk-averse entrepreneurs contract with financiers to fund their projects. Projects can be operated under green or dirty technologies. We explore the role of limited commitment in determining the adoption of green technologies when governments enact carbon taxes and/or directed investment subsidies. We show that entrepreneurial (resp., financier) limited commitment makes it more (resp., less) costly for governments to encourage green technology adoptions. Because green technologies are still at an early stage, the cash flows they generate are back-loaded. Entrepreneurial limited commitment forces consumption to increase over time thereby undermining risk-sharing and making dirty technologies more attractive. By contrast, under financier limited commitment, the possibility that front-loaded dirty technologies become obsolete forces consumption to decrease over time thereby undermining risk-sharing and making green technologies more attractive. We also show that carbon taxes (directed technology subsidies) are more cost-effective when entrepreneurs (financiers) display limited commitment.

Keywords: Sustainable Finance, Financial Frictions, Limited Commitment, Optimal Taxation.

JEL codes: G30, G38, H23.

---

[*] We thank Manuel Adelino, Jean-Marie Meier, Michael Rebello, Nina Baranchuk, Christopher Reilly, Han Xia, Hong Liu, Jennie Bai, William Fuchs, Constantine Yannelis, Francois Gourio, Klaus Desmet, Esteban Rossi-Hansberg, Alessio Piccolo, and participants at the 2023 MFA Conference, 2022 Chicago Both Rising Scholars Conference, 2022 Midwest Macro Meeting, 7th Vietnam Symposium in Banking and Finance, and UT-Dallas seminar for helpful discussions and comments. Research supported by the National Science Foundation under grant DMS-1907116 and the Research Grants Council of the Hong Kong Special Administrative Region (CityU 1130316).

[†] Jindal School of Management, University of Texas at Dallas, axb046100@utdallas.edu.

[‡] School of Data Science, City University Hong Kong.

[§] emlyon business school, benoit.chevalier-roignant@outlook.com.

[¶] Jindal School of Management, University of Texas at Dallas, Nam.Nguyen.Hoai@utdallas.edu.

[‖] Jindal School of Management, University of Texas at Dallas, alejandro.riveramesias@utdallas.edu.

1 Introduction

Since Nordhaus's (1994) seminal work, economists have coalesced around the need to implement carbon taxes to address the negative externalities of greenhouse gas emissions on temperatures.[1] Under this paradigm, properly designed carbon taxes induce firms to internalize the cost to society of their emissions, thereby restoring the socially optimal allocation. Recently, however, Acemoglu, Aghion, Bursztyn and Hemous (2012) have argued that path dependencies and positive spillovers for green technologies imply that a directed investment subsidy represents an ideal complement to carbon taxes in delivering the optimal transition towards environmental sustainability. As such, the relative merits of *both* of these policy instruments need to be evaluated by policy makers when designing a comprehensive environmental tax policy.

By and large, this discussion has assumed away financial and agency frictions and has focused on situations in which firms do not display any kind of commitment, moral hazard, or agency issues.[2] While theoretically important, these friction-less (first best) benchmarks are not sufficiently informative for policy-makers given the broad empirical evidence documenting the importance of financial frictions in driving firm behavior (e.g., Gilchrist, Sim and Zakrajšek (2014); Hennessy, Levy and Whited (2007); Buera, Kaboski and Shin (2015)). It is thus natural to ask: How are the relative merits of carbon taxes and directed investment subsidies affected when firms face financial frictions? Do financial frictions tilt the scale in favor of either of these policy instrument relative to the friction-less benchmark?

This paper addresses these questions by focusing on a particular type of friction, namely limited commitment: the possibility for either party in a contract to renege on its obligation in case a better outside option arises. To that end, we study the design of a contract between an entrepreneur and a financier when either party can display limited commitment.[3] Importantly, the optimal

---

[1] The letter entitled "Economist's Statement on Carbon Dividends" (Akerlof et al., 2019) signed by over 3,000 economists including 28 Nobel Laureates in Economics and 4 Former Federal Reserve Chairs provides details on the rationale for carbon taxes. Moreover, the monograph by Gollier (2019) contains a thorough discussion about the delicate nuances involved around computing the appropriate carbon tax.

[2] Section 3.6 of the special Climate Finance issue by Hong, Karolyi and Scheinkman (2020) highlights this inconvenient void: "Given that corporations and insiders (CEOs) ultimately need to make investments to address climate change, two traditional corporate finance issues loom large: agency problems associated with corporate short-termism and financing frictions."

[3] For the purpose of our model, "financiers" can be interpreted in a broad sense as any type of investor willing to

contract entails a joint optimization over (a) the choice of technology (green versus dirty), (b) the entrepreneur's compensation scheme, and (c) the firm's investment policy. This optimization allows us to characterize the type and magnitude of government intervention required to incentivize green technologies.

We model firm's cash flows as given by the product of its size and its profitability. The dynamics of the firm size depend on the type of technology it operates, the firm's investment rate, and an idiosyncratic firm specific shock. We assume that firms operating the dirty technology have a higher profitability than those operating the green technology. This assumption reflects the head-start advantage enjoyed by dirty firms over the last century. However, firms operating the green technology have a faster growth rate than dirty ones, reflecting the growing concern for the environment and the consequent demand for environmentally friendly products by consumers. We study a situation in which governments can enact carbon taxes and/or directed investment subsidies to encourage firms to adopt the green technology in lieu of the dirty one.[4]

Our model adopts the following timeline: a risk-averse entrepreneur contracts with a risk-neutral financier for the funding of the firm he operates and wants to smooth his consumption. The entrepreneur takes as given the tax policies enacted by the government and chooses the operating technology (green vs dirty). The agreed contract specifies the firm's investment plan and the entrepreneur's compensation (as a function of cash flows generated by the venture). Importantly, contracts are *endogenously incomplete* due to the fact that entrepreneurs and/or financiers can display limited commitment.[5] That is, we allow for either party to renege on the initial contract and quit when the continuation contract (after a given history) is worse than their respective outside options. As a result, feasible contracts are required to satisfy a limited commitment constraint. The optimal contract has to balance the trade-off between insuring the risk-averse entrepreneur and the need to adjust his consumption to ensure the limited commitment constraint is satisfied. In particular, under entrepreneurial (resp., financier) limited commitment, the optimal contract

---

provide contingent funding to the project (e.g., private equity, venture capital, or a bank line of credit).

[4] Carbon taxes are born by firms operating dirty technologies and are proportional to their green house emissions. Investment subsidies are enjoyed by green firms and reduce their investment costs.

[5] By contrast, exogenously incomplete contracts directly restrict the contract space imposing, for instance, an exogenous borrowing limit (e.g., Aiyagari, 1994).

features a constant consumption stream for the entrepreneur whenever the constraint does not bind, and an increment (resp., reduction) in consumption after good (resp., bad) performance in order to keep the entrepreneur (resp., financier) contributing to the venture.

Our model delivers three important insights. First, under limited commitment, it is not enough for policy-makers to determine the difference in net present value (NPV) between the green versus the dirty technology in order to back-out the tax incentive required to incentivize the adoption of green technologies. Thus, additional considerations regarding the term-structure of cash flows and the extent of either party's commitment are needed to determine the required tax incentive.

Second, the required carbon tax on dirty technologies should be higher (resp., lower) than the difference in NPVs between the dirty and the green technology when the entrepreneur (resp., financier) features limited commitment. Because the green technology ensures higher growth potential, the entrepreneur's (resp., financier's) limited commitment constraint is more (resp., less) likely to bind when the firm adopts the green technology, thereby undermining (resp., enhancing) risk-sharing. As a result, entrepreneurial (financier) limited commitment makes green projects relatively less (more) desirable than their dirty counterparts, and therefore the required tax incentive to close this wedge is higher (lower) than under a first-best benchmark without commitment considerations (i.e., the NPV criterion).

Third, the allocation between directed investment subsidies and carbon taxes depends on which type of commitment friction prevails in the economic environment. When entrepreneurs feature limited commitment, direct investment subsidies constitute a prohibitive approach to incentivize green technology adoption. Because investment subsidies encourage firms to grow, the entrepreneurial limited commitment constraint is more likely to bind, therefore inducing an inferior risk-sharing arrangement for green firms. By contrast, when financiers feature limited commitment, the investment subsidy has a double benefit for green firms: it renders investment cheaper (standard effect), but also makes the financier's limited commitment constraint less likely to bind. The latter effect arises because a stronger growth increases the firm's future cash flows, making the financier less prone to renege on the contract. This additional benefit makes investment subsidies more cost-effective than carbon taxes when the financier has limited commitment. Table 1 summarizes

Policy intervention	**Entrepreneurial Limited Commitment**	**Financier Limited Commitment**
Carbon Taxes	*Higher* carbon taxes required relative to first-best benchmark. (see Section 4.1)	*Lower* carbon taxes required relative to first-best benchmark. (see Section 4.2)
Investment Subsidies	Investment subsidies are *less* cost-effective than carbon taxes. (see Section 5.1)	Investment subsidies are *more* cost-effective than carbon taxes. (see Section 5.2)

Table 1: **Schematic summary of our results**

schematically our results.

Our findings uncover novel forces governing the interaction between limited commitment frictions and the back-loaded (front-loaded) structure of cash flows generated by green (dirty) firms. As a result, we are able to provide guidance for policy-makers regarding the type and magnitude of the intervention required to incentivize green technologies in settings with limited commitment. Because our analysis delivers delicate asymmetric implications depending on whether entrepreneurs or financiers are more likely to feature commitment problems, it is extremely important for policy-makers to tailor their policies to the specific economic environment in which they are intervening. In practice, empirical work and institutional knowledge helping to assess which party is more likely to feature limited commitment is a required input for our analysis to be fruitful in policy-making circles.

1.1 Literature Review

Our paper is closely related to the two optimal taxation paradigms regarding climate change externalities. The first paradigm pioneered by the Dynamic Integrated Climate Change (DICE) models starting with Nordhaus (1994) developed realistic scenarios integrating insights from geophysics and climate science with models of economic growth. These models focus on the negative externalities associated with greenhouse emissions and on the optimal carbon tax. Recent contributions include Acemoglu et al. (2016) which endogenizes the growth rate by explicitly modeling a firm's innovation decision and Golosov et al. (2014) which explicitly models taxes on fossil fuels as a finite resource. The second paradigm pioneered by Acemoglu et al. (2012) emphasizes positive externalities associated with path dependencies for innovations in green technologies. In a recent work, Aghion et al. (2016) show evidence of path dependency and aggregate spillovers in the automotive industry for dirty versus clean technologies. This paradigm argues that directed investment subsidies are required to internalize this externality in a more effective way than carbon taxes alone can do it on their own. Most of this vast body of work abstracts away from financial frictions. We therefore contribute to this debate by providing an additional perspective on the relative merits of these two policy instruments when limited commitment is a friction of first-order importance in the economic environment.[6]

Our contribution builds on the large microeconomics literature on contracting under limited commitment following Harris and Holmstrom (1982). These authors study a model of optimal insurance for a risk-averse worker unable to commit to a long-term contract. Hart and Moore (1994) develop a theory of endogenous debt capacity arising from the inalienability of human capital, a form of limited commitment. Relatedly, the seminal work of Thomas and Worrall (1990) shows that one-sided limited commitment precludes perfect-risk sharing and that the agent's consumption needs to increase over time in order to keep the agent in the contract. Building on these contributions, Alvarez and Jermann (2000) extend the welfare theorems to a macroeconomic setting with limited commitment. Albuquerque and Hopenhayn (2004) extend previous analyses to highlight the impact of limited commitment on firm's growth and their dynamics.[7] The contribution of our analysis relative to this literature is to provide a first exploration of the role played by limited commitment on the environmental transition and its associated tax policies.

Our paper is methodologically related to the continuous-time contracting literature under lim-

---

[6] Notably, a large and growing literature in economics and finance studies climate-change externalities from a variety of angles beyond carbon taxes and investment subsidies. These contributions include the study of capital reallocation to ESG funds (Halbritter and Dorfleitner, 2015; Goldstein et al., 2021), the implications of financing constraint and socially responsible capital on firms' technology and production choices (Oehmke and Opp, 2020), the use of environmentally friendly investing mandates among college endowments (Bessembinder, 2016) and sovereign wealth funds (Bolton et al., 2012), the potential benefit of investment income taxes (Nguyen et al., 2021), the impact of active mandates on firm's policies (Broccardo et al., 2020; Oehmke and Opp, 2020)), and the impact of green investing on firms' carbon emissions (De Angelis et al., 2022), among others.

[7] Limited commitment as also been successfully applied to other areas in economics including labor dynamics (e.g., Rudanko (2009)), development economics (e.g., Ligon et al. (2002)), international finance (e.g., Kehoe and Perri (2002)), firm dynamics (e.g., Ai et al. (2021)), and externalities in executive compensation (e.g., Chemla et al. (2021)), amongst others. The survey by Golosov et al. (2016) and chapter 17 of Ljungqvist and Sargent (2018) provide excellent overviews of this vast literature.

ited commitment. Grochulski and Zhang (2011) study a one-sided limited commitment problem in which the agent features Constant Relative Risk Aversion (CRRA) preferences. They lever on the tractability of continuous-time to provide a closed-form solution for the optimal contract and directly relate their findings to the solvency constraints in Alvarez and Jermann (2000). Miao and Zhang (2015) use duality techniques—in the spirit of Marcet and Marimon (2011)—to obtain a tractable linear partial differential equation for both types of limited commitment. More recently, Ai and Li (2015) explore the impact of limited commitment on firm's investments and CEOs' compensation, while Bolton et al. (2019) focus on the joint determination of investment and risk-management policies. Importantly, for our purposes, these papers also provide computationally fast and reliable algorithms, which allow us to efficiently compute optimal contracts and value functions under various government tax policies.

2 Model

2.1 Technology and Preferences

We consider a continuous-time setting with infinite horizon in which there are two types of players: financiers and entrepreneurs. Financiers are risk-neutral, while entrepreneurs are risk-averse. Everyone discounts the future at a constant rate $r > 0$.

The firm can use either of two technologies: ecofriendly ("green") or non-ecofriendly ("dirty") technology. We denote the first type with the index g and the second type with the index d. At the onset, the financier chooses the technology. Because financiers cannot operate the project, they must hire an entrepreneur to do it, as described below. Denote by Y_t the cumulative cash flows generated by a project until time t. Cash flows are proportional to the projects' capital stock as in Hayashi (1982):

$$dY_t = b_n K_t dt, \tag{1}$$

where $n \in \{g, d\}$, and $b_n > 0$ captures the profitability of each technology per unit of firm size K_t. The law of motion of the firm size follows standard neoclassical dynamics:

$$dK_t = (\mu_n K_t + I_t)dt + \sigma_n K_t dB_t \quad \text{and} \quad K(0) = K_0, \tag{2}$$

in which B_t is a standard Brownian motion capturing the idiosyncratic risk of the project and μ_n the baseline grow rate of the firm driven by exogenous factors (e.g., demand for clean energy, appetite for electric vehicles, etc). We denote by $\mathcal{B}^t$ the $\sigma-$algebra generated by the Brownian motion, $\mathcal{B}^t = \sigma(B_s, s \leq t)$. The investment policy I_t is adapted to the filtration $(\mathcal{B}^t)_t$.

Let C_t be the compensation offered to the entrepreneur for operating the project, which is a control, also adapted to the filtration $\mathcal{B}^t$. The entrepreneur's preferences are represented by CRRA preferences. For tractability, it is easier to work with the entrepreneur's certainty equivalent:

$$X_t = \left[E_t\left(\int_t^\infty r\, e^{-r(s-t)} C_s^{1-\gamma} ds\right)\right]^{\frac{1}{1-\gamma}}, \tag{3}$$

with E_t denoting the mathematical expectation conditional on the time t information $\mathcal{B}^t$.

A contract $(I_t, C_t)_{t\geq 0}$ specifies the compensation to the agent and the investment rate. Admissible contracts are subject to standard integrability conditions specified in the Appendix. The payoff to the financier from a given contract $J(I(.), C(.))$ is equal to the discounted net present value of the cash flows generated by the project net of the entrepreneur's compensation and the cost of investment:

$$J(I(.), C(.)) = E_0\left[\int_0^\infty e^{-rt}\Big(b_n K_t - h(i_t)K_t - C_t\Big)dt\right], \tag{4}$$

where $i_t := I_t/K_t$ denotes the investment rate, and we assume that the cost of investment is homogeneous of degree one in capital, i.e., $h\big(i_t\big)K_t$.

2.2 Entrepreneurial Limited Commitment

Our first benchmark focuses on the case in which the entrepreneur has limited commitment. Following Albuquerque and Hopenhayn (2004), the entrepreneur can take away a fraction of the project's capital and proceed to default on the contract. Upon default, the entrepreneur can utilize the capital to produce consumption goods, but he is no longer allowed to contract with financiers. As a result, the entrepeneur's outside option is proportional to the current capital, K_t. Entrepreneurial limited commitment implies that the certainty equivalent of the entrepreneur must be larger than the outside option at all times:

$$X_t \geq \bar{x}_n K_t, \tag{5}$$

where the portion $\bar{x}_n > 0$ of capital that can be stolen by the entrepreneur can vary by technology type n.

2.3 Financier Limited Commitment

We also consider the benchmark in which financiers face limited commitment and can renege on their contractual obligations when the value they obtain from the *continuation* contract is negative. That is, we consider the case in which, after a history of poor performance, the financier decides not to make transfers to the entrepreneur, which implies at all times:

$$E_t\left[\int_t^\infty e^{-r(s-t)}\left(b_n K_s - h(i_s)K_s - C_s\right)ds\right] \geq 0. \tag{6}$$

2.4 Externalities and Taxes

We incorporate two type of environmental externalities and associated taxes in our setting:

Social Cost of Carbon (SCC): We introduce an externality associated with CO2 emissions as in the neoclassical DICE model pioneered by Nordhaus (1994). The environment is negatively affected by temperature, temperature increases with the emissions of carbon, and emissions of carbon increases with the output of projects operating under the dirty technology. Under the assumption that firms operate in competitive markets, cash flows and output are linearly related. Therefore, to incorporate the negative externality associated with CO2 emissions, governments need to introduce a tax capturing the social cost of carbon (SCC) denoted by τ. In our setting this implies that the effective profitability of the dirty technology becomes

$$b_d \longrightarrow (1-\tau)b_d, \text{ following the implementation of that tax.} \tag{7}$$

Directed Technological Change (DTC): Profitability is not exogenous, but instead affected by positive spill-overs from other firms' investments as suggested by Acemoglu et al. (2012). If more firms invest in the green (resp., dirty) technology, the more efficient this technology becomes and the larger the market share of green (resp., dirty) projects.[8] To internalize this externality, a DTC investment subsidy for green firms $s \in [0,1]$ must be introduced.[9] In our setting this implies that the effective investment cost becomes:

$$h(i_t) \longrightarrow (1-s)h(i_t), \text{ if the government puts such a scheme in place.} \tag{8}$$

3 Solution to the Optimal Contract

In this section, we determine the optimal contract offered to the entrepreneurs by the financiers. We sketch the key ideas and defer mathematical details to the Appendix. First, we provide the first-best neoclassical benchmark in which there are no commitment issues. Next, we identify the recursive structure of the problem under limited commitment using the entrepreneur's certainty equivalent and the firm's size as state variables. Finally, we exploit the problem's homogeneity to reduce it to a single-state stochastic control problem for which there is a complete characterization.[10]

3.1 First Best

In the first best benchmark, the financier's value function V^{FB} is given by

$$V^{FB}(K_0, X_0) = K_0 \frac{b - h(i^{FB})}{r - (\mu + i^{FB})} - \frac{X_0}{r}, \tag{9}$$

where i^{FB} is the neoclassical first-best investment rate.

Proof. See Appendix 7.1. □

---

[8] See Aghion et al. (2016) for direct evidence of this mechanism in the auto industry.

[9] One way to think about the DTC externality is to allow the profitability of firms to depend on the average investment rate in the industry. That is, $b_g \longrightarrow b_g + \lambda \bar{i}$, where $\bar{i}$ is the average investment rate by firms operating green technologies and $\lambda > 0$ a parameter capturing the positive spill-overs from aggregate investment in green technology on individual firms.

[10] See Bensoussan et al. (2022).

That is, in the first-best allocation, the financier perfectly insures the entrepreneur by providing him with a stream of constant consumption that has net present value (NPV) equal to $\frac{X_0}{r}$ and collects all the cash flows generated by the project under the optimal investment rate , a claim which has a NPV $K_0\frac{b-h(i^{FB})}{r-(\mu+i^{FB})}$. As we will show later, under limited commitment, there will be two sources of welfare losses: i) perfect consumption insurance for the entrepreneur will not be possible and ii) the first-best investment rate will be distorted. Both of these forces reduce the financier's value relative to the first-best benchmark and play a critical role in determining the technology adopted by financiers in equilibrium.

3.2 Recursive Formulation

The Appendix shows that: if a stochastic process solves the SDE given by:

$$dX_t = X_t\big[\tfrac{r}{1-\gamma}\big(1-\big(\tfrac{C_t}{X_t}\big)^{1-\gamma}\big) + \tfrac{1}{2}\gamma\sigma^2 g_t^2\big]dt + \sigma X_t g_t dB_t, \tag{10}$$

where g_t is measurable with respect to $\mathcal{B}^t$, then it corresponds to the certainty equivalent in eq. (3). Hence, it is possible to chose g_t and the initial state X_0 conveniently and to take the contract features C_t, I_t, and g_t as control variables, while X_t and K_t are state variables.

3.3 Dimensional Reduction

Next, we use the firm's size K_t as a scaling factor and consider the stochastic processes

$$x_t = \frac{X_t}{K_t},\ i_t = \frac{I_t}{K_t},\ c_t = \frac{C_t}{K_t}. \tag{11}$$

We can now reformulate eqs. (2), (4) and (10). In particular, the scaled certainty equivalent of the entrepreneur x_t solves

$$dx_t = x_t\big[\tfrac{r}{1-\gamma}\big(1-\big(\tfrac{c_t}{x_t}\big)^{1-\gamma}\big) - i_t - \mu + \sigma^2\big(1-g_t+\tfrac{\gamma}{2}g_t^2\big)\big]dt + x_t(g_t-1)\sigma dB_t \tag{12}$$

for given initial value $x(0) = x_0$ to be determined in equilibrium, while the dynamics of capital K_t are given by eq. (2). The payoff to the financier is now given by:

$$J_{K,x}\big(i(\cdot), c(\cdot), g(\cdot)\big) = E_0\bigg[\int_0^\infty e^{-rt} K_t\big(b_n - h(i_t) - c_t\big)dt\bigg]. \tag{13}$$

Furthermore, the limited commitment constraint in eq. (5) becomes:

$$x_t \geq \bar{x}, \tag{14}$$

while the limited commitment constraint in eq. (6) is equivalent to:

$$x_t \leq x^*, \tag{15}$$

where x^* is a free boundary with the boundary conditions to be specified later.

Finally, the value function for the financier V maximizes her payoff within the set of admissible contracts, which—among other conditions—satisfy the limited commitment constraints in eq. (14) or (15). That is:

$$V(K, x) = \sup_{i(\cdot),c(\cdot),g(\cdot)} J_{K,x}\big(i(\cdot), c(\cdot), g(\cdot)\big) \tag{16}$$

We will show in the sequel that $V(K, x) = Kv(x)$, where $v(\cdot)$ satisfies a Bellman equation for which we provide a complete characterization.[11]

3.4 Bellman Equation Solution

The Bellman equation for the stochastic control problem (16) readily obtains as

$$\begin{aligned} 0 = \sup_{c,i,g} \bigg\{ & b - h(i) - c + v(x)(i + \mu - r) + \Big[\tfrac{r}{1-\gamma}\big(1 - \big(\tfrac{c}{x}\big)^{1-\gamma}\big) - i - \mu + \tfrac{1}{2}\gamma\sigma^2 g^2\Big] x v'(x) \\ & + \tfrac{1}{2}\sigma^2 (g-1)^2 x^2 v''(x) \bigg\}, \end{aligned} \tag{17}$$

---

[11] See Bensoussan et al. (2022).

subject to boundary conditions at (a) $x = \bar{x}$ and $x \to \infty$ in the case of entrepreneurial limited commitment or (b) $x = 0$ and $x = x^*$ in the case of financier limited commitment. Those boundaries conditions are specified in Appendix 7.3. The optimal controls can be computed from the scaled value function $v(x)$ in feedback forms by taking first-order conditions in eq. (17).

Theorem 1. *Under technical assumptions, Bellman equation (17), subject to the boundary conditions specified in Appendix 7.2, has one and only one solution.*

Proof. See Bensoussan et al. (2022). ☐

4 Carbon Taxes and Technology Adoption

This section studies the carbon tax implications on technology adoption under *limited commitment.* In particular, we are interested in the forces driving the choice between green and dirty technologies. To that end, we first make a standard zero-profit condition on the financier side.

Zero Profit Condition: We assume the financial sector is competitive, so that the rents earned by the financiers are driven down to zero.[12] Therefore, the initial promised value to an entrepreneur operating the green technology g (resp., dirty d) denoted by x_0^g (resp., x_0^d) must be such that:

$$v_g(x_0^g) = 0 \quad \text{and} \quad v_d(x_0^d) = 0, \tag{18}$$

where the slight abuse of notation using subscripts g and d for the value function simply denotes the difference in parameters under each technology. This is due to the fact that since the problems solved by financiers operating different technologies correspond to “the same” problem solved in Section 3 up to the difference in parameters from each technology. In fact, we turn next to the issue of providing a realistic calibration of the model's parameters that highlight the key differences between the green and dirty technologies.

Calibration: There are two important considerations for a realistic calibration of the model. First, the dirty technology is more productive because of a head-start advantage. Second, the

---

[12] Our results do not depend on the degree of competition in the financial sector and this assumption is made only to deal with the most tractable case.

green technology is more likely to experience growth in the future as the demand for their output grows. That is, the cash flows generated by green technologies are more back-loaded, which implies a higher growth rate for green capital. Taken together, these two key features distinguishing the two technologies imply that $b_d > b_g$ and $\mu_d < \mu_g$, which we impose below.

The parameters for a firm operating a dirty technology are calibrated in line with the limited commitment model of Ai and Li (2015). That is, $b_d = 0.241$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, and $h(i) = i + \theta\frac{i^2}{2}$, where $\theta = 5$. Following Nikolov and Whited (2014), we set a decay rate for the dirty technology of $\mu_d = -0.13$. For the green technology, we keep the same calibration except for the parameters b_g and μ_g. Acemoglu et al. (2016) estimate the innovation step size and the distribution of initial productivity gap between dirty and green technologies. We adhere to the study and set a lower profitability of the green technology (per unit of capital), with $b_g = \frac{b_d}{1.063^4}$ to match the innovation step size and the long tail of the productivity gap distribution. In addition, to match the average difference in estimations for the dirty and green sectors documented in Li et al. (2016), we set $\mu_g = -0.1$.

4.1 Carbon Tax under Entrepreneurial Limited Commitment

This section illustrates the implications of carbon taxes τ on the adoption of green technologies when the entrepreneur has limited commitment. Because the financial sector is competitive, it suffices to determine whether the green technology is adopted at the onset to compute which of the green or the dirty technology generates higher entrepreneurial value. Thus, our quantity of interest is the difference in the (initial) certainty equivalents:

$$\Delta x := x_0^g - x_0^d, \tag{19}$$

where x_0^n is the initial value of the state process in eq. (41). Figure 1 plots this quantity $\Delta x(\tau)$ as a function of the carbon taxes τ. We also plot the first-best benchmark $\Delta x^{FB}(\tau)$ in which we compute (19) under full commitment as described in Section 3.1.

We obtain two important insights. First, and a direct result of our calibration, is the fact that $\Delta x(0) < 0$. That is, in the absence of carbon taxes $\tau = 0$, the entrepreneur prefers to operate a dirty technology. This is because the dirty technology is intrinsically more productive and because the firm does not internalize the damage this technology causes to the environment. Hence, the acknowledged need for government intervention, e.g., via a carbon tax. As this tax increases, adopting the green technology becomes increasingly lucrative for the entrepreneur. Above a cut-off value for that tax, denoted τ_*^E (resp., τ_*^{FB}), an entrepreneur featuring limited (resp., full) commitment will favor the green technology. Second, and more interestingly,

$$\tau_*^E > \tau_*^{FB}, \tag{20}$$

which means that, when entrepreneurial limited commitment matters in the economic environment, the government should raise the carbon-tax rate more to encourage the adoption of green technologies (compared to the frictionless benchmark).

The intuition for this result is as follows. Because the cash flows generated by green technologies are more back-loaded in time (since green firms grow faster than dirty firm), it is more difficult for the optimal contract to provide insurance for the entrepreneur since a green entrepreneur will be tempted to quit in the future as the capital of the firm it operates grows. As time goes by, there are two sources of welfare loss resulting from the fact that the entrepreneurs' limited commitment constraints bind more often under the green than under the dirty technology: i) the entrepreneur's consumption needs to increase over time, limiting risk-sharing, and ii) in order to prevent the entrepreneur from leaving the firm, the optimal contract features under-investment relative to the first-best investment rate (see Figure 2). Because the financial sector is competitive, these welfare losses imply that entrepreneurial limited commitment makes green technologies even less attractive for entrepreneurs; hence, a larger carbon tax on dirty technologies is required to incentivize green technology adoption. As we will see in Section 4.2 this result is reversed when we consider financier's limited commitment.

We conclude this section by noting an important warning for policy makers designing incentives that encourage the adoption of green technologies. They must beware that, in the presence of limited commitment frictions, the difference in NPV between green and dirty technologies is *not* a sufficient statistic to determine the necessary tax incentives. It is required to look not only at

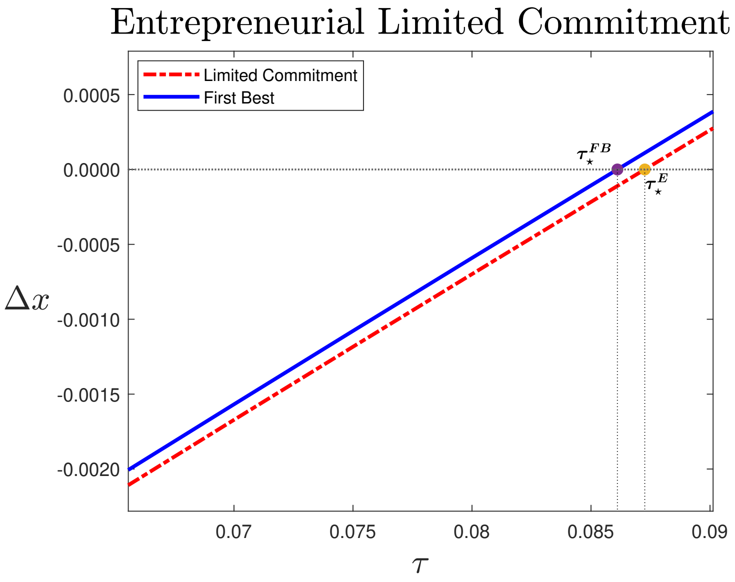

Figure 1: **Difference between certainty equivalents in eq. (19) as a function of carbon tax τ under entrepreneurial limited commitment.** Parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

the NPV of each technology, but also at how the cash flows of each technology are distributed over time. This insight will play a critical role in all of our subsequent findings.

4.2 Carbon Tax under Financier Limited Commitment

In this section we explore the implications of carbon taxes τ on the adoption of green technologies when the financier (instead of the entrepreneur) has limited commitment. To that end, Figure 3 again plots $\Delta x(\tau)$ as a function of the carbon tax τ. We note that the order between the carbon tax needed in first-best versus the financier limited commitment case is reversed compared the one in eq. (20) under entrepreneurial limited commitment:

$$\tau_*^E > \tau_*^{FB} > \tau_*^F,$$

where τ_*^F here denotes the minimum carbon tax needed for entrepreneurs to adopt the green technology when financiers have limited commitment and can walk away from their contractual

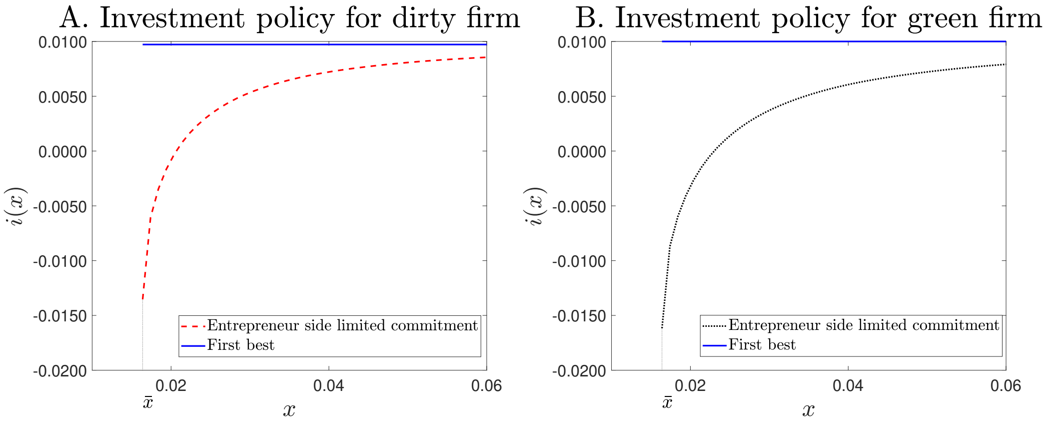

Figure 2: **Green and dirty firm's normalized investment rates featuring entrepreneurial limited commitment under the minimum tax required for green technology adoption**. Parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

obligations.

The intuition for this result is the following. Because the cash flows of dirty technologies are front-loaded, the constraint on the financier's limited commitment is more likely to bind in the future. That is, as the dirty technologies become obsolete, the financiers will have an incentive to walk away from their commitments to finance such projects. To prevent them from doing so, it is necessary to i) reduce the consumption of the entrepreneur over time, thereby undermining risk-sharing and ii) distort, above the first-best benchmark, the investment rate of the project. Both of these mechanisms reduce the value of projects operated under dirty technologies, and hence make green technologies relatively more attractive. Interestingly, financier limited commitment can make it "cheaper" for governments to incentivize green technology adoption than in the absence of frictions.

We conclude Section 4 by highlighting the asymmetric impact of limited commitment constraints on the carbon tax required to incentivize green technologies. Entrepreneurial (resp., financier) limited commitment increases (resp., decreases) the required carbon tax needed to embrace green technologies relative to the friction-less first-best benchmark. In practice, it is an empirical question which of these two types of commitment issues are more relevant in a given context. Our

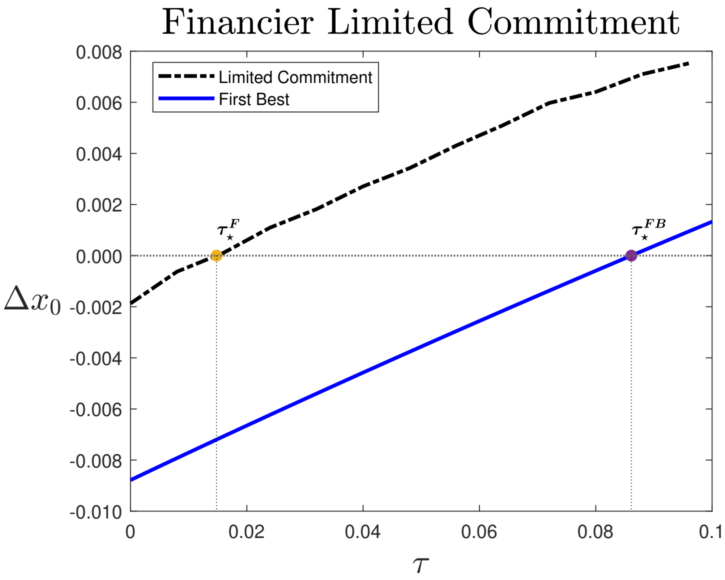

Figure 3: **Certainty equivalent difference under financier's limited commitment**. Parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

goal with this analysis is to inform policy decision-makers regarding the expected direction in which carbon taxes need to be adjusted depending on which friction is most relevant in their economic context.

5 Directed Subsidies and Technology Adoption

We now consider directed technology subsidies aimed at fostering the adoption of green technologies. Our goal in this section is to contrast the merits of the traditional carbon approach (Nordhaus, 1994) versus the directed technological change (Aghion et al., 2016) when limited commitment is a critical feature in the economic environment. Like in section 4, we proceed in two steps, first focusing on entrepreneurial limited commitment and then on financier limited commitment.

5.1 Directed Subsidies under Entrepreneurial Limited Commitment

We recall the modeling of directed subsidies as a transfer s from the government to green firms for every addition to one's capital stock (see eq. (8)). Figure 4 depicts $\Delta x(s)$ as a function of the directed technological subsidy s. The first observation is that entrepreneurial limited commitment necessitates a larger subsidy from the government than under the first-best setting (i.e., $s_*^E > s_*^{FB}$), in a fashion similar to our finding in Section 4.1 for the carbon tax case. The second, and more important observation, is that the investment subsidy needed under entrepreneurial limited commitment is *significantly* larger than in the first-best setting. Moreover, this commitment friction has an even larger impact in the case of directed subsidies than carbon taxes:

$$\frac{\tau_*^E - \tau_*^{FB}}{\tau_*^{FB}} < \frac{s_*^E - s_*^{FB}}{s_*^{FB}}. \tag{21}$$

Intuitively, investment subsidies are beneficial for green firms because, by definition, they make investment cheaper. However, entrepreneurial limited commitment makes investment less desirable, because high growth makes it more difficult to retain the entrepreneur in the contract, making the limited commitment constraint more likely to bind and hence reducing firm value. As a result, this unintended negative effect of investment subsidies reduces firm value. Therefore, the subsidy needed to incentivize green technology adoption is significantly larger than in the first-best case. Moreover, the fact that the subsidy makes the constraint more likely to bind explains why the required increment in the subsidy from the first-best benchmark is larger than the respective increment in carbon tax described in (21). See Table 2 where we compare the RHS and the LHS of inequality (21) for some of the key parameters in our model near our baseline calibration.

To summarize, this section uncovers a novel asymmetry between carbon taxes and directed tax subsidies under limited commitment. This asymmetry stems from our recurring theme regarding the delicate role played by any government intervention beyond its impact on the NPV of the firms but also on the term-structure of cash flow. Put differently, because investment, by nature, delivers back-loaded cash flows , and entrepreneurial limited commitment is more problematic in such a situation, directed investment subsidies constitute a very expensive approach of inducing green

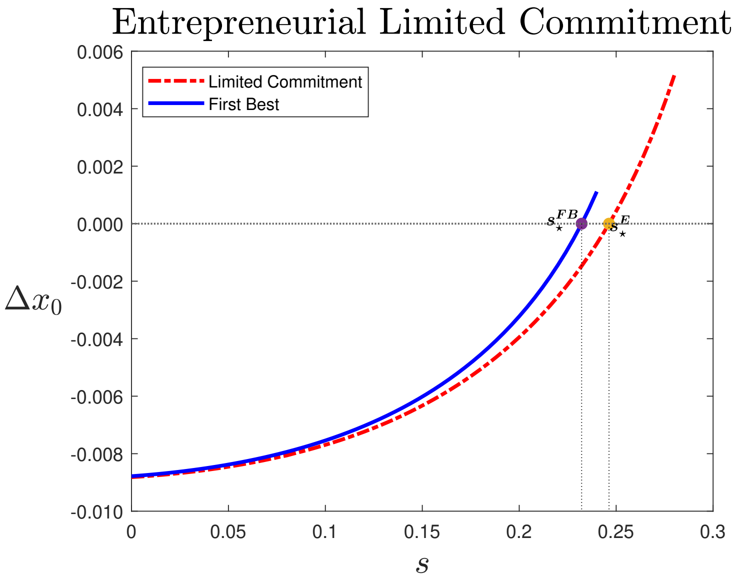

Figure 4: **Certainty equivalent difference under entrepreneurial limited commitment**. Parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

technology adoption. By contrast, and as we will see in the next section, these results are reversed when financiers (instead of entrepreneurs) feature limited commitment.

5.2 Directed Subsidies under Financier Limited Commitment

We complete our analysis by studying the magnitude of the directed subsidy required to incentivize green technologies when financiers face limited commitment. Figure 5 depicts $\Delta x(s)$ as a function of the directed technological subsidy s. We note that limited commitment on the financier's side renders a smaller subsidy sufficient to incentivize green technologies relative to the subsidy needed in first-best. This finding is identical to our findings for carbon taxes in Section 4.2. Importantly, however, we notice that the reduction is *significantly larger* in this case, i.e.,

$$\frac{\tau_*^{FB} - \tau_*^{F}}{\tau_*^{FB}} < \frac{s_*^{FB} - s_*^{F}}{s_*^{FB}}. \tag{22}$$

Intuitively, financier limited commitment is more of a problem when the cash flows of the firm

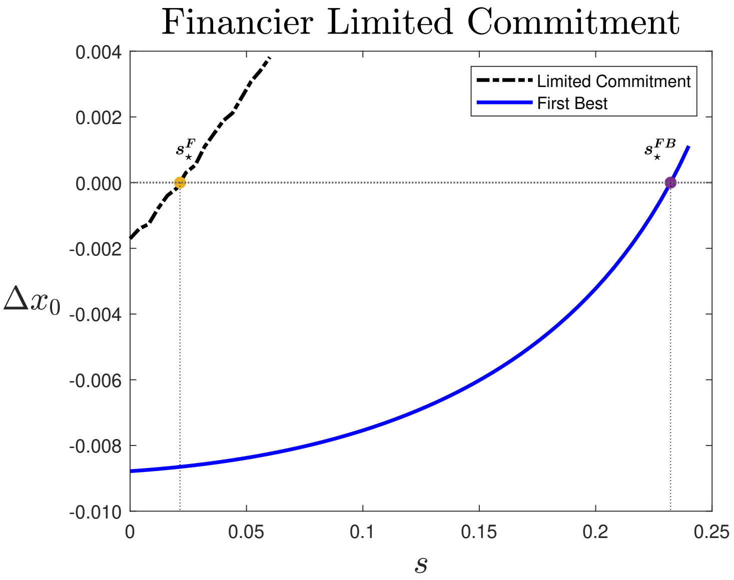

Figure 5: **Difference between certainty equivalents under financier's limited commitment**. Parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

are front-loaded. In this case, as time goes by, the remaining cash flows may result in negative NPV and the financier may want to renege on its contractual obligations. To prevent that, the contract stipulates reductions in the entrepreneur's compensation of the manager (undermining risk-sharing) and an excessively high investment rate. Therefore, an investment subsidy for green firms is highly beneficial because it not only increases the NPV of the firm, but also allows it to relax the financier limited commitment constraint by helping it back-load its cash flows through a higher investment rate. Table 2 compares the right-hand side (RHS) and the left-hand side (LHS) of inequality (22) for some of the key parameters in our model near our baseline calibration.

6 Discussion and Conclusion

In this paper we compare the merits of carbon taxes and directed technological subsidies in encouraging the adoption of green technologies when limited commitment is a key friction in the financial contract between the entrepreneur and the financier. We show that, contrary to the results in the

Parameter changes compared to the baseline	**Entrepreneurial Limited Commitment (Inequality 21)**	**Financier Limited Commitment (Inequality 22)**
$\delta_d = 0.117$	LHS=0.0027 $\leq$ RHS=0.0887.	LHS=0.2825 $\leq$ RHS=0.4882.
$b_d = 0.265$	LHS=0.0032 $\leq$ RHS=0.1184.	LHS=0.3871 $\leq$ RHS=0.7705.
$\theta = 5.5$	LHS=0.0068 $\leq$ RHS=0.0539.	LHS=0.9401 $\leq$ RHS=0.9446.

Table 2: **Robustness check.** Baseline parameter values are $b_g = 0.188$, $b_d = 0.241$, $\mu_g = -0.1$, $\mu_d = -0.13$, $\sigma_g = 0.36$, $\sigma_d = 0.36$, $\gamma = 2$, $r = 0.08$, $\theta = 5$.

frictionless first-best benchmark studied in the literature, policy-makers need to look beyond the impact of their policies on the NPV of the firms, but also assess their impact on the term-structure of cash flows. Such is the case because green (resp., dirty) firms cash flows are more back-loaded (resp., front-loaded) which makes the entrepreneurial (resp., financier) limited commitment more likely to bind.

Our analyses yield two important set of insights for policy makers. First, when entrepreneurial (resp., financier) limited commitment is the main friction in the environment, the carbon taxes required to encourage green technologies should be higher (resp., lower) than what a simple NPV rule would imply. Second, carbon taxes (resp., directed technology subsidies) are the more cost-effective interventions when entrepreneurial (resp., financier) limited commitment is the main friction in the economic environment. As a consequence, our analysis does not prescribe a simple rule for choosing amongst these policy instruments. However, our goal is to inform policy-makers of the forces that can be at play in the industry and country in which they operate. In reality, entrepreneurial and financier limited commitment are both likely to be at play, and policy-makers can use our insights as an additional item in their checklist economic considerations.

Our results raise various important questions for future research. For instance, which policy intervention is most desirable when other frictions such as moral hazard (e.g., DeMarzo and Sannikov (2006)), adverse selection (e.g., Daley and Green (2012)), or financing constraints (e.g., Oehmke and Opp (2020)) also matter? What is the optimal intervention when firms can choose to "reform" themselves and transition from being dirty to green (as in Heinkel et al. (2001))? What are the quantitative implications of a structurally estimated model with two-sided limited commitment?

7 Appendix

7.1 Appendix for Section 3.1

Lemma 2. *In the first best benchmark, the financier's value function* V^{FB} *is given by:*

$$V^{FB}(K_0, X_0) = K_0 \frac{b - h(i^{FB})}{r - (\mu + i^{FB})} - \frac{X_0}{r}, \tag{23}$$

where i^{FB} *is the neoclassical first-best investment rate that satisfies:*

$$h'(i^{FB}) = \frac{b - h(i^{FB})}{r - (\mu + i^{FB})}. \tag{24}$$

Proof. Under full commitment, the optimization problem is to choose optimal investment and compensation policies to maximize:

$$E\left[\int_0^\infty e^{-rt}\Big(bK_t - h(i_t)K_t - C_t\Big)dt\right] \tag{25}$$

subject to the participation constraint:

$$\left[E\left(\int_0^\infty r\, e^{-rt} C_t^{1-\gamma} dt\right)\right]^{\frac{1}{1-\gamma}} \geq X_0, \tag{26}$$

with the dynamic of the capital following (2).

The problem can be broken into two parts: First to choose the investment policy to maximize $E[\int_0^\infty e^{-rt}(bK_t - h(i_t)K_t)dt]$ with the dynamics of the capital in (2), and second to choose the compensation policy in order to minimize $E[\int_0^\infty e^{-rt}C_t dt]$ subject to the participation constraint (26).

Denote $V_1(K) = \sup_i E[\int_0^\infty e^{-rt}(bK_t - h(i_t)K_t)dt]$. The HJB equation associated with the optimal investment problem is:

$$rV_1(K) = \sup_i \left\{ bK - h(i)K + V_1'(K)\, K\, (\mu + i) + \tfrac{1}{2} V_1''(K)\, K^2\, \sigma^2 \right\}. \tag{27}$$

We obtain the optimal the feedback controls:

$$h'(i^{FB}) = V_1'(K). \tag{28}$$

The solution for (27) is given by $V_1(K) = \bar{v}K$, where:

$$r\bar{v} = \big[b - h(i^{FB}) + \bar{v}\,(\mu + i^{FB})\big]. \tag{29}$$

This implies:

$$\bar{v} = \frac{b - h(i^{FB})}{r - (\mu + i^{FB})}. \tag{30}$$

From (28) and (30), we obtain (24). The value function for the maximization problem is:

$$V_1(K) = K\,\frac{b - h(i^{FB})}{r - (\mu + i^{FB})}. \tag{31}$$

For the minimization problem, denote $V_2(X) = \sup_{C,g}\, E[\int_0^\infty e^{-rt}(C_t)dt]$, where the dynamic of X_t is given by (10). The HJB equation for the minimization problem is:

$$rV_2(X) = \sup_{C,g}\Big\{ -C + V_2'(X)\,X\,\big[\tfrac{r}{1-\gamma}\big(1 - \big(\tfrac{C}{X}\big)^{1-\gamma}\big) + \tfrac{1}{2}\gamma\sigma^2 g^2\big] + \tfrac{1}{2}V_2''(X)\sigma^2 X^2 g^2\Big\} \tag{32}$$

The optimal the feedback controls are:

$$C = X\,\big[-r\,V_2'(X)\big]^{\frac{1}{\gamma}} \quad \text{and} \quad g = 0. \tag{33}$$

It is easily seen that the solution for (32) is given by:

$$V_2(X) = \frac{-X}{r}, \tag{34}$$

and the optimal compensation policy is $C = X$.

Finally, combining (31) and (34), we obtain (23). □

7.2 Appendix for Section 3.2 and 3.3

The following integrability conditions are needed for the admissibility of a contract:

$$c_t, i_t > 0,\ E\biggl(\int_0^{\infty} e^{-rt} K_t\, c_t dt\biggr) < \infty \tag{35}$$

$$E\biggl(\int_0^{+\infty} e^{-rt} K_t dt\biggr) < \infty, E\biggl(\int_0^{+\infty} e^{-rt} K_t\, h(i_t) dt\biggr) < \infty \tag{36}$$

$$E\biggl(\int_0^{+\infty} e^{-2rt} X_t^{2(1-\gamma)} g_t^2 dt\biggr) < \infty \tag{37}$$

Lemma 3. *Assume that*

$$E\biggl[\biggl(\int_0^{+\infty} e^{-rt}\, C_t^{1-\gamma} dt\biggr)^2\biggr] < \infty \tag{38}$$

then X_t has the Ito differential

$$dX_t = X_t\biggl\{\tfrac{r}{1-\gamma}\Bigl[1-\bigl(\tfrac{C_t}{X_t}\bigr)^{1-\gamma}\Bigr] + \tfrac{1}{2}\gamma\sigma^2 g_t^2\biggr\}dt + \sigma X_t\, g_t dB_t, \tag{39}$$

where the process $(g_t)_t$ is adapted to the filtration $(\mathcal{B}^t)_t$ and satisfies

$$E\biggl(\int_0^{+\infty} e^{-2rt} X_t^{2(1-\gamma)} g_t^2 dt\biggr) < \infty. \tag{40}$$

Introducing the stochastic processes x_t, i_t, and c_t (see (11)), then

$$dx_t = x_t\biggl\{\tfrac{r}{1-\gamma}\bigl[1-\bigl(\tfrac{c_t}{x_t}\bigr)^{1-\gamma}\bigr] - i_t - \mu + \sigma^2(1 - g_t + \tfrac{\gamma}{2} g_t^2)\biggr\}dt + \sigma\, x_t\,(g_t - 1)dB_t. \tag{41}$$

Proof. From the definition of X_t (see (3)), we have

$$e^{-rt}\, X_t^{1-\gamma} = -r\int_0^t e^{-rs}\, C_s^{1-\gamma} ds + r\, E\biggl(\int_0^{+\infty} e^{-rs}\, C_s^{1-\gamma} ds\Bigm|\mathcal{B}^t\biggr).$$

From the martingale representation theorem , we can state that:

$$E\left(\int_0^{+\infty} e^{-rs}\, C_s^{1-\gamma} ds \middle| \mathcal{B}^t\right) = E\left(\int_0^{+\infty} e^{-rs}\, C_s^{1-\gamma} ds\right) + \int_0^t \zeta_s dB_s,$$

with ζ_t adapted and

$$E\left(\int_0^{+\infty} \zeta_s^2 ds\right) \leq E\left[\left(\int_0^{+\infty} e^{-rt}\, C_t^{1-\gamma} dt\right)^2\right]. \tag{42}$$

Denote $V_t = X_t^{1-\gamma}$. We get immediately that the ito differential of V_t is

$$dV_t = (rV_t - r\, C_t^{1-\gamma})dt + r\, e^{rt}\, \zeta_t dB_t.$$

Since $X_t = V_t^{\frac{1}{1-\gamma}}$, by apply Ito's calculus , and defining g_t as

$$\zeta_t = \frac{g_t\,(1-\gamma)\,\sigma\, e^{-rt}\, X_t^{1-\gamma}}{r},$$

we obtain immediately the result (39),(40). Finally, applying Ito's lemma to the process x_t, we achieve the dynamics of the scaled certainty equivalent of the entrepreneur as stated in (41).

□

7.3 Appendix for Section 3.4

Using the optimality principle of Dynamic Programming, we get equation (17) to which we must add boundary conditions at $x = \bar{x}$ and when $x \to +\infty$ in the case of entrepreneurial limited commitment, as well as at $x = 0$ and $x = x^*$ in the case of financier limited commitment. Within the bracket, we can optimize with respect to c, g , which leads to feedbacks

$$c(x) = x\,[-r\, v'(x)]^{\frac{1}{\gamma}} \quad \text{and} \quad g(x) = \frac{x\, v''(x)}{\gamma\, v'(x) + x\, v''(x)} \tag{43}$$

Note that admissible controls must satisfy (35),(36),(37).

Thus, equation (17) reduces to:

$$\begin{aligned} 0 =& b - (-\mu + r)\, v(x) + \sup_{i} \{-h(i) + i\,[v(x) - x\, v'(x)]\} \qquad (44) \\ &+ (\tfrac{r}{1-\gamma} - \mu)\, x\, v'(x) + \tfrac{\gamma}{1-\gamma}\, x\, [-r\, v'(x)]^{\frac{1}{\gamma}} + \tfrac{1}{2}\sigma^2 \gamma \tfrac{x^2\, v'(x)\, v''(x)}{\gamma\, v'(x) + x\, v''(x)}. \qquad (45) \end{aligned}$$

When the entrepreneur displays limited commitment, $v(x)$ is the solution to (44) on $[\bar{x}, \infty)$ subject to the boundary conditions:[13]

$$v''(\bar{x}) = -\infty;\; v(x) - (\bar{v} - \tfrac{x}{r}) \to 0, \text{as } x \to +\infty. \tag{46}$$

When the financier displays limited commitment $v(x)$ is the solution to (44) on $(0, x^*]$ subject to the boundary conditions:

$$v(x^*) = 0; v''(x^*) = -\infty;\; v(x) \to \bar{v}, \text{as } x \to 0. \tag{47}$$

---

[13] See Ai and Li (2015).

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous, "The environment and directed technical change," *American Economic Review*, 2012, *102* (1), 131–66.

_ , Ufuk Akcigit, Douglas Hanley, and William Kerr, "Transition to clean technology," *Journal of Political Economy*, 2016, *124* (1), 52–104.

Aghion, Philippe, Antoine Dechezleprêtre, David Hemous, Ralf Martin, and John Van Reenen, "Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry," *Journal of Political Economy*, 2016, *124* (1), 1–51.

Ai, Hengjie and Rui Li, "Investment and CEO compensation under limited commitment," *Journal of Financial Economics*, 2015, *116* (3), 452–472.

_ , Dana Kiku, Rui Li, and Jincheng Tong, "A unified model of firm dynamics with limited commitment and assortative matching," *The Journal of Finance*, 2021, *76* (1), 317–356.

Aiyagari, S Rao, "Uninsured idiosyncratic risk and aggregate saving," *The Quarterly Journal of Economics*, 1994, *109* (3), 659–684.

Akerlof, George, Robert Aumann, A Deaton, P Diamond, R Engle, E Fama, L Hansen, O Hart, B Holmström, D Kahneman et al., "Economistsâ statement on carbon dividends," *Wall Street Journal*, 2019, p. A13.

Albuquerque, Rui and Hugo A Hopenhayn, "Optimal lending contracts and firm dynamics," *Review of Economic Studies*, 2004, *71* (2), 285–315.

Alvarez, Fernando and Urban J. Jermann, "Efficiency, Equilibrium, and Asset Pricing with Risk of Default," *Econometrica*, 2000, *68* (4), 775–797.

Angelis, Tiziano De, Peter Tankov, and Olivier David Zerbib, "Climate impact investing," *Management Science*, 2022.

Bensoussan, Alain, Benoit Chevalier-Roignant, Nam Nguyen, and Alejandro Rivera, "Managerial limited commitment: A new class of stochastic control problems," *SSRN*, 2022.

Bessembinder, Hendrik, "Frictional costs of fossil fuel divestment," *Available at SSRN 2789878*, 2016.

Bolton, Patrick, Frederic Samama, and Joseph E Stiglitz, *Sovereign wealth funds and long-term investing*, Columbia University Press, 2012.

_ **, Neng Wang, and Jinqiang Yang**, "Optimal contracting, corporate finance, and valuation with inalienable human capital," *Journal of Finance*, 2019, *74* (3), 1363–1429.

Broccardo, Eleonora, Oliver D Hart, and Luigi Zingales, "Exit vs. voice," Technical Report, National Bureau of Economic Research 2020.

Buera, Francisco J, Joseph P Kaboski, and Yongseok Shin, "Entrepreneurship and financial frictions: A macro-development perspective," Technical Report, National Bureau of Economic Research 2015.

Chemla, Gilles, Alejandro Rivera, and Liyan Shi, "Too Much, Too Soon, for Too Long: The Dynamics of Competitive Executive Compensation," *Too Soon, for Too Long: The Dynamics of Competitive Executive Compensation (June 8, 2021)*, 2021.

Daley, Brendan and Brett Green, "Waiting for News in the Market for Lemons," *Econometrica*, 2012, *80* (4), 1433–1504.

DeMarzo, Peter M. and Yuliy Sannikov, "Optimal Security Design and Dynamic Capital Structure in a Continuous-Time Agency Model," *Journal of Finance*, 2006, *61* (6), 2681–2724.

Gilchrist, Simon, Jae W Sim, and Egon Zakrajšek, "Uncertainty, financial frictions, and investment dynamics," Technical Report, National Bureau of Economic Research 2014.

Goldstein, Itay, Alexandr Kopytov, Lin Shen, and Haotian Xiang, "On ESG Investing: Heterogeneous Preferences, Information, and Asset Prices," *Information, and Asset Prices (April 9, 2021)*, 2021.

Gollier, Christian, *Le climat après la fin du mois*, Presses Universitaires de France, 2019.

Golosov, Mikhail, Aleh Tsyvinski, and Nicolas Werquin, "Recursive contracts and endogenously incomplete markets," in "Handbook of Macroeconomics," Vol. 2, Elsevier, 2016, pp. 725–841.

_ **, John Hassler, Per Krusell, and Aleh Tsyvinski**, "Optimal taxes on fossil fuel in general equilibrium," *Econometrica*, 2014, *82* (1), 41–88.

Grochulski, Borys and Yuzhe Zhang, "Optimal risk sharing and borrowing constraints in a continuous-time model with limited commitment," *Journal of Economic Theory*, 2011, *146* (6), 2356–2388.

Halbritter, Gerhard and Gregor Dorfleitner, "The wages of social responsibility-where are they? A critical review of ESG investing," *Review of Financial Economics*, 2015, *26*, 25–35.

Harris, Milton and Bengt Holmstrom, "A theory of wage dynamics," *The Review of Economic Studies*, 1982, *49* (3), 315–333.

Hart, Oliver and John Moore, "A theory of debt based on the inalienability of human capital," *Quarterly Journal of Economics*, 1994, *109* (4), 841–879.

Hayashi, Fumio, "Tobin's marginal q and average q: A neoclassical interpretation," *Econometrica*, 1982, pp. 213–224.

Heinkel, Robert, Alan Kraus, and Josef Zechner, "The effect of green investment on corporate behavior," *Journal of Financial and Quantitative Analysis*, 2001, *36* (4), 431–449.

Hennessy, Christopher A, Amnon Levy, and Toni M Whited, "Testing Q theory with financing frictions," *Journal of Financial Economics*, 2007, *83* (3), 691–717.

Hong, Harrison, G Andrew Karolyi, and José A Scheinkman, "Climate finance," *The Review of Financial Studies*, 2020, *33* (3), 1011–1023.

Kehoe, Patrick J and Fabrizio Perri, "International business cycles with endogenous incomplete markets," *Econometrica*, 2002, *70* (3), 907–928.

Li, Shaojin, Toni M. Whited, and Yufeng Wu, "Collateral, Taxes, and Leverage," *The Review of Financial Studies*, 06 2016, *29* (6), 1453–1500.

Ligon, Ethan, Jonathan P Thomas, and Tim Worrall, "Informal insurance arrangements with limited commitment: Theory and evidence from village economies," *Review of Economic Studies*, 2002, *69* (1), 209–244.

Ljungqvist, Lars and Thomas J Sargent, *Recursive macroeconomic theory*, MIT press, 2018.

Marcet, Albert and Ramon Marimon, "Recursive contracts," 2011.

Miao, Jianjun and Yuzhe Zhang, "A duality approach to continuous-time contracting problems with limited commitment," *Journal of Economic Theory*, 2015, *159*, 929–988.

Nguyen, Nam, Alejandro Rivera, and Harold H Zhang, "Incentivizing Investors for a Greener Economy," *Available at SSRN 3944305*, 2021.

Nikolov, Boris and Toni M. Whited, "Agency Conflicts and Cash: Estimates from a Dynamic Model," *Journal of Finance*, 2014, *69* (5), 1883–1921.

Nordhaus, William D, *Managing the global commons: the economics of climate change*, Vol. 31, MIT press Cambridge, MA, 1994.

Oehmke, Martin and Marcus M Opp, "A theory of socially responsible investment," *Swedish House of Finance Research Paper*, 2020, *20* (2).

Rudanko, Leena, "Labor market dynamics under long-term wage contracting," *Journal of Monetary Economics*, 2009, *56* (2), 170–183.

Thomas, Jonathan and Tim Worrall, "Income fluctuation and asymmetric information: An example of a repeated principal-agent problem," *Journal of Economic Theory*, 1990, *51* (2), 367–390.