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FINANCING THE ADOPTION OF CLEAN TECHNOLOGY

Andrea Lanteri
Adriano A. Rampini

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ABSTRACT

We analyze the adoption of clean technology by heterogeneous firms subject to financing constraints. In the model, capital goods differ in terms of their energy needs and age. In equilibrium, cleaner and newer capital requires more financial resources. Therefore, financial constraints induce an endogenous pattern in clean technology adoption: Financially constrained, smaller firms optimally invest in dirtier and older capital than unconstrained, larger firms. The model is consistent with the empirical patterns of technology adoption we document using data on commercial shipping fleets. We use a calibrated version of our model to simulate the aggregate transition dynamics to cleaner technology.

Andrea Lanteri
Duke University
Department of Economics
233 Social Sciences Building
Durham, NC 27708
andrea.lanteri@duke.edu

Adriano A. Rampini
Duke University
Fuqua School of Business
100 Fuqua Drive
Durham, NC 27708
and NBER
rampini@duke.edu

1 Introduction

The effects of economic activity on climate change make it paramount to understand the drivers of firms' decisions to adopt clean technologies. Energy efficiency is to a large extent embodied in capital goods and there is substantial heterogeneity in energy requirements across different types of capital goods—such as the various types of engines used in transportation equipment. Furthermore, technological progress makes newer vintages of capital more energy efficient over time. However, because this technological progress is embodied in durable assets with a long productive life, at any point in time firms can operate newer technologies at the frontier of energy efficiency, or older and dirtier technologies.

What are the equilibrium patterns of clean-technology adoption when firms are heterogeneous in their financial resources? This paper addresses this question by developing a novel general equilibrium model of firm dynamics and clean-technology adoption with financial constraints. Our main insight is that if both clean and dirty technologies are used in equilibrium, investment in clean capital must require more financial resources, because clean capital must be more expensive. Thus, financially constrained firms optimally invest in dirty new technologies as well as in older technologies, resulting in a positive relation between firm size and energy efficiency.

Our model features stochastic overlapping generations of firms and heterogeneous technologies embodied in capital goods. Different types of new capital vary in their energy efficiency. Financial constraints are modeled as collateral constraints, and the collateralizability of the residual value of capital is limited. We show that, if both clean and dirty technologies are used in equilibrium, clean capital must be more expensive than dirty capital in terms of down payments. Thus, less financially constrained firms invest in clean capital, whereas more financially constrained firms invest in dirty capital due to the lower financing need associated with such capital.

We also consider an economy in which lenders charge a lower interest rate on loans against clean capital. We show that subsidized lending against clean capital affects firms differentially, benefitting less constrained firms while leaving sufficiently constrained firms unaffected. The endogenous pattern in clean-technology adoption we emphasize thus implies that these effects are heterogeneous and in fact regressive.

Our main insight on the role of financing constraints for clean-technology adoption generalizes to the case in which the use of energy imposes direct, linear utility costs on firms, for example, because of the associated environmental damage. Even if all firms partly internalize this environmental cost, financially constrained firms operate using more dirty capital. It may thus appear as if well-capitalized firms have stronger environmental concerns, suggesting a non-homotheticity in preferences, but importantly our model suggests that this basic pattern in technology adoption arises because of an induced preference due to financial conditions, not because preferences themselves are non-homothetic.

Our theory moreover suggests that financial development, which improves legal enforcement and hence collateralizability, can increase aggregate output while decreasing aggregate energy use at the same time. The reason is that an increase in collateralizability facilitates clean-technology adoption. Thus, financial development does not just affect the level of investment, as is well-understood, but also the composition of investment in terms of the adoption of clean technology.

We then extend the model to allow for a choice of capital age. New capital goods are more expensive than old capital goods in terms of down payments. As a result, large and unconstrained firms adopt clean new technologies, whereas small, financially constrained firms choose to operate older vintages of capital, which tend to be less energy efficient. Thus, financially constrained firms are less energy efficient for two reasons, because they adopt dirtier new technologies and because they operate old capital.

After developing our theoretical analysis, we leverage a rich dataset on commercial ships to document empirical patterns on the allocation of heterogeneous capital goods across firms of different size. Transportation equipment, and shipping specifically, is a natural empirical laboratory for our analysis for two main reasons. First, the transportation sector accounts for a large share of global carbon emissions (23% of energy-related CO_2 emissions in 2010 according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change). Second, different types and vintages of transportation equipment, such as commercial ships, vary substantially in their degree of energy efficiency, as we show in our empirical analysis. Moreover, ships are long-lived assets, which makes vintage effects particularly salient.

We show that larger fleets operate, on average, ships with higher energy efficiency. We then illustrate that this pattern arises for several concurrent reasons, consistent with our model predictions. First, when firms invest in new ships, larger firms are more likely to order new ships with cleaner engines. Second, larger firms tend to operate ships of newer vintages. Because technological progress makes new vintages cleaner over time, a lower average age of the capital stock contributes to make larger fleets cleaner.

Finally, we combine model and data and use a calibrated version of our model to analyze transition dynamics. We consider several scenarios that differ in the underlying source of technological progress. Specifically, we simulate the effects of improvements in the energy efficiency of capital or in the cost of producing clean capital. This analysis highlights that our main insights on the role of financing constraints for technology adoption are highly relevant to understand both aggregate and cross-sectional patterns of substitution across technologies.

We stress that while we focus on a model with heterogeneous firms subject to financial constraints, a similar trade-off between environmental concerns and distributional consequences arises in the adoption of clean durable goods by households. Our theory explains why less financially constrained households buy new, energy-efficient durables, such as houses, cars, and appliances, whereas more financially constrained households buy old, less energy-efficient durables, even in the absence of non-homotheticities in environmental concerns. The distributional consequences in the household context might be particularly noteworthy and may be key to understanding the heterogeneity in political views about environmental policies within and across countries.

Furthermore, while we focus on the energy needs of capital goods directly, the model can be easily extended to consider carbon emissions associated with such energy needs, as well as potential environmental consequences. Thus, our framework provides a natural laboratory to analyze the distributional effects of environmental policies in the presence of financing constraints.

The rest of the paper proceeds as follows. Section 2 describes the most relevant related literature. Section 3 presents a model with two types of capital, in which clean capital is more energy efficient than dirty capital, but more expensive. Section 4 considers a model with new and old capital. Together, these two versions of our theory predict a relation between firms' financial constraints, energy efficiency, and capital age. Section 5 discusses the empirical evidence. Section 6 analyzes the transition dynamics associated with improvements in energy efficiency in a quantitative version of our model. Section 7 concludes.

2 Related Literature

This paper contributes to several strands of literature, most importantly the literature on investment and capital reallocation with financing constraints and the literature on energy efficiency in macroeconomics and finance. The paper is also related to the literature on heterogeneity in macroeconomics, especially on the heterogeneous effects of policies, and on innovation, technology adoption, and growth more broadly.

Investment and Capital Reallocation with Financing Constraints. Starting with Eisfeldt and Rampini (2006), a large literature studies the process of reallocation of capital goods across heterogeneous producers.[1] A robust empirical finding of this literature is that financially constrained agents tend to buy assets in the secondary market (Eisfeldt and Rampini, 2007; Gavazza and Lanteri, 2021; Ma, Murfin, and Pratt, 2022). Leveraging this insight, Lanteri and Rampini (2023) build on the framework of Rampini (2019) to analyze the constrained-efficient (re-)allocation of capital across firms subject to collateral constraints (Kiyotaki and Moore, 1997; Rampini and Viswanathan, 2010, 2013). However, this literature abstracts from heterogeneous energy efficiency of new and old capital goods. By introducing heterogeneous technologies with different energy requirements, we develop a new model with an endogenous firm distribution of financial resources, energy efficiency, and capital age.

Energy Efficiency in Macroeconomics. A growing literature analyzes energy efficiency and environmental concerns in dynamic general equilibrium models. In an early contribution, Atkeson and Kehoe (1999) analyze two alternative dynamic models of capital investment and energy use. Hassler, Krusell, and Smith (2016) emphasize the choice between technologies (or energy sources) with different impact on the quality of the environment. See, for instance, Acemoglu, Aghion, Bursztyn, and Hemous (2012) and Acemoglu, Akcigit, Hanley, and Kerr (2016) for endogenous growth models with clean and dirty technologies, or Golosov, Hassler, Krusell, and Tsyvinski (2014) and Barrage (2020) for quantitative general equilibrium analyses of optimal carbon taxes.[2] In recent work, Känzig (2023) analyzes

[1] Lanteri (2018) combines a general equilibrium model with heterogeneous firms with data from secondary markets for capital goods to explain the patterns of reallocation over the business cycle. Eisfeldt and Shi (2018) survey the literature on capital reallocation.

[2] Acharya, Engle, and Wang (2025) analyze the strategic incentives for large firms to commit to clean-technology adoption in a model with environmental and innovation externalities.

the heterogeneous effects of shocks to energy prices on households. Kuhn and Schlattmann (2024) analyze the effects of subsidies on energy-efficient durable goods in a quantitative model of household consumption. Iovino, Martin, and Sauvagnat (2024) focus on the relationship between corporate taxation and firms' emission intensity. We contribute to this literature by analyzing equilibrium technology adoption in a new framework that features heterogeneous firms facing financial constraints. Our theory suggests that financially constrained agents have an induced preference for dirty technologies, even in the absence of non-homotheticities.[3]

Energy Efficiency in Finance. Several recent contributions provide empirical analyses of the impact of firms' financial conditions on energy use and the environment. Gentet-Raskopf (2022) studies empirically the trade-off between firms' investments in preventing environmental damage ex ante and in treating such damage ex post. Hartzmark and Shue (2024) provide a measure of the elasticity of environmental impact with respect to financing costs at the firm level and find that increases in financing costs increase emissions. Martinsson, Sajtos, Strömberg, and Thomann (2024) estimate the effects of carbon pricing on firms' carbon emissions. We provide a theoretical analysis of the role of financing constraints for clean-technology adoption.[4] Finally, our paper is also related to the literature on the effect of investors' preferences on investment in clean and dirty firms. In an early contribution, Heinkel, Kraus, and Zechner (2001) explore the effect on the composition of investment when some investors exclude dirty firms from their portfolios. More recently, Oehmke and Opp (2024) consider firms' choice between clean and dirty technologies when some investors take the environmental consequences of the firms they invest in into account.

[3]Relatedly, Gillingham and Palmer (2014) and Berkouwer and Dean (2022) discuss the role of credit constraints and other frictions for the lack of adoption of energy-efficient technologies by households. Azomahou, Boucekkine, and Nguyen-Van (2012) introduce energy-saving technical change in a model of vintage capital, but abstract from heterogeneity. Capelle, Kirti, Pierri, and Villegas-Bauer (2023) provide evidence of a positive correlation between capital age and carbon emissions at the firm level. A literature in industrial organization also considers vintage-capital models with environmental externalities and policies; see, for instance, Bento, Goulder, Jacobsen, and von Haefen (2009) and Barahona, Gallego, and Montero (2020). Barnett, Brock, and Hansen (2020) consider the effect of uncertainty in a macroeconomic model with investment and environmental concerns.

[4]Consistent with our focus on financing constaints, De Haas and Popov (2023) show that easier access to external financing stimulates clean growth and Aghion, Bergeaud, De Ridder, and Van Reenen (2024) analyze the negative effects of credit shocks on green innovation by young firms.

3 Clean Technology Adoption with Financial Constraints

We now describe a model of firm investment subject to financing constraints with two types of capital, which are heterogeneous in their energy use: Clean capital goods require less energy than dirty capital goods. This model features new investment in both clean and dirty technologies and predicts that more financially constrained firms invest in dirty capital which uses more energy.

The main trade-off is that, if both types of capital are used in equilibrium, clean capital must be more expensive and require more internal funds than dirty capital as clean capital requires lower energy use. In contrast, the frictionless user cost per unit of clean capital, including energy costs, must be lower than that of dirty capital, if clean capital is used at all. Therefore, financially unconstrained firms use clean capital, whereas sufficiently constrained firms use dirty capital due to its lower financing need. We also show that limited collateralizability is essential for this result and discuss how legal enforcement affects clean-technology choice. Finally, we consider the effect of subsidized lending against clean capital, the case in which firms internalize a private disutility of energy use, and the case of a social preference for clean capital.

3.1 Model with Clean vs. Dirty Technology Choice

Time is discrete and the horizon infinite. We consider the stationary equilibrium of a stochastic overlapping generations model of firm dynamics with financial constraints.

Preferences. A representative household ranks sequences of consumption C_t according to the utility function $\sum_{t=0}^{\infty} \beta^t u(C_t)$, where $\beta \in (0,1)$ is the discount factor and u is strictly increasing and strictly concave, $u_c > 0$ and $u_{cc} < 0$.

Technology. There are over-lapping generations of firms owned by the representative household. At each date, a continuum of firms with measure $\rho \in (0,1]$ is born and measure ρ of existing firms die after production. Each firm has access to a production function $f(x)$ which is strictly increasing and strictly concave in composite input x, and satisfies $f(0) = 0$, $\lim_{x \to 0} f_x(x) = +\infty$, and $\lim_{x \to \infty} f_x(x) = 0$.

There are two types of capital k_j, $j \in \mathcal{J} \equiv \{C, D\}$, clean capital k_C and dirty capital k_D, which both depreciate at rate $\delta \in (0,1)$. Production requires capital and energy as inputs.

A unit of type-j capital requires $\gamma_j > 0$ units of energy to operate, that is, for each type of capital, capital and energy are used in fixed proportions, so $\min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$, where e_j is energy used for type-j capital. Assume that clean capital is more energy efficient than dirty capital:

Assumption 1 *There are two types of capital that differ in their associated energy needs γ_j; clean capital requires less energy than dirty capital to operate: $\gamma_C < \gamma_D$.*

The two types of capital (with appropriate energy inputs) are perfect substitutes as inputs in production, so composite input x is determined by the input aggregator $x \equiv \sum_{j\in\mathcal{J}} \min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$. Investing composite input x in the current period yields output $f(x)$ next period. We assume that the two types of capital, suitably combined with energy, are perfect substitutes here, but we will relax this assumption in the quantitative work. Further, we assume that both capital and energy inputs need to be purchased this period, although the basic insight is the same when energy can be purchased when production occurs next period, as we show in Appendix A.1.

Output can be used to make both types of capital; it costs q_j units of output to make type-j capital, and thus the price of type-j capital q_j is determined by its linear production technology and exogenous. Notice that because the output good is produced using energy and capital is produced using the output good as an input, our model features a notion of "embodied energy" in capital.[5] The price of energy is $p_e > 0$.[6]

Financial Frictions. New firms receive a stochastic initial amount of net worth w_0, which is drawn from a distribution $\pi_0(w_0)$. Firms can raise additional internal funds from the representative household subject to an increasing and convex cost of equity issuance $\phi(-d)$, for $d < 0$, and zero otherwise, where d denotes firms' dividends; negative dividends amount to raising equity and incur a positive and convex cost.[7]

In addition, firms can borrow b at an interest rate $R = \beta^{-1}$ from the representative household. Limited enforcement implies that firms need to collateralize all promises and

[5]Therefore, in our model the two types of capital have the same fraction of embodied energy, as does consumption, and, for simplicity, we abstract from differential embodied energy needed to produce different types of capital or consumption.

[6]The price of energy p_e could be normalized to one, as only the product of $\gamma_j p_e$ is required in what follows, but we keep the price of energy explicit for clarity.

[7]We could alternatively assume that dividends have to be non-negative without affecting our conclusions.

can only credibly promise to pay up to a fraction $\theta \in [0,1)$ of the resale value of capital.[8] In a stationary equilibrium, the marginal utility of consumption of the representative agent is constant and hence we treat firms as risk-neutral with the rate of time preference $\beta \in (0,1)$, subject to the financial constraints on equity and debt finance described above.

Firms' Problem. Given their initial net worth w, firms maximize the present discounted value of their dividends net of equity issuance costs, that is, their value to the household, by choosing dividends d, borrowing b, clean and dirty capital k_C and k_D, and associated energy inputs e_j, $j \in \{C, D\}$, to solve

$$v(w) \equiv \max_{\{d,b,k_j,e_j\} \in \mathbb{R}^2 \times \mathbb{R}^4_+} d - \phi(-d) + R^{-1}\{\rho w' + (1-\rho)v(w')\} \tag{1}$$

subject to the budget constraints for the current and next period,

$$w + b = d + \sum_{j \in \{C,D\}} q_j k_j + \sum_{j \in \{C,D\}} p_e e_j, \tag{2}$$

$$f(x) + \sum_{j \in \{C,D\}} q_j k_j (1-\delta) = w' + Rb, \tag{3}$$

and the collateral constraint

$$\theta \sum_{j \in \{C,D\}} q_j k_j (1-\delta) \geq Rb, \tag{4}$$

where $x \equiv \sum_{j \in \{C,D\}} \min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$ and $v(w)$ denotes the value function conditional on continuation and variables next period are denoted with a prime.[9] At an optimum, firms match each unit of type-j capital with the appropriate amount of energy, $e_j = \gamma_j k_j$, $\forall j \in \{C, D\}$, and we can thus substitute out e_j going forward.

Cum-Energy User Cost and Down Payment. Following Jorgenson (1963), we define the frictionless user cost of type-j capital measured as of the beginning of the period as $u_j \equiv R^{-1} q_j (r + \delta)$. We define the down payment for type-j capital as $\wp_j \equiv q_j(1 - R^{-1}\theta(1-\delta))$; this is the minimal amount of internal funds that the firm needs to deploy one unit of

[8] Rampini and Viswanathan (2010, 2013) derive such collateral constraints in an environment with limited enforcement without exclusion.

[9] The constraint set is convex, and the value function that solves the Bellman equation is unique, strictly increasing, and concave.

type-j capital. Note that $\wp_j = u_j + R^{-1}(1-\theta)q_j(1-\delta) > u_j$, that is, the down payment per unit of capital exceeds the frictionless user cost by the present value of the residual value of capital that the firm cannot pledge. Since capital needs to be combined with the appropriate amount of energy, we can define the user cost of type-j capital including the associated energy costs, which we refer to as the *cum-energy user cost of capital*, as

$$u_j^e \equiv u_j + \gamma_j p_e = R^{-1}q_j(r+\delta) + \gamma_j p_e,$$

and analogously we define the down payment for type-j capital including the associated energy costs, that is, the *cum-energy down payment*, as

$$\wp_j^e \equiv \wp_j + \gamma_j p_e = q_j(1 - R^{-1}\theta(1-\delta)) + \gamma_j p_e.$$

We stress that our model does not feature fixed costs of investment or technology adoption. Both user costs and down payments are defined as costs per unit of capital.

Using the multipliers μ, $\beta\mu'$, and $\beta\lambda'$ for the budget constraints in the current and next period, and the collateral constraint, respectively, we can write the investment Euler equations (IEEs) as

$$1 \geq R^{-1}\frac{\mu'}{\mu}\frac{f_x(x) + (1-\theta)q_j(1-\delta)}{\wp_j^e}, \tag{5}$$

where we use the definition of the cum-energy down payment. Using the definition of the cum-energy user cost and down payment, we can further re-write the investment Euler equation as

$$u_j^e + \frac{\lambda'}{\mu'}\wp_j^e \geq R^{-1}f_x(x). \tag{6}$$

The choice between clean and dirty capital is determined by the trade off between the cum-energy user cost of type-j capital and the cum-energy down payment for type-j capital.[10]

Moreover, the first-order conditions with respect to debt, dividends, and the envelope

[10] The IEE for type-j capital can also be written as $(r + R\lambda'/\mu')\wp_j^e + rR^{-1}q_j\theta(1-\delta) + q_j\delta + \gamma_j p_e \geq f_x(x)$, where the first two terms can be interpreted as the weighted-average cost of capital; investment requires a cum-energy down payment $\wp_j^e$ at a shadow-cost of internal funds $r + R\lambda'/\mu'$, whereas $R^{-1}q_j\theta(1-\delta)$ can be financed externally at the net interest rate r.

condition give

$$\lambda' = \mu - \mu' \quad (7)$$

$$\mu = 1 + \phi_d \quad (8)$$

$$\mu' = 1 + (1-\rho)\phi'_d. \quad (9)$$

Using the envelope condition in the current period, we conclude that $v_w(w) = \mu = 1 + \phi_d \geq 1$, that is, the marginal value of net worth weakly exceeds 1, and we can interpret ϕ_d as the premium on internal funds.

First Best. When financing is frictionless, the marginal value of net worth of all firms is 1, and the collateral constraints are slack, so $\lambda' = 0$. Therefore, the investment Euler equation (6) implies that all firms simply compare the frictionless user cost of capital including associated energy costs, and therefore, as we argue below, invest in clean capital only.

3.2 Determinants of Clean Technology Adoption

We now characterize the choice between clean and dirty capital when firms are subject to financial constraints. We focus on the interesting case in which neither clean nor dirty capital are dominated. Notice that if the cum-energy user cost of type-j capital is lower than that of type-i capital, $u^e_j < u^e_i$, then the cum-energy down payment for type-j capital must be larger than that for type-i capital, $\wp^e_j > \wp^e_i$, as otherwise type-i capital would be dominated as can be seen from the investment Euler equation (6). We now show that this implies that the price of clean capital must exceed the price of dirty capital $q_C > q_D$ if neither type of capital is dominated. To see this, note that if $u^e_j = R^{-1}q_j(r+\delta) + \gamma_j p_e < R^{-1}q_i(r+\delta) + \gamma_i p_e = u^e_i$, then, as argued above, $\wp^e_j = R^{-1}q_j(r+\delta) + \gamma_j p_e + R^{-1}(1-\theta)q_j(1-\delta) > R^{-1}q_i(r+\delta) + \gamma_i p_e + R^{-1}(1-\theta)q_i(1-\delta) = \wp^e_i$; but then $q_j > q_i$. Moreover, for the first inequality to hold, it must be that $\gamma_j < \gamma_i$, and therefore $j = C$. Thus, the price of clean capital must be higher than that of dirty capital, $q_C > q_D$, which immediately implies that $u_C > u_D$ as well as $\wp_C > \wp_D$. Clean capital is more expensive, has a higher frictionless user cost, and requires a higher down payment per unit of capital. Furthermore, the down payment per unit of clean capital including associated energy costs, that is, the cum-energy down payment is also higher. However, the frictionless user cost of clean capital including associated energy costs, that is, the cum-energy user cost, must be lower than that of dirty capital.

We summarize this insight in the following Proposition.

Proposition 1 (Trade off) *If both clean and dirty capital are used in equilibrium, then the price, user cost, down payment, and cum-energy down payment of clean capital are higher than those of dirty capital:* $q_C > q_D$, $u_C > u_D$, $\wp_C > \wp_D$, *and* $\wp_C^e > \wp_D^e$. *In contrast, the cum-energy user cost of clean capital is lower than that of dirty capital:* $u_C^e < u_D^e$.

Proposition 1 implies that $\frac{\gamma_C p_e}{\wp_C^e} < \frac{\gamma_D p_e}{\wp_D^e}$, that is, energy costs are a smaller fraction of the cum-energy down payment for clean capital than dirty capital. Further, the proposition implies that $\frac{\gamma_C p_e}{u_C} < \frac{\gamma_D p_e}{u_D}$. Therefore, using the fact that $\frac{\gamma_j p_e}{u_j^e} = \frac{1}{(\gamma_j p_e/u_j)^{-1}+1}$, we conclude that $\frac{\gamma_C p_e}{u_C^e} < \frac{\gamma_D p_e}{u_D^e}$, that is, energy costs are a smaller fraction of the cum-energy user cost of clean capital than dirty capital. To summarize these implications:

Corollary 1 *Under the conditions of Proposition 1, energy costs are a smaller fraction of the cum-energy down payment and cum-energy user cost of clean capital than dirty capital.*

Price Difference between Clean and Dirty Capital and Collateralizability. The higher price of clean capital in part reflects the future energy savings. Indeed, the future energy cost savings put an upper bound on the price difference between clean and dirty capital. To see this, note that the inequality $u_C^e < u_D^e$ implies the following upper bound on the difference in the price of clean and dirty capital:

$$q_C - q_D < \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta},$$

that is, the price difference has to be less than the present value of the energy savings from the vantage point of an unconstrained firm. Otherwise, the cum-energy user cost of clean capital would exceed that of dirty capital, and clean capital would be dominated. Notice that the admissible difference in the price of the two types of capital is higher the lower the depreciation rate of capital δ, and hence the higher the durability of capital $1/\delta$. Thus, all else equal, potential price differences between clean and dirty capital might be particularly large for more durable types of capital, such as ships, aircraft, structures, and infrastructure.

There is an interesting subtlety here. A higher price of clean capital implies that the residual value of clean capital is also higher. Thus, the firm can borrow more against clean capital due to the higher collateral value. Indeed, we can also derive a lower bound on the price difference between clean and dirty capital, which depends on the collateralizability, that is, the financing frictions. Specifically, the inequality $\wp^e_C > \wp^e_D$ implies the following lower bound on the difference in the price of clean and dirty capital:

$$q_C - q_D > \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta + (1-\theta)(1-\delta)}.$$

This lower bound is the present value of the pledgeable fraction of the energy savings associated with clean capital. To understand the economic intuition for this lower bound, notice that we can write this present value as follows:

$$\begin{aligned}(\gamma_D - \gamma_C)p_e \left(1 + R^{-1}\theta(1-\delta) + R^{-2}\theta^2(1-\delta)^2 + ...\right) &= \frac{(\gamma_D - \gamma_C)p_e}{1 - R^{-1}\theta(1-\delta)} \\ &= \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta + (1-\theta)(1-\delta)}.\end{aligned}$$

Recall that each period the price difference has to exceed at least the energy savings in that period, $(\gamma_D - \gamma_C)p_e$, on what remains of the unit of capital in period t, $(1-\delta)^t$, of which fraction $(\theta)^t$ is pledgeable. This highlights the essential role of limited collateralizability in our model, that is, the assumption that $\theta < 1$. In fact, as the collateralizability parameter θ goes to 1, the admissible region for the difference in the price of clean and dirty capital converges to a point, given by the present value of energy savings. This means that if residual value were fully pledgeable, the price difference would have to equal the value of the energy cost savings, and the cum-energy user cost and down payments of clean and dirty capital would be the same, making all firms indifferent between the two.[11]

We characterize firms' choice between clean and dirty capital next. Financially unconstrained firms, which pay non-negative dividends, have a marginal value of net worth

[11] Notice that as δ goes to 1, the lower bound also converges to the upper bound, meaning that if capital were not durable, then the price of clean capital simply reflects the current energy cost savings $(\gamma_D - \gamma_C)p_e$, and firms would again be indifferent between the two types of capital.

equal to 1, that is, $\mu = 1$, and the collateral constraint is slack for these firms; since $1 = \mu = \mu' + \lambda' \geq \mu' \geq 1$, $\mu' = 1$ and $\lambda' = 0$. The investment Euler equation (6) then implies that unconstrained firms simply compare the frictionless cum-energy user cost of capital and thus only invest in clean capital.

In contrast, firms that are sufficiently constrained compare the cum-energy down payments per unit of capital. In the limiting case in which the cost of issuing equity is infinite and thus dividends have to be non-negative, as w goes to 0, so must x, and therefore equation (5) implies that $\mu'/\mu \to 0$. Using the first-order condition for debt (7), $\lambda'/\mu' \to +\infty$, which means that by equation (6) such firms compare the cum-energy down payments.[12] Thus, sufficiently constrained firms use the less energy-efficient, dirty technology to conserve net worth.

For firms that are indifferent between clean and dirty capital, we have $u^e_C + \frac{\lambda'}{1+(1-\rho)\phi'_d}\wp^e_C = u^e_D + \frac{\lambda'}{1+(1-\rho)\phi'_d}\wp^e_D$. Notice that the first-order condition with respect to debt implies $\frac{\lambda'}{1+(1-\rho)\phi'_d} = \frac{1+\phi_d}{1+(1-\rho)\phi'_d} - 1$. We can define the effective discount rate of these firms as $\bar{R} \equiv \frac{R(1+\phi_d)}{1+(1-\rho)\phi'_d}$. Using the indifference condition between clean and dirty capital, we have $\bar{R} = R(1 + \frac{u^e_D - u^e_C}{\wp^e_C - \wp^e_D}) > R$ and we can express the investment Euler equations as follows:

$$1 = \bar{R}^{-1}\frac{f_x(x) + (1-\theta)q_j(1-\delta)}{\wp^e_j}.$$

We summarize this characterization of the choice between clean and dirty capital in the following Proposition.

Proposition 2 (Clean-technology adoption) *Financially unconstrained firms invest in clean capital. Sufficiently constrained firms invest in dirty capital. Firms in an intermediate range of net worth are indifferent at the margin and gradually substitute from dirty to clean capital as net worth w increases.*

We show that a similar endogenous pattern of technology adoption obtains in the case of households choosing between clean and dirty durable goods in Appendix A.2.

[12] Alternatively, we can rewrite (5) as $\wp^e_j + R^{-1}\mu'/\mu(1-\theta)q_j(1-\delta) \geq R^{-1}\mu'/\mu f_x(x)$ and note that as $\mu'/\mu \to 0$, the right-hand side goes to the cum-energy down payment.

3.3 Generality of Main Insight

We have shown that, when both clean and dirty technologies are used in equilibrium, investment in clean capital must be more expensive and require a higher down payment. This price difference reflects part of the future energy cost savings associated with the clean technology. Because of the higher down payment, sufficiently financially constrained firms optimally choose to invest in the dirty technology, whereas unconstrained firms optimally invest in the clean technology.

We stress that this characterization applies generally, beyond the focus of this paper on energy efficiency. Our theory is relevant whenever there are multiple technologies embodied in capital which differ in terms of a required complementary input. The technology that provides future savings on the complementary input cost must be more expensive from an ex-ante perspective and thus require more financial resources. As a consequence, higher firm net worth is associated with a higher likelihood of adopting technologies that allow future cost savings. This theory may thus prove useful to analyze other important types of technology adoption, such as automation, which allows firms to reduce future labor costs. Consistent with this insight, Acemoglu, Lelarge, and Restrepo (2020) provide empirical evidence that large firms account for the bulk of investment in automation.

3.4 Subsidized Lending against Clean Capital

In our baseline model, firms can borrow at interest rate $R = \beta^{-1}$ against both clean and dirty capital. However, consider the case in which firms can borrow at a lower interest rate against clean capital, be it because such lending is subsidized by the government or because financial institutions have incentives to engage in such lending or because lenders simply have a preference for lending against clean capital. Specifically, suppose clean capital can be financed at a subsidized interest rate $R_C \leq R_D = R = \beta^{-1}$.[13]

Firms' problem is as before, except that firms can separately choose borrowing against clean and dirty capital b_C and b_D, to maximize (1) subject to the budget constraints for

[13] For example, in the global shipping industry, the Poseidon Principles (www.poseidonprinciples.org) provide a framework for financial institutions to integrate climate considerations into their lending decisions, specifically the emissions intensity of their shipping loan portfolios.

the current and next period,

$$w + \sum_{j \in \{C,D\}} b_j = d + \sum_{j \in \{C,D\}} q_j k_j + \sum_{j \in \{C,D\}} p_e e_j, \tag{10}$$

$$f(x) + \sum_{j \in \{C,D\}} q_j k_j (1-\delta) = w' + \sum_{j \in \{C,D\}} R_j b_j, \tag{11}$$

and the collateral constraints for loans backed by clean and dirty capital, respectively,

$$\theta q_j k_j (1-\delta) \geq R_j b_j, \tag{12}$$

for all $j \in \{C, D\}$, where $x \equiv \sum_{j \in \{C,D\}} \min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$.

Defining the cum-energy user cost and down payment analogously to before and denoting the multipliers on the collateral constraints (12) by $\beta\lambda'_j$, the investment Euler equations can be stated as

$$R_j u_j^e + \frac{\lambda'_j}{\mu'} R_j \wp_j^e \geq f_x(x).$$

In our baseline model, $R_C = R_D = R$, and assuming both types of capital are used in equilibrium, $R_C u_C^e < R_D u_D^e$ whereas $R_C \wp_C^e > R_D \wp_D^e$ (Proposition 1). Using this starting point, consider the effect of changing the interest rate R_C on loans backed by clean capital on the (scaled) cum-energy user cost $\frac{\partial}{\partial R_C}(R_C u_C^e) > 0$ and on the (scaled) cum-energy down payment $\frac{\partial}{\partial R_C}(R_C \wp_C^e) > 0$. Subsidized lending against clean capital therefore lowers both the (scaled) user-cost and (scaled) cum-energy down payment of clean capital.

But given the endogenous patterns in technology adoption (Proposition 2), subsidized lending against clean capital has differential effects on firms. Well-capitalized firms invest in clean capital and expand when the (scaled) user cost (and down payment) of clean capital decreases. Firms in an intermediate range, which are indifferent at the margin and invest in both types of capital, shift investment towards clean capital, and the range of net worth where firms are indifferent shifts down. In contrast, sufficiently constrained firms continue to invest in dirty capital and are unaffected. In this sense, subsidized lending against clean capital is regressive. That said, a sufficiently large subsidy of loans backed by clean capital could reduce the (scaled) down payment on clean capital below the one on dirty capital, in which case clean capital would dominate and all firms would operate with clean capital only. In general though, the endogenous patterns in clean-technology adoption is critical for the evaluation of the heterogenous effects of subsidies for loans against clean capital across firms, and our model predicts that the effects of such subsidies are regressive.

3.5 Private Disutility from Energy Use

So far, our analysis assumes that energy use does not impose utility costs on households and that firms only face pecuniary costs from energy use. We now consider the case in which aggregate energy consumption also has a direct negative effect on household utility because of its impact on the quality of the environment. We show that our main insights are robust with respect to this relevant modification of the assumptions on household preferences.

Specifically, we assume that this disutility term is linear in aggregate energy use, that is, the household utility function becomes $\sum_{t=0}^{\infty} \beta^t \left(u(C_t) - \chi E_t\right)$, with $\chi > 0$ and where E_t denotes total energy used by all firms at date t, combined with either clean or dirty capital in production.

Furthermore, we assume that firms internalize the effect of their investment decisions on household utility. To obtain a sharper characterization, we consider our baseline model and focus on the special case in which firms are alive only at two dates, that is, $\rho = 1$.[14] Thus, the problem of a new firm born with net-worth w is

$$v(w) \equiv \max_{\{d,b,k_j,e_j\} \in \mathbb{R}^2 \times \mathbb{R}_+^4} d - \phi(-d) - \chi \sum_j e_j + R^{-1} w',$$

subject to the budget constraints (2), (3), and the collateral constraint (4).

The investment Euler equations for $j = \{C, D\}$ can be expressed as follows:

$$u_j^e + \gamma_j \chi + \lambda' \wp_j^e \geq R^{-1} f_x(x).$$

This optimality condition shows that, if both technologies are used in equilibrium, one of them must be less expensive in terms of user cost *plus marginal disutility from energy* $\gamma_j \chi$, whereas the other is less expensive in terms of down payment. Formally, if $u_j^e + \gamma_j \chi = R^{-1} q_j (r + \delta) + \gamma_j (p_e + \chi) < R^{-1} q_i (r + \delta) + \gamma_i (p_e + \chi) = u_i^e + \gamma_i \chi$, then $\wp_j^e = R^{-1} q_j (r + \delta) + \gamma_j (p_e + \chi) + R^{-1} (1 - \theta) q_j (1 - \delta) - \gamma_j \chi > R^{-1} q_i (r + \delta) + \gamma_i (p_e + \chi) + R^{-1} (1 - \theta) q_i (1 - \delta) - \gamma_i \chi = \wp_i^e$.

[14] We analyze the general case $\rho \leq 1$ in Appendix A.3.

Furthermore, it has to be the case that the clean technology is more expensive in terms of down payment. To see this, suppose $j = D$ and $i = C$. Then, the first inequality implies $q_D < q_C$, but then $R^{-1}(1-\theta)q_D(1-\delta) - \gamma_D\chi < R^{-1}(1-\theta)q_C(1-\delta) - \gamma_C\chi$, which contradicts the second inequality. Therefore, $j = C$ and $i = D$. Moreover, $\wp^e_C > \wp^e_D$ and $\gamma_C < \gamma_D$ imply $q_C > q_D$, that is, clean capital is more expensive than dirty capital. Using the above inequalities, we obtain that the bounds on the price difference between clean and dirty capital are

$$q_C - q_D \in \left(\frac{R(\gamma_D - \gamma_C)p_e}{r + \delta + (1-\theta)(1-\delta)}, \frac{R(\gamma_D - \gamma_C)(p_e + \chi)}{r + \delta} \right).$$

Note that, because clean capital has a smaller impact on disutility from energy, it is possible that $u^e_C = R^{-1}q_C(r+\delta) + \gamma_C p_e > R^{-1}q_D(r+\delta) + \gamma_D p_e = u^e_D$. Thus, it is possible that clean capital would be dominated, were it not for the disutility from energy use.

Given this trade-off between user costs—appropriately corrected for disutility from energy use—and down payments, sufficienctly financially constrained firms optimally invest in dirty capital, whereas unconstrained firms invest in clean capital. It may thus appear as though only sufficiently large, well capitalized firms appreciate the environmental cost of dirty capital. However, this is not the case, because all firms internalize the disutility of energy use equally. Instead it is financial constraints that induce firms with low net worth to invest in dirty capital because of its lower financing needs.

3.6 Social Preference for Clean Capital

We now consider the case in which there is a social preference for clean capital, perhaps because clean capital is associated with lower environmental impact or desirable from a social perspective in some other way. Specifically, suppose the government imposes a tax τ_D per unit of dirty capital that a firm uses, so that a firm with k_D dirty capital pays a tax $\tau_D k_D$ at the beginning of the period, that is, we assume that taxes on capital are paid in advance. Similarly, the government imposes a tax τ_C on clean capital (which could be negative, that is, could be a subsidy). Assume that $\tau_D > \tau_C$, so the tax on dirty capital is higher than that on clean capital. For simplicity and without loss of generality, we assume that production requires only capital, so energy is not an input; the two types of capital are perfect substitutes in production, and a firm with total capital k this period produces output $f(k)$ next period. Clean and dirty capital differ only in their taxation and their price $q_j > 0$, $j \in \{C, D\}$, which is a parameter of the model. There is no other distinction between the two types of capital. Finally, we assume that tax revenues are rebated lump sum to the representative household. Otherwise, the model is the same as the baseline model.

The firms choose $\{d, b, k_j\} \in \mathbb{R}^2 \times R_+^2$ to maximize (1) subject to the budget constraint for the current period,

$$w + b = d + \sum_{j \in \{C,D\}} q_j k_j + \sum_{j \in \{C,D\}} \tau_j k_j,$$

the budget constraint for the next period (3) and the collateral constraint (4), with total capital $k \equiv \sum_{j \in \{C,D\}} k_j$.

The investment Euler equations for $j = \{C, D\}$ can be expressed as follows:

$$u_j + \tau_j + \frac{\lambda'}{\mu'}(\wp_j + \tau_j) \geq R^{-1} f_k(k).$$

This optimality condition shows that, if both technologies are used in equilibrium, one of them must be less expensive in terms of user cost *plus tax* τ_j, whereas the other is less expensive in terms of down payment *plus tax* τ_j. Arguing along similar lines as before, we conclude that $q_C > q_D$, and therefore $u_C > u_D$, $\wp_C > \wp_D$, and further $\wp_C + \tau_C > \wp_D + \tau_D$, but critically $u_C + \tau_C < u_c + \tau_D$. Moreover, $q_C - q_D \in \left(\frac{R(\tau_D - \tau_C)}{r + \delta + (1-\theta)(1-\delta)}, \frac{R(\tau_D - \tau_C)}{r+\delta} \right)$. The key insight is that the patterns in clean-technology adoption are the same in this case, too.[15]

3.7 Effect of Legal Enforcement and Financial Development

Finally, we briefly discuss the effect of legal enforcement and financial development on the choice of energy efficiency, by considering the effect of collateralizability θ. As we argued previously, limited collateralizability, that is, the fact that $\theta < 1$ is critical for our results. However, here we consider the effect of collateralizability θ more generally, while maintaining the assumption that $\theta < 1$. To understand the basic intuition for the effect

[15] If there were differential taxes on the production of the two types of capital as well, firms' decisions would take the after-tax price of capital into account, but the main prediction of our model would remain unchanged, as long as neither type of capital is dominated and clean and dirty capital differ in either their associated energy use or their taxes on the use of capital.

of collateralizability, notice that as θ goes to one, the down payment goes to the user cost, that is, $\lim_{\theta\to 1}\wp_j = \lim_{\theta\to 1} u_j + R^{-1}(1-\theta)q_j(1-\delta) = u_j$. This of course also means that $\lim_{\theta\to 1}\wp_j^e = u_j^e$, that is, the cum-energy down payment goes to the cum-energy user cost.

To consider the effect of legal enforcement we take all the technological parameters as given, and make the dependence of the cum-energy down payment on legal enforcement explicit by writing $\wp_j^e(\theta)$. Assume that there is an economy with legal enforcement $\theta_0 \in [0,1)$ for which $u_C^e < u_D^e$ and $\wp_C^e(\theta_0) > \wp_D^e(\theta_0)$ as we have assumed throughout. Then there exists a $\underline{\theta} \in (\theta_0, 1)$ for $\underline{\theta}$ suitably defined, such that for sufficiently strong legal enforcement, that is, for $\theta \geq \underline{\theta}$, we have $\wp_C^e(\theta) < \wp_D^e(\theta)$, and thus clean capital dominates dirty capital. This means that there may be types of dirty capital that are dominated in strong legal enforcement economies, but nevertheless used in weak legal enforcement economies. Firms in such weak legal enforcement economies may choose this type of dirty capital, because of its lower financing need. In addition, when neither type of capital is dominated, the threshold level of net worth at which firms switch from dirty to clean capital decreases with legal enforcement.[16] All told, in our economy stronger legal enforcement increases clean-technology adoption.

Financial development, which we interpret as an increase in collateralizability θ, increases aggregate investment and hence aggregate output in the steady state in our economy all else equal. But what does financial development imply for aggregate energy use in the economy? Recently, a concern has arisen that financial development may increase aggregate energy use, and hence potentially associated carbon emissions, because it increases aggregate output. Our model shows that this line of reasoning overlooks a plausibly important effect, namely that financial development may also affect the composition of investment in terms of clean vs. dirty capital. Specifically, recall that if legal enforcement is sufficiently strong, clean capital dominates dirty capital as we have argued above. But then if clean capital is sufficiently clean, that is, $\gamma_C < \overline{\gamma}_C$, for $\overline{\gamma}_C > 0$ suitably defined, energy demand must decrease. Therefore, our theory suggests that financial development can both increase aggregate output while decreasing aggregate energy use. The key insight is that financial development does not just affect the level of investment, but also the composition of investment in terms of the adoption of clean technology.

[16] To see this, note that the discount rate at which firms are indifferent $\bar{R}(\theta) = R(1+(u_D^e - u_C^e)/(\wp_C^e(\theta) - \wp_D^e(\theta))) = R(1+(u_D^e - u_C^e)/(u_D^e - u_C^e + R^{-1}(1-\theta)(q_C - q_D)(1-\delta)))$ is increasing in θ.

4 Clean Technology and Capital Age

In this section, we extend the model to introduce a choice of capital age, which is another relevant dimension of heterogeneity in energy efficiency. We show that financially constrained firms optimally choose to operate older capital.

4.1 Model with Clean vs. Dirty Technology and Capital Age

We maintain the assumptions on preferences and financial constraints from the previous section. We modify the assumptions on technology as follows. Most notably, we consider capital that has a finite useful life of two periods; that is, new capital has two periods of useful life remaining, while old capital has only one period of useful life left.

Technology. As before, there are two types of capital, clean and dirty capital. However, both types of capital have a useful life of two periods and depreciation is of the one-hoss shay type. New capital becomes old capital after production; old capital fully depreciates after production. The input in production is a constant elasticity of substitution bundle of new and old capital, x_N and x_O, respectively:

$$x = g(x_N, x_O) \equiv \left(\sigma_N^{\frac{1}{\epsilon}} x_N^{\frac{\epsilon-1}{\epsilon}} + \sigma_O^{\frac{1}{\epsilon}} x_O^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}, \tag{13}$$

where ϵ denotes the elasticity of substitution between new and old capital and σ_N (σ_O) is the input share of new (old) capital. In turn, new and old capital are given by $x_a \equiv \sum_{j\in\{C,D\}} \min\left\{\frac{e_{ja}}{\gamma_j}, k_{ja}\right\}$, where $a \in \mathcal{A} \equiv \{N, O\}$ denotes capital age. As in the previous section, clean and dirty capital are perfect substitutes and each of them requires a complementary energy input, with $\gamma_C < \gamma_D$.

Output can be used to make both types of new capital; it costs q_{jN} units of output to make type-j new capital, and thus the price of type-j new capital q_{jN} is determined by its linear production technology. The prices of clean and dirty old capital are instead determined in equilibrium. The market clearing condition for old type-j capital is

$$\int k_{jN} d\pi(w) = \int k_{jO} d\pi(w), \tag{14}$$

for $j \in \mathcal{J} \equiv \{C, D\}$, where $\pi(w)$ is the stationary distribution of firm net worth.

Firms' Problem. Given their initial net worth w, firms maximize the present discounted value of their dividends net of equity issuance costs, that is, their value to the household, by choosing dividends d, borrowing b, clean new, dirty new, clean old, and dirty old capital, k_{ja}, and associated energy inputs e_{ja}, for $(j, a) \in \mathcal{J} \times \mathcal{A}$, to solve

$$v(w) \equiv \max_{\{d,b,k_{ja},e_{ja}\} \in \mathbb{R}^2 \times \mathbb{R}^8_+} d - \phi(-d) + \beta\{\rho w' + (1-\rho) v(w')\} \tag{15}$$

subject to the budget constraints for the current and next period,

$$w + b = d + \sum_{(j,a) \in \mathcal{J} \times \mathcal{A}} q_{ja} k_{ja} + \sum_{(j,a) \in \mathcal{J} \times \mathcal{A}} p_e e_{ja}, \tag{16}$$

$$f(x) + \sum_{j \in \mathcal{J}} q_{jO} k_{jN} = w' + Rb, \tag{17}$$

and the collateral constraint

$$\theta \sum_{j \in \mathcal{J}} q_{jO} k_{jN} \geq Rb, \tag{18}$$

where $x = \left(\sum_{a \in \mathcal{A}} \sigma_a^{\frac{1}{\epsilon}} x_a^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}$ and $x_a \equiv \sum_{j \in \mathcal{J}} \min\left\{ \frac{e_{ja}}{\gamma_j}, k_{ja} \right\}$ for $a \in \mathcal{A}$.

A *stationary equilibrium* is defined as a collection of policy functions for investment $k_{ja}(w)$ and energy use $e_{ja}(w)$, for $j \in \{C, D\}$ and $a \in \{N, O\}$, dividends $d(w)$, and debt $b(w)$, a distribution of net worth $\pi(w)$, and prices of old capital q_{jO} for $j \in \{C, D\}$, such that the policy functions solve the firms' problem in (15) through (18), the distribution is induced by the policy functions, and the markets for old type-j capital clear, that is, (14) holds.

4.2 Determinants of Clean Technology and Vintage Adoption

We define the cum-energy user costs of new and old capital as follows: $u^e_{jN} \equiv q_{jN} + \gamma_j p_e - R^{-1} q_{jO}$ and $u^e_{jO} \equiv q_{jO} + \gamma_j p_e$. Moreover, we define the cum-energy down payments for new and old capital as follows: $\wp^e_{jN} \equiv q_{jN} + \gamma_j p_e - R^{-1}\theta q_{jO}$ and $\wp^e_{jO} \equiv q_{jO} + \gamma_j p_e$.

Note that we have $\wp^e_{jN} > u^e_{jN}$ and $\wp^e_{jO} = u^e_{jO}$, that is, for both clean and dirty capital, the cum-energy down payment on new capital is larger than the cum-energy user cost of new capital, whereas cum-energy down payment and cum-energy user cost are equal to each other for old capital. Furthermore, because clean and dirty old capital are perfect substitutes and both fully depreciate after production, in equilibrium they must have the same cum-energy user cost (and down payment): $u^e_{CO} = u^e_{DO} = \wp^e_{CO} = \wp^e_{DO}$. To facilitate the analysis, we denote this cum-energy user cost by u^e_O, which is determined in equilibrium, and u^e_O in turn implies the equilibrium type-j old capital prices q_{jO}, $j \in \{C, D\}$.

As in the previous section, we can characterize the admissible difference between the price of clean new capital and dirty new capital, when neither is dominated in equilibrium. In this case, we have $u^e_{CN} < u^e_{DN}$ and $\wp^e_{CN} > \wp^e_{DN}$. These inequalities imply that

$$q_{CN} - q_{DN} \in \left((1 + R^{-1}\theta)(\gamma_D - \gamma_C)p_e, (1 + R^{-1})(\gamma_D - \gamma_C)p_e\right).$$

As before, the upper bound on the difference in price is given by the present value of the energy savings associated with clean capital, whereas the lower bound is given by the present value of the pledgeable fraction of these savings. As is evident, limited collateralizability, that is, $\theta < 1$, is again critical for there to be a non-trivial choice.

Using the definitions of cum-energy user costs and down payments, we can express the investment Euler equations for clean new, dirty new, and (clean and dirty) old capital as

$$u^e_{jN} + \frac{\lambda'}{1 + (1 - \rho)\phi'_d}\wp^e_{jN} \geq R^{-1} f_x(x) \frac{\partial x}{\partial x_N} \tag{19}$$

$$u^e_O \left(1 + \frac{\lambda'}{1 + (1 - \rho)\phi'_d}\right) = R^{-1} f_x(x) \frac{\partial x}{\partial x_O}. \tag{20}$$

Inequality (19) holds with equality for either clean or dirty new capital (or both). Proceeding as in the previous section, we can show that sufficiently constrained firms invest in dirty new capital, whereas unconstrained firms invest in clean new capital.

To analyze the choice between new and old capital, consider the type-j new capital for which (19) holds with equality. Dividing by (20) and using the definition of x, we obtain the optimal ratio between new and old capital:

$$\frac{x_N}{x_O} = \frac{\sigma_N}{\sigma_O} \left(\frac{u^e_{jN}}{u^e_O}\right)^{-\epsilon} \left(\frac{1 + \frac{\lambda'}{1+(1-\rho)\phi'_d} \frac{\wp^e_{jN}}{u^e_{jN}}}{1 + \frac{\lambda'}{1+(1-\rho)\phi'_d}}\right)^{-\epsilon}. \tag{21}$$

For financially unconstrained firms ($\lambda' = 0$), this ratio equals $\frac{\sigma_N}{\sigma_O}\left(\frac{u^e_{jN}}{u^e_O}\right)^{-\epsilon}$. For firms that are financially constrained, the term $\frac{\lambda'}{1+(1-\rho)\phi'_d}$ distorts the investment choice toward the type of capital that is relatively cheaper in terms of cum-energy down payment. Because $\frac{\wp^e_{jN}}{u^e_{jN}} > 1$, new capital is relatively more expensive in terms of cum-energy down payment, and thus firms with lower net worth invest relatively more in old capital to preserve their net worth. We summarize these insights in the following proposition.

Proposition 3 (Clean technology and vintage adoption) *Financially unconstrained firms invest in clean new capital. Sufficiently constrained firms invest in dirty new capital. Firms in an intermediate range of net worth are indifferent at the margin and gradually substitute from dirty new to clean new capital as net worth w increases.*

Financially constrained firms use a larger share of old capital than unconstrained firms.

4.3 Higher Energy Efficiency of New Capital

Technological progress is making newer vintages of capital more energy efficient over time (see the empirical evidence in Section 5). To mimic the effects of such technological progress in our stationary economy, we now generalize the technological assumptions of our model by assuming that type-j old capital has higher associated energy needs than type-j new capital. As in the previous subsection, new capital is given by $x_N \equiv \sum_{j\in\{C,D\}} \min\left\{\frac{e_{jN}}{\gamma_j}, k_{jN}\right\}$. In contrast, old capital is given by $x_O \equiv \sum_{j\in\{C,D\}} \min\left\{\frac{e_{jO}}{\kappa\gamma_j}, k_{jO}\right\}$, where $\kappa > 1$ captures the energy efficiency loss associated with using an older vintage of capital.

With these assumptions, we can express cum-energy user costs (and down payments) for old capital as $u^e_{jO} = \wp^e_{jO} = q_{jO} + \kappa\gamma_j p_e$. Clean and dirty old capital must have the same user cost to be both used in equilibrium, so $u^e_O \equiv u^e_{CO} = u^e_{DO}$. Hence, we have $q_{CO} - q_{DO} = \kappa(\gamma_D - \gamma_C)p_e$. Using this condition, we can express the bounds on the difference in price between clean new and dirty new capital as

$$q_{CN} - q_{DN} \in \left((1 + R^{-1}\theta\kappa)(\gamma_D - \gamma_C)p_e, (1 + R^{-1}\kappa)(\gamma_D - \gamma_C)p_e\right).$$

As in the model with $\kappa = 1$, we can express the optimality conditions as equations (19), (20), and (21). Thus, we still conclude that financially constrained firms invest in dirty new capital and in a larger share of old capital. Financially constrained firms are thus less energy efficient for two reasons: first, they invest in dirty new capital, and second, they invest in relatively more old capital, which is less energy efficient, too.

5 Empirical Patterns in Commercial Shipping

In this section, we leverage rich micro data on commercial shipping to document empirical patterns on the distribution of energy efficiency across heterogeneous firms. We document that larger firms operate cleaner capital. Consistent with our model, this pattern arises because of two concurrent reasons. First, when we focus on new investment, we find that larger firms are more likely to purchase energy efficient new ships. Second, when we focus on the stock of capital, we find that larger firms operate newer ships; technological progress improves the degree of energy efficiency of new vintages of ships, which implies that capital age is relevant for energy efficiency.

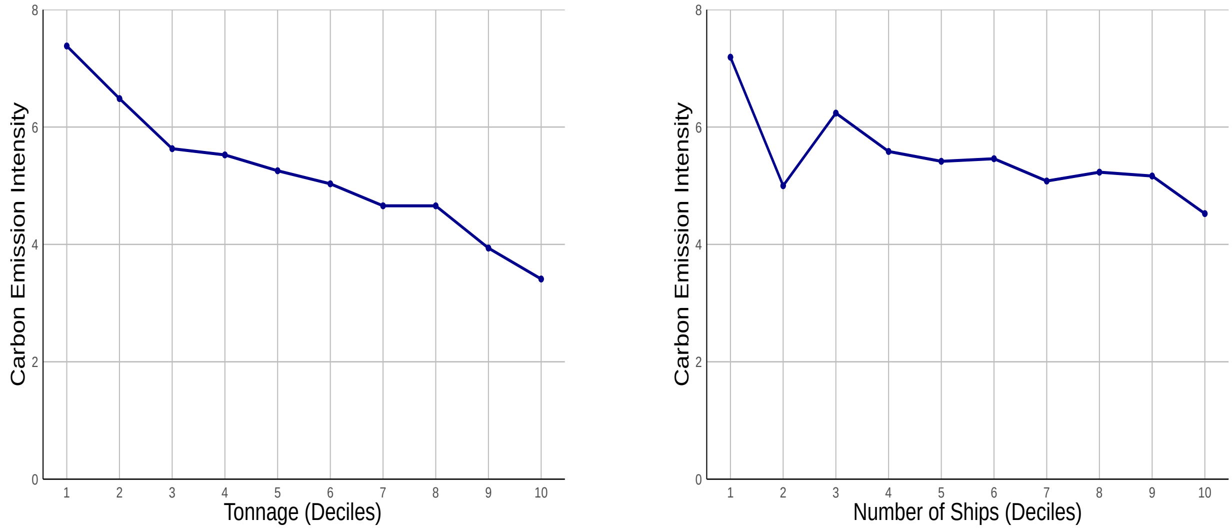
5.1 Data Description

We study a dataset on the global commercial shipping fleet, compiled by a leading private firm in shipping intelligence and research. The dataset reports detailed information about the universe of active commercial ships—that is, the global stock of shipping capital—during 2022. For each ship, the dataset identifies its type (for instance, container ship, tanker, bulker, etc.), the shipping company that owns it as well as the company that operates it. Moreover, it reports several physical characteristics of the vessel, such as age and tonnage. Furthermore, the dataset includes information about the order book of new ships—that is, new investment in ships—during 2022.[17] We complement the dataset with information on the average energy efficiency of different types of ships.

5.2 Larger Firms Operate Cleaner Capital

To perform our empirical analysis, we first aggregate information about ships at the owner level to measure our variables of interest at the firm (fleet) level. In this analysis, we focus on commercial shipping fleets with at least three ships, to reduce the noise due to the fact that most fleets are small and operate one or two ships. Our main findings are robust to aggregating ships to construct fleets using their operating companies instead of their owners. Moreover, the findings are robust to focusing on specific types of ships, such as

[17] Kalouptsidi (2014) leverages similar data on commercial ships to estimate a model of entry and exit in bulk shipping.



(a) TONNAGE (b) NUMBER OF SHIPS

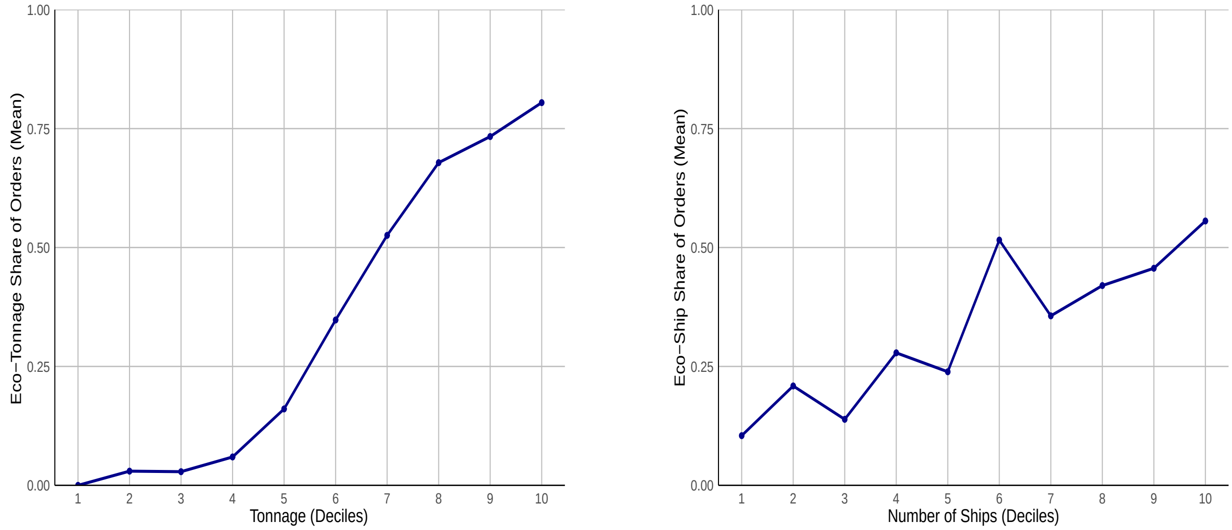
Figure 1: Fleet Size and Carbon Emission Intensity

Notes: The figure displays the relationship between fleet size and carbon emission intensity. Specifically, the left panel reports the Annual Efficiency Ratio (AER, a measure of carbon emission intensity expressed in grams of CO_2 per deadweight tonnage and distance travelled) on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. The right panel reports the same measure of emission intensity for all deciles of fleet size, measured by number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on bulkers, container ships, and oil tankers and on fleets with at least three ships.

bulkers or containers, as well as to alternative cutoffs for firm size. Appendix B documents the robustness of the stylized facts with alternative definitions of fleet and subsamples.

When we analyze the patterns of energy efficiency across shipping fleets, we find that larger fleets operate cleaner technologies. In Figure 1, we show the relationship between fleet size (measured as total tonnage in the left panel and number of ships in the right panel) and the Annual Efficiency Ratio, an average measure of carbon emission intensity expressed in grams of CO_2 per deadweight tonnage and distance travelled. We obtain this measure of energy efficiency for three major types of ships: bulkers, container ships, and oil tankers. We stress that despite the term "efficiency," a high Annual Efficiency Ratio indicates a high level of carbon emission intensity.

The figure shows that there is a steep reduction in carbon emission intensity going from smaller fleets to larger ones. Specifically, the average emission intensity of fleets in the lowest decile of total tonnage is approximately twice as large as the emission intensity of



(a) Fleet Tonnage (b) Number of Ships

Figure 2: Fleet Size and Eco Ship Orders

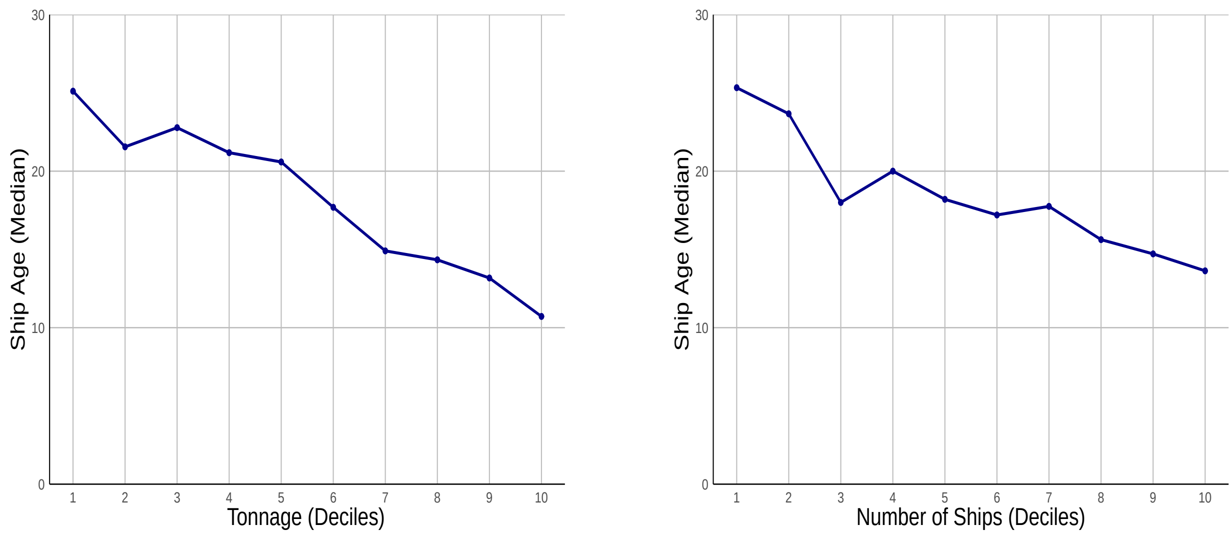
Notes: The figure displays the relationship between fleet size and the share of new investment accounted for by Eco (low-emission) Ships. Specifically, the left panel reports the share of new-ship orders accounted for by Eco Ships on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. The right panel reports the share of new-ship orders accounted for by Eco Ships for all deciles of fleet size, measured by the number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on fleets with at least three ships.

fleets in the highest decile. We also test the relationship between fleet size and emission intensity controlling for fixed effects for fleet type and typical vessel size and confirm this significant relationship (Table B1). Next, we proceed to analyze the drivers of the negative correlation between fleet size and emission intensity.

5.3 Larger Firms Invest in Cleaner New Capital

One reason why large fleets are more energy efficient is that, when they invest in new ships, they purchase a higher share of Eco ships, that is, ships with low-emission engines. Figure 2 displays the share of Eco ships among new-ship orders as a function of fleet size, again measured as total tonnage or number of ships. Strikingly, the smallest fleets by tonnage do not purchase any Eco ships, whereas the share of new investment in Eco ships is approximately equal to 75% for the largest fleets.

We also test the relationship between fleet size and clean new investment controlling for



(a) Fleet Tonnage (b) Number of Ships

Figure 3: Fleet Size and Capital Age

Notes: The figure displays the relationship between fleet size and capital age. Specifically, the left panel reports median ship age on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. The right panel reports median ship age for all deciles of fleet size, measured by the number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on fleets with at least three ships.

fixed effects for ship types and confirm this significant relationship (Table B2). For bulkers, a common type of ship with a large share of Eco ships among new orders, increasing fleet size (total tonnage) by one standard deviation relative to the average, the fraction of low-emission new-ship orders goes from 79% to 86%. Accordingly, fleet size is also positively associated with the share of Eco ships in the stock of ships (Table B3). Specifically, increasing bulkers fleet size by one standard deviation relative to the average, the fraction of the stock accounted for by Eco ships goes from 27% to 32%.

5.4 Larger Firms Operate Newer Capital

There is another reason why large firms are more energy efficient: On average, they operate newer ships. To illustrate this pattern, we measure the age composition of each shipping fleet. Figure 3 shows that median ship age declines sharply as fleet size increases, whether we measure fleet size by total tonnage or number of ships. Larger fleets tend to operate ships of newer vintages.

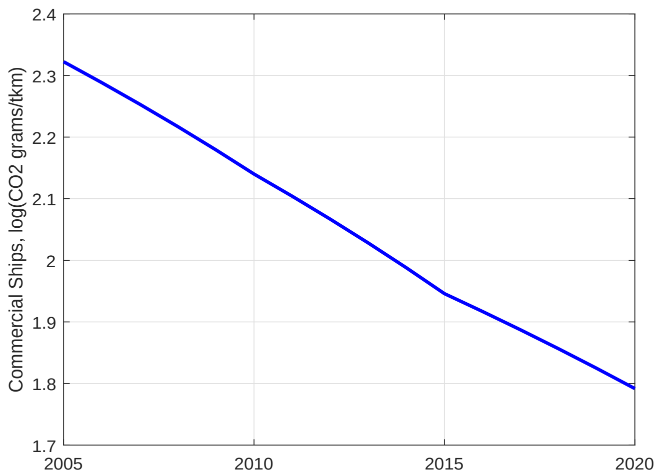


Figure 4: Technological Progress in Shipping Emission Intensity

Notes: The figure displays average commercial ships CO_2 emissions (grams per tonne-kilometer) during 2005-2020. Source: International Energy Agency.

To buttress this finding, we regress average ship age on our measures of fleet size, controlling for fixed effects for ship types. Table B4 shows that, across several specifications, there is a significant negative relationship between fleet size and average ship age. Increasing fleet size by one standard deviation relative to the average, average capital age goes from 20 to 15 years (and from 12 to 10 when we restrict attention to bulkers).

5.5 New Vintages of Capital are Cleaner

Finally, we show that technological progress makes new vintages of capital significantly more energy efficient over time. Figure 4 shows the steady pace of reduction in carbon emission intensity achieved in global commercial shipping between 2005 and 2020. During this period, shipping emission intensity measured in grams of CO_2 per tonne-kilometer has decreased by over 40%.

Because of this technological progress and because ships are long-lived assets, heterogeneity in firm investment across vintages of capital results in large variation in energy efficiency across firms.

6 Transition to Cleaner Technology

In this section we use the empirical evidence to calibrate our model and analyze its equilibrium transition dynamics as technological progress may lead to improvements in energy efficiency. This analysis shows that our analytical insights on the role of financing constraints for technology adoption in stationary equilibrium are relevant to understand the effects of a transition to cleaner technology.

6.1 Calibration

Table 1 reports the parameter values that we use in our quantitative analysis. We assume that a period in the model corresponds to 10 years, allowing us to split the long life of durable capital, such as commercial ships, into two periods (new and old). We further assume that all firms exit after one period, that is, after 10 years.

We assume that the production function is Cobb-Douglas: $f(x) = Ax^{\alpha}$, with $A > 0$ and $\alpha \in (0, 1)$. New capital is given by a CES composite of clean new and dirty new capital:

$$x_N \equiv \left(\sigma_{CN}^{\frac{1}{\eta}} (k_{CN})^{\frac{\eta-1}{\eta}} + (1 - \sigma_{CN})^{\frac{1}{\eta}} (k_{DN})^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}},$$

where η denotes the elasticity of substitution between clean new and dirty new capital. We set $\eta = 50$ to obtain a high substitutability as in the model of Section 4 while ensuring that the optimal investment bundle is interior. We maintain the assumption from Section 4 that clean old and dirty old capital are perfect substitutes to facilitate the computation by having a single market-clearing condition for old capital. We also maintain the assumption that new and old capital are combined in the CES aggregator (13) with elasticity of substitution ϵ. We parameterize this elasticity as in Lanteri and Rampini (2023).

We set the values of γ_C and γ_D in the initial stationary equilibrium such that the relative energy efficiency of new capital is consistent with the typical reduction in emissions associated with Eco Ships in our dataset. As we do not directly observe the prices of clean and dirty new capital in the data, but Eco Ships are more expensive than other ships, we set the value of q_{CN} and q_{DN} in the initial stationary equilibrium so that clean new capital is 10% more expensive than dirty new capital, which induces patterns of technology adoption that are broadly consistent with the empirical evidence of Section 5.

Table 1: Parameter Values

		Parameter	Value
Preferences	Discount factor	β	0.96^{10}
Life cycle	Death probability	ρ	1
Technology	Returns to scale	α	0.8
	TFP	A	2
	Elasticity of subst. Clean/Dirty New	η	50
	Clean New share	σ_{CN}	0.5
	Elasticity of subst. New/Old	ϵ	5
	New share	σ_N	0.5
	Price Clean New	q_{CN}	1.1
	Price Dirty New	q_{DN}	1
	Energy input Clean	γ_C	0.125
	Energy input Dirty	γ_D	0.188
	Energy price (normalization)	p_e	1
Financial constraints	Collateralizability	θ	0.5
	Equity cost	ϕ_0	0.3
	Equity cost	ϕ_1	2
	Net worth distribution	w_{min}	0
	Net worth distribution	α_1	4.6
	Net worth distribution	α_2	25

In order to closely match the empirical firm size distribution in the shipping industry, we assume that the distribution of net worth is a Pareto distribution, with probability density function $g(w) \equiv \frac{\alpha_1}{\alpha_2\left(1+\frac{w-w_{min}}{\alpha_2}\right)^{1+\alpha_1}}$ and $w \geq w_{min}$. We residualize firm size in the data (that is, fleet tonnage) by removing fixed effects for ship type. We assume that the median firm is financially unconstrained. We then parameterize the distribution of net worth so that firm size at the 10th and the 25th percentile relative to the median are closely matched in model and data.

We parameterize the convex cost of equity issuance as a power function: $\phi(-d) \equiv \phi_0(-d)^{\phi_1}$ for $d < 0$, with $\phi_0 > 0$ and $\phi_1 > 1$. We calibrate these parameters to obtain a distribution of marginal cost of equity issuance similar to the one in Lanteri and Rampini (2023). Following the same paper, we assume that half of the resale value of capital is pledgeable as collateral.

6.2 Effects of Technological Progress on Technology Adoption

First, we consider a scenario in which both clean and dirty capital become more energy efficient over time. We simulate the aggregate equilibrium dynamics and analyze the heterogeneous patterns of technology adoption during this transition. Along the transition path, we compute the equilibrium dynamics of the cum-energy user cost of old capital $u^e_{O,t}$, which depends on the exogenous energy requirements and the endogenous prices of old capital. Appendix C reports the model equilibrium conditions along the transition dynamics.

The top-left panel of Figure 5 displays the exogenous path of the technological parameters $\gamma_{C,t}$ and $\gamma_{D,t}$. Starting from the initial stationary equilibrium, both parameters decline at a common constant rate for 50 years (5 periods in the model), after which the economy reaches a new stationary equilibrium. In each period during the transition dynamics of $\gamma_{C,t}$ and $\gamma_{D,t}$, old capital is less energy efficient than new capital, because the latest vintage of capital has lower energy needs, whereas old capital retains the higher energy needs of the previous vintage.

The other panels of the figure display the aggregate effects of this exogenous technological progress. Most notably, the aggregate energy intensity of the economy (top-right) decreases by less than the technological parameters $\gamma_{j,t}$, showing that the economy is substituting towards the dirty technology during the transition. This result arises because when both clean and dirty capital become more energy efficient at the same rate, the difference in energy requirement $(\gamma_{D,t} - \gamma_{C,t})$ decreases over time. Thus, as the cost savings associated with the clean technology become smaller, firms substitute toward dirty capital, which remains less expensive in terms of the price of capital. At the same time, both aggregate energy use and output increase as the reduction in the cum-energy user cost of capital leads to an aggregate expansion.

We also use this simulation to investigate firms' heterogeneous patterns of technology adoption during the transition. Figure 6 shows that, consistent with the analytical results of the previous subsection that refer to a stationary equilibrium, firms with lower net worth invest in a higher share of dirty new capital and in a higher share of old capital. Moreover, firms with lower net worth produce at an overall smaller scale and face a higher marginal value of internal funds. Thus, our model accounts for the empirical evidence on

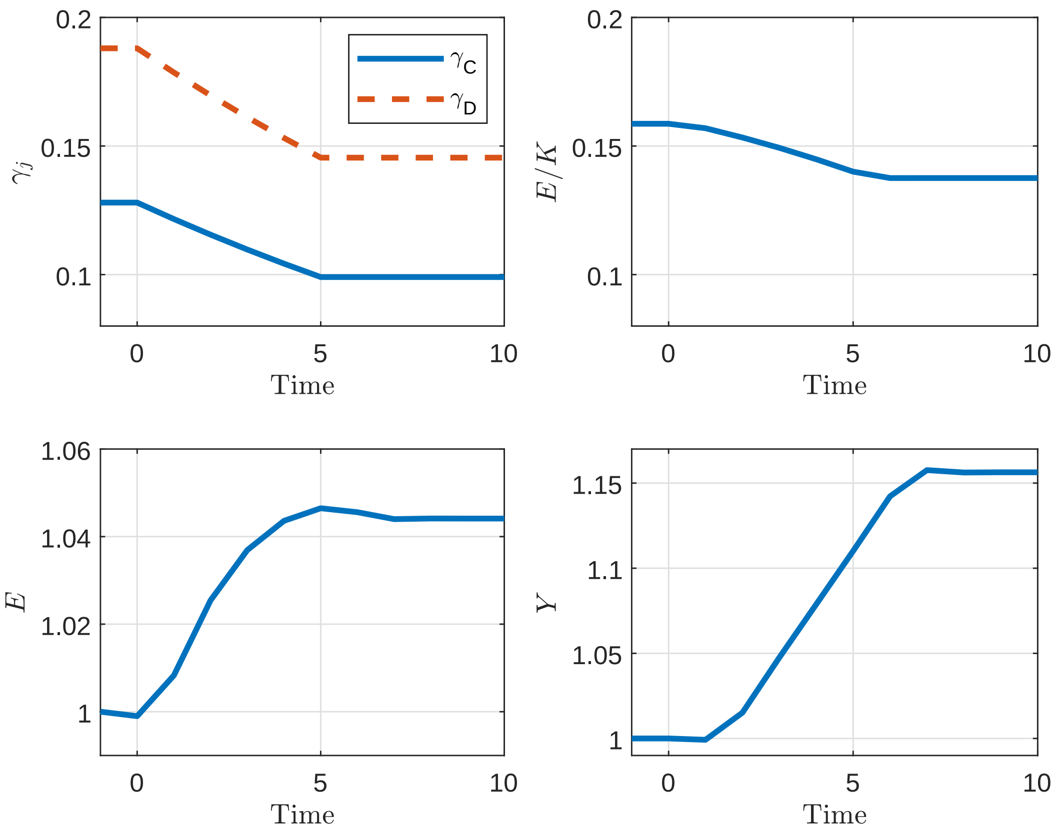


Figure 5: Improvement in Energy Efficiency of Clean and Dirty Capital

Notes: The figure displays the transition dynamics associated with an exogenous, gradual decrease in both $\gamma_{C,t}$ and $\gamma_{D,t}$. The top-left panel displays the path of $\gamma_{C,t}$ and $\gamma_{D,t}$ over time; the top-right panel displays the path of aggregate energy intensity, defined as aggregate energy use divided by aggregate capital; the bottom-left panel displays the path of aggregate energy use; the bottom-right panel displays the path of aggregate output.

the adoption of clean technology also along an aggregate transition path to cleaner energy.

Next, we analyze an alternative scenario in which only clean capital becomes cleaner, whereas the energy requirement of dirty capital does not change over time. Figure 7 displays the aggregate dynamics. As the clean technology improves over time, more firms substitute toward clean capital, and thus the energy intensity of the economy decreases significantly. In contrast with the previous scenario, when only $\gamma_{C,t}$ decreases, the difference in energy requirement $(\gamma_D - \gamma_{C,t})$ increases over time, inducing substitution toward clean capital, which leads to aggregate improvements in energy efficiency. Compared to the case in which

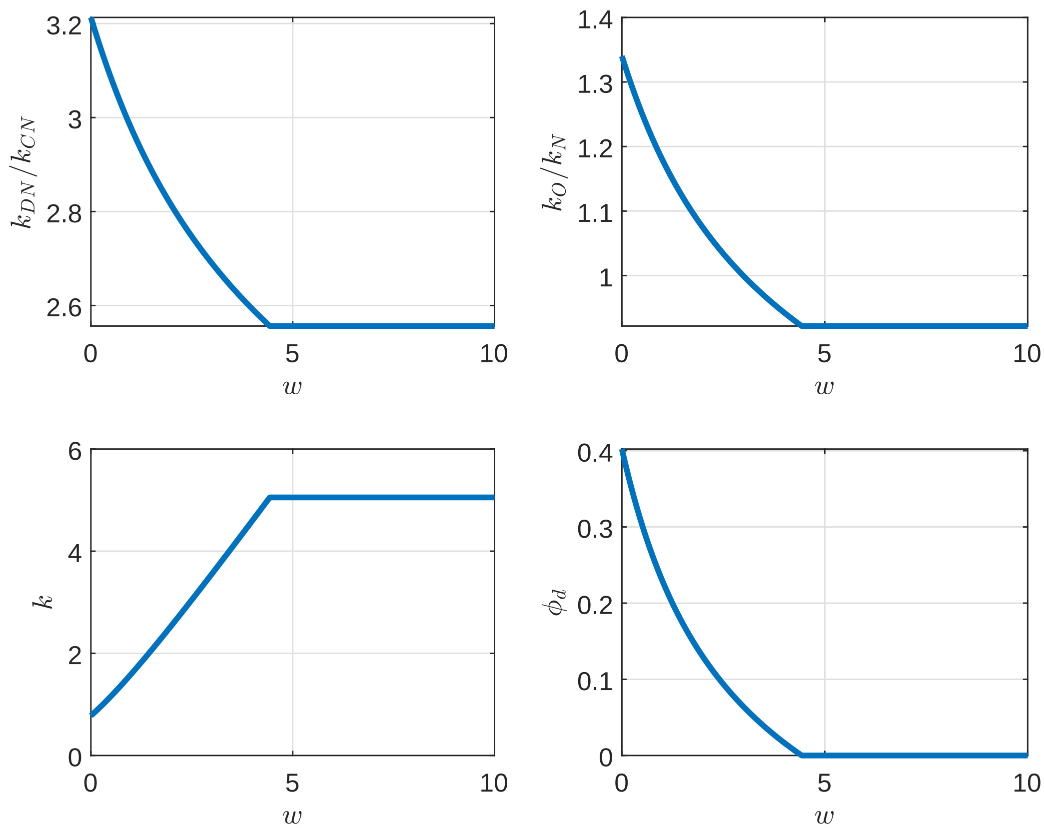


Figure 6: Patterns of Technology Adoption During Transition (γ_C and γ_D)

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transition dynamics associated with an exogenous, gradual decrease in $\gamma_{C,t}$ and $\gamma_{D,t}$. The x-axis is net worth w in all panels. The top-left panel displays the ratio of dirty-new capital to clean-new capital $k_{DN,t}/k_{CN,t}$; the top-right panel displays the ratio of old capital to new capital $k_{O,t}/k_{N,t}$; the bottom-left panel displays total capital; the bottom-right panel displays the marginal cost of equity issuance $\phi_{d,t}$.

both $\gamma_{C,t}$ and $\gamma_{D,t}$ change over time, this scenario features a smaller increase in aggregate output, but a larger reduction in energy intensity. Indeed, aggregate energy use decreases over time as the economy expands.

Despite this stark difference at the aggregate level, Figure C1 in Appendix C shows that the cross-sectional patterns of technology adoption are similar across the two scenarios. During the transition, the early adopters of cleaner technology are financially unconstrained firms. In contrast, firms with low net worth invest in a larger share of dirty and old capital.

Finally, we analyze a scenario in which technological progress reduces the cost of produc-

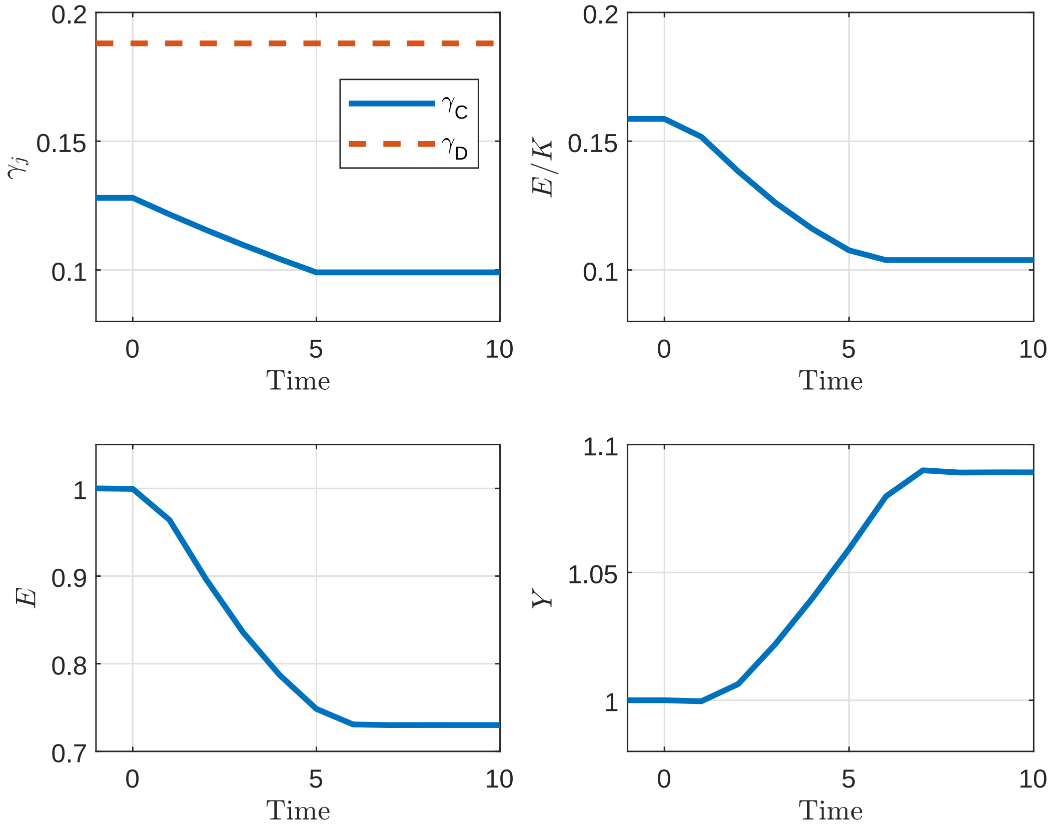


Figure 7: Improvement in Energy Efficiency of Clean Capital

Notes: The figure displays the transition dynamics associated with an exogenous, gradual decrease in $\gamma_{C,t}$ only. The top-left panel displays the path of $\gamma_{C,t}$ and $\gamma_{D,t}$ over time; the top-right panel displays the path of aggregate energy intensity, defined as aggregate energy use divided by aggregate capital; the bottom-left panel displays the path of aggregate energy use; the bottom-right panel displays the path of aggregate output.

ing clean capital. Beyond the context of clean-technology adoption in commercial shipping, this scenario is also relevant for other durable assets, in particular to study the effects of the reduction in the cost of producing batteries for electric vehicles. We assume that the price of clean-new capital $q_{CN,t}$ decreases exogenously. We display the aggregate effects of the transition to cheaper clean capital in Figure 8. As the figure shows, output increases and aggregate energy intensity decreases because over time all firms—including financially constrained ones—substitute away from dirty capital.

In this scenario, aggregate energy consumption shows a non-monotone pattern. Early

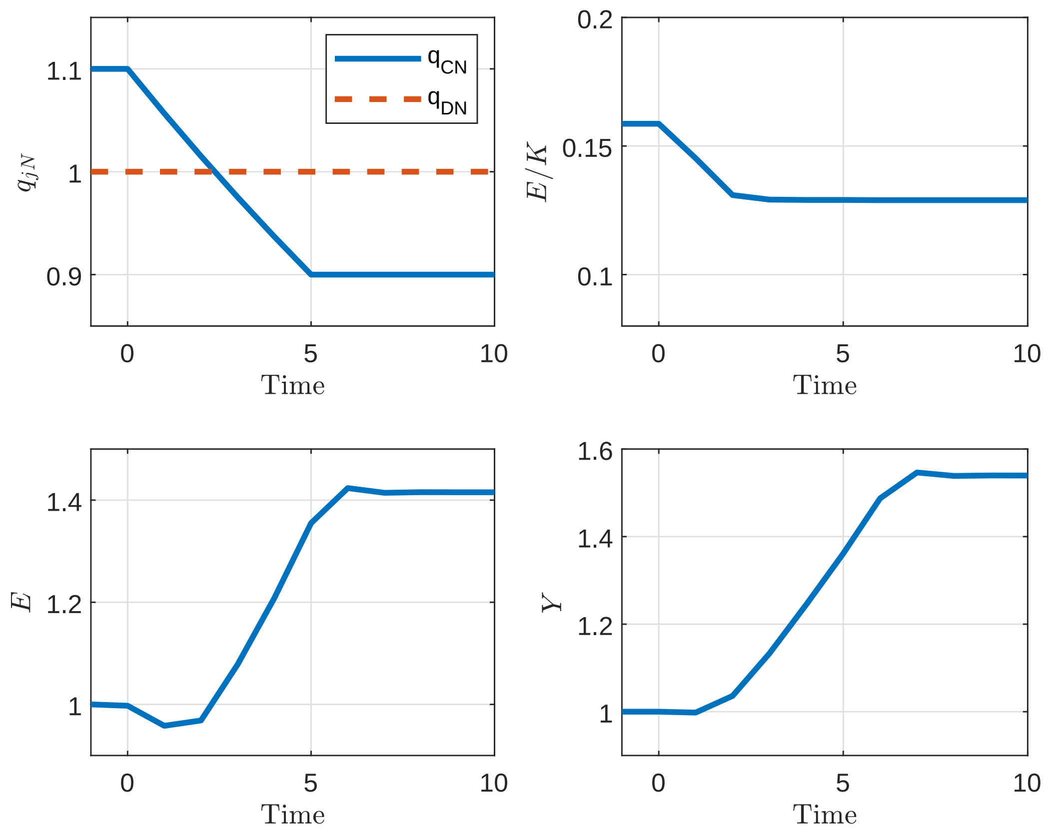


Figure 8: Reduction in Cost of Clean Capital

Notes: The figure displays the transition dynamics associated with an exogenous, gradual decrease in $q_{CN,t}$. The top-left panel displays the path of $q_{CN,t}$ and q_{DN}; the top-right panel displays the path of aggregate energy intensity, defined as aggregate energy use divided by aggregate capital; the bottom-left panel displays the path of aggregate energy use; the bottom-right panel displays the path of aggregate output.

during the transition, as firms substitute toward clean capital, aggregate energy use decreases. After the substitution has taken place, however, the economy keeps expanding using predominantly the clean technology. Thus, output and energy use increase, highlighting that further improvements in energy efficiency could only come from changes in the technological parameter γ_C. Furthermore, Figure C2 in Appendix C confirms that net worth plays an important role for the adoption of clean and new capital during the transition, because the shares of dirty and old capital remain decreasing in net worth, as in the previous scenarios.

We draw two main conclusions from these simulations. First, the underlying source of technological progress in the energy transition matters greatly for both the long-run effects on aggregate energy consumption and the patterns of substitution during the transition. Accounting for financing constraints is critical to understand the effects of these transitions, because they determine the response of firms to differences in energy needs and differences in investment prices, as our model highlights.

Second, despite these important differences in aggregate dynamics, the cross-sectional insights of our model on the role of net worth for technology adoption in stationary equilibrium remain valid across the different underlying sources of technological change.

7 Conclusions

We develop a model of clean-technology adoption with heterogeneous firms subject to financing constraints. In our model, energy efficiency is embodied in capital goods which differ in their energy needs. When both clean and dirty new capital are used in equilibrium, clean capital requires more internal funds. Thus, financially constrained firms optimally invest in dirty capital.

Furthermore, new capital requires relatively more financial resources than old capital, because new capital has a longer residual life. As a result, financially constrained firms invest relatively more in older capital. When technological progress makes newer vintages of capital more energy efficient, this pattern of investment across vintages contributes to make financially constrained firms less energy efficient.

We show that the predictions of our model are consistent with empirical patterns in a large dataset on the global commercial shipping fleet. Larger fleets invest more in new ships with clean engines and operate younger ships, which are more energy efficient because of technological improvements.

This endogenous pattern of clean-technology adoption is also relevant when firms have a preference for clean capital and when social preferences for clean capital lead to taxes on dirty capital. The critical role of financial constraints in the adoption of clean technology implies that environmental policy has important distributional consequences, as we show in the case of subsidized lending for clean capital, which is regressive in our model.

A calibrated version of our model shows that financial constraints determine the aggregate patterns of substitution toward clean capital along the transition dynamics induced by technological progress, both when capital becomes more energy efficient over time and when the production of clean capital becomes more efficient over time.

Our main insight on the role of financial constraints in clean-technology adoption is also relevant to understand household choices of durable goods with different levels of energy efficiency. Thus, our theory may provide a useful laboratory to analyze induced preferences over environmental policies when households are heterogeneous in wealth and technology adoption is endogenous.

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APPENDIX

A Additional Model Analyses

A.1 Energy Cost Paid in Arrears

In this appendix, we assume that firms pay for energy at the same time as they use it in production. We show that the main insights of Section 3 apply also in this case.

The firm budget constraints for the current and next period are

$$\begin{aligned} w + b &= d + \sum_{j \in \{C,D\}} q_j k_j, \\ f(x) + \sum_{j \in \{C,D\}} q_j k_j (1-\delta) &= w' + Rb + \sum_{j \in \{C,D\}} p_e e_j, \end{aligned}$$

For this case we define the cum-energy user cost of capital as $u_j^e \equiv u_j + R^{-1}\gamma_j p_e$. The investment Euler equations for $j = \{C, D\}$ can then be expressed as follows:

$$u_j^e + \frac{\lambda'}{\mu'} \wp_j \geq R^{-1} f_x(x).$$

If $u_j^e < u_i^e$, then $\wp_j > \wp_i$, which implies $q_j > q_i$. Thus, for the first inequality to hold, $j = C$. The bounds on the price difference between clean and dirty capital are

$$q_C - q_D \in \left(0, \frac{(\gamma_D - \gamma_C) p_e}{r + \delta}\right).$$

As in the baseline case of energy cost paid in advance, the clean technology requires a larger down payment. Thus, sufficiently financially constrained firms invest in dirty capital, whereas unconstrained firms invest in clean capital.

A.2 Financing Clean Technology Adoption by Households

This appendix considers the financing of clean-technology adoption in the household finance context. We consider risk-averse households that have a choice between clean and dirty durable goods. As in the baseline model of firm investment, we consider a discrete-time, infinite-horizon economy with stochastic overlapping generations; the economy is otherwise deterministic. Households can borrow from a risk-neutral lender at gross interest rate $R \equiv 1+r = \beta^{-1}$, where $\beta \in (0,1)$ is the discount factor of the household, which accounts for both the rate of time preference $\tilde{\beta}$ and the probability of survival $1-\rho$, that is, $\beta \equiv \tilde{\beta}(1-\rho)$.

Households have preferences $\sum_{t=0}^{\infty} \beta^t u(c_t)$, where c is consumption of durable goods services, and $u(c)$ is strictly increasing, strictly concave, twice continuously differentiable, and satisfies $\lim_{c\to 0} u_c(c) = +\infty$ and $\lim_{c\to\infty} u_c(c) = 0$. Households receive a constant endowment $y > 0$ each period. A household's total consumption c of durable goods services is determined by the input aggregator $c \equiv \sum_{j\in\mathcal{J}} \min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$, where clean durables k_C and dirty durables k_D are perfect substitutes in consumption and need to be combined with energy inputs in fixed proportions. As in the baseline firm investment model, $\gamma_C < \gamma_D$, so clean durables are more energy efficient than dirty durables. Both types of durables depreciate at rate $\delta \in (0,1)$. Durables purchased this period and held until next period produce durable goods services that are consumed this period. Households can borrow up to fraction $\theta \in [0,1)$ of the resale value of their durable goods. The price of type-j durables is $q_j > 0$, $j \in \mathcal{J}$, and the price of energy is $p_e > 0$.

The household's problem is to choose borrowing b, clean and dirty durables, k_C and k_D, and associated energy inputs, e_C and e_D, to solve

$$v(w) \equiv \max_{\{b,k_j,e_j\}\in\mathbb{R}\times\mathbb{R}^4_+} u(c) + \beta v(w')$$

subject to the budget constraints for the current period (2) and for the next period

$$y + \sum_{j\in\{C,D\}} q_j k_j (1-\delta) = w' + Rb,$$

and the collateral constraint (4), where $c = \sum_{j\in\mathcal{J}} \min\left\{\frac{e_j}{\gamma_j}, k_j\right\}$.

Note that $e_j = \gamma_j k_j$ and hence $c = \sum_{j\in\mathcal{J}} k_j$. Using the same definitions of the (cum energy) user costs and down payments, the investment Euler equations (IEEs) can be written as

$$1 \geq \frac{1}{\mu} \frac{u_c(c) + \beta\mu'(1-\theta)q_j(1-\delta)}{\wp_j^e} \quad \text{or} \quad u_j^e + \frac{\lambda'}{\mu'}\wp_j^e \geq \frac{u_c(c)}{\mu'}. \tag{A1}$$

If neither type of durable is dominated, then $u_j^e < u_i^e$ implies $\wp_j^e > \wp_i^e$. As before, we conclude that $q_j > q_i$ and, indeed, $j = C$, so $q_C > q_D$, and furthermore, $u_C^e < u_D^e$,

$\wp^e_C > \wp^e_D$, $u_C > u_D$, and $\wp_C > \wp_D$.

Unconstrained households, for which $\lambda' = 0$, use clean durables only, that is, $k_D = 0$, as $u^e_C < u^e_D$ (see equation (A1)). Moreover, for such households, $\mu = \mu'$ and hence since $v(\cdot)$ is globally strictly concave in the household case, $w = w'$; the minimum amount of net worth for such households is $\overline{w} = \wp^e_C \overline{k}_C$ where $\overline{k}_C = \frac{y}{\wp^e_C - (1-\theta)q_C(1-\delta)}$.

Severely constrained households in contrast use dirty durables only. To see this, note that as $w \to 0$, $k_j \to 0$, $\forall j \in \mathcal{J}$, and hence $c \to 0$, so $u_c(c) \to +\infty$ and, by (A1), $\mu \to +\infty$. Since $w' \geq y + \sum_{j\in\mathcal{J}}(1-\theta)q_j k_j(1-\delta) \geq y \gg 0$, μ' is bounded above, and hence $\frac{\mu'}{\mu} \to 0$. Combining the IEEs for the two types of durables and denoting the multiplier on the non-negativity constraints for durables of type-j by ν_j, we obtain

$$1 = \beta \frac{\mu'}{\mu} \frac{(1-\theta)(q_C - q_D)(1-\delta)}{\wp^e_C - \wp^e_D} + \frac{\nu_C}{\wp^e_C} - \frac{\nu_D}{\wp^e_D},$$

and thus as $\frac{\mu'}{\mu} \to 0$, $\nu_C > 0$, implying that $k_C = 0$.

Suppose instead that clean and dirty durables are imperfect substitutes with

$$c = g(\{k_j, e_j\}_{j\in\mathcal{J}}) \equiv \left(\sum_{j\in\mathcal{J}} \sigma^\epsilon_j \min\{k_j, \frac{e_j}{\gamma_j}\}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}},$$

where the elasticity of substitution ϵ satisfies $0 < \epsilon < +\infty$. Clean capital is clean in the sense that energy costs are a smaller fraction of the cum-energy down payment and cum-energy user cost, or equivalently, $\frac{\gamma_C}{q_C} < \frac{\gamma_D}{q_D}$. This property is also satisfied in the baseline firm investment model (see Corollary (1)). The investment Euler equations, which hold with equality as all households use both types of durables, can be written as

$$1 = \frac{1}{\mu} \frac{u_c(c)\frac{\partial c}{\partial k_j} + \beta\mu'(1-\theta)q_j(1-\delta)}{\wp^e_j} \quad \text{or} \quad u^e_j + \frac{\lambda'}{\mu'}\wp^e_j = \frac{u_c(c)\frac{\partial c}{\partial k_j}}{\mu'}.$$

By dividing the IEE for clean durables by the one for dirty durables we obtain

$$\frac{k_C}{k_D} = \frac{\sigma_C}{\sigma_D} \left(\frac{u^e_C + \frac{\lambda'}{\mu'}\wp^e_C}{u^e_D + \frac{\lambda'}{\mu'}\wp^e_D} \right)^{-\epsilon} = \frac{\sigma_C}{\sigma_D} \left(\frac{\wp^e_C - \beta\frac{\mu'}{\mu'}(1-\theta)q_C(1-\delta)}{\wp^e_D - \beta\frac{\mu'}{\mu'}(1-\theta)q_D(1-\delta)} \right)^{-\epsilon}.$$

For unconstrained households, the ratio of clean to dirty durables $\frac{k_C}{k_D}$ is determined by the ratio of the cum-energy user costs, as $\lambda' = 0$, whereas for severely constrained households, that is, as $w \to 0$, $\frac{\mu'}{\mu} \to 0$ arguing as above, and thus the ratio of clean to dirty durables is determined by the ratio of the cum-energy down payments. Moreover, given that energy costs are a larger fraction of the cum-energy user costs for dirty capital, $\frac{\wp_C^e}{\wp_D^e} > \frac{u_C^e}{u_D^e}$. Therefore, constrained households' durable goods choice is distorted away from clean durables towards dirty durables.

A.3 Private Disutility from Energy Use: General Case

In this section, we consider again the model with private disutility from energy use (Section 3.5), but allow for the general case $\rho \leq 1$. In this case, the investment Euler equations can be expressed as follows:

$$u_j^e + \gamma_j \chi + \frac{\lambda'}{\mu'}(\wp_j^e + \gamma_j \chi) - \frac{\mu - 1}{\mu'}\gamma_j \chi \geq R^{-1} f_x(x) \tag{A2}$$

Consider a stationary equilibrium in which both clean and dirty are used. We show that this implies $u_C^e + \gamma_C \chi < u_D^e + \gamma_D \chi$. Assume by way of contradiction that $u_C^e + \gamma_C \chi \geq u_D^e + \gamma_D \chi$. Then, $u_C^e > u_D^e$ and $q_C > q_D$. But these inequalities imply $\wp_C^e > \wp_D^e$. Moreover, $\wp_C^e - \wp_D^e > u_C^e - u_D^e$ and thus $\wp_C^e + \gamma_C \chi > \wp_D^e + \gamma_D \chi$. In this case, we have

$$u_C^e + \gamma_C \chi + \frac{\lambda'}{\mu'}(\wp_C^e + \gamma_C \chi) - \frac{\mu - 1}{\mu'}\gamma_C \chi \geq u_D^e + \gamma_D \chi + \frac{\lambda'}{\mu'}(\wp_D^e + \gamma_D \chi) - \frac{\mu - 1}{\mu'}\gamma_D \chi$$

and the optimality conditions (A2) imply that dirty capital is (at least weakly) preferred by all firms.

Because $u_C^e + \gamma_C \chi < u_D^e + \gamma_D \chi$ and both clean and dirty technology are used, the optimality conditions (A2) imply that for some constrained firms,

$$\frac{\lambda'}{\mu'}(\wp_C^e + \gamma_C \chi) - \frac{\mu - 1}{\mu'}\gamma_C \chi > \frac{\lambda'}{\mu'}(\wp_D^e + \gamma_D \chi) - \frac{\mu - 1}{\mu'}\gamma_D \chi,$$

or, equivalently

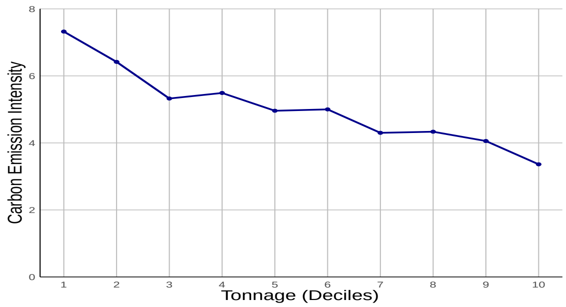
$$\frac{\lambda'}{\mu'}\wp_C^e - \frac{\mu' - 1}{\mu'}\gamma_C \chi > \frac{\lambda'}{\mu'}\wp_D^e - \frac{\mu' - 1}{\mu'}\gamma_D \chi.$$

If $\mu' = 1$ (as in the case $\rho = 1$), we get $\wp_C^e > \wp_D^e$. In general, it is possible that $\wp_C^e < \wp_D^e$ because financially constrained firms effectively discount the higher utility cost associated with dirty capital.

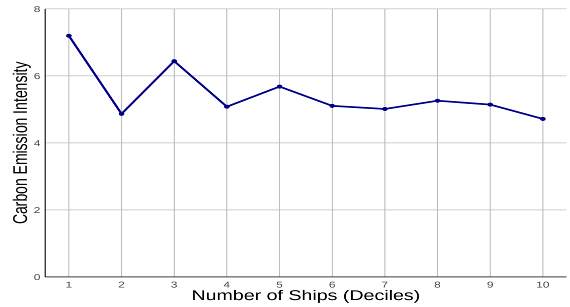
B Additional Empirical Evidence

In this appendix, we provide additional empirical evidence on the stylized facts of Section 5. Figures B1, B2, and B3 document the stylized facts when we aggregate ships into fleets based on their operating company, instead of owner, as well as when we focus on bulker fleets or oil-tanker fleets. Operators and owners do not coincide in the case of leased vessels.

Tables B1, B2, B3, and B4 document the sylized facts based on a regression analysis that controls for the composition of fleets across types of ships.

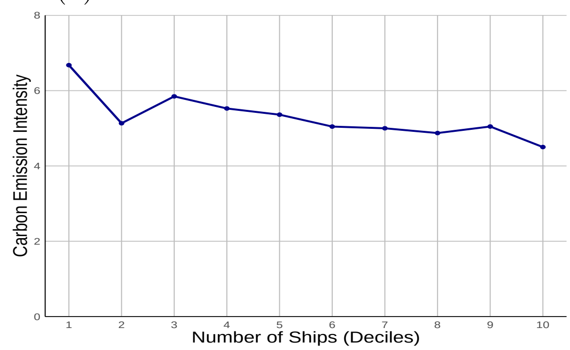


(a) Operator - Tonnage

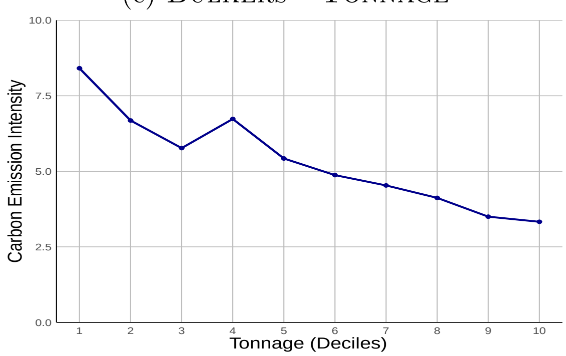


(b) Operator - Number of Ships

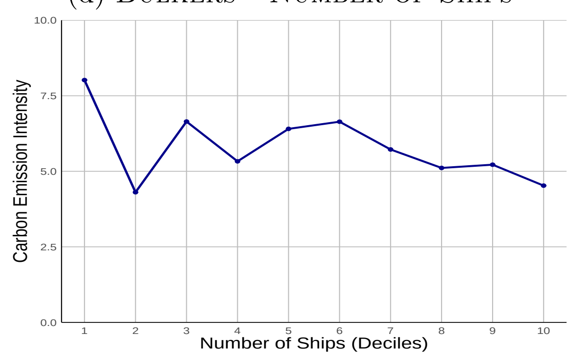
(c) Bulkers - Tonnage



(d) Bulkers - Number of Ships



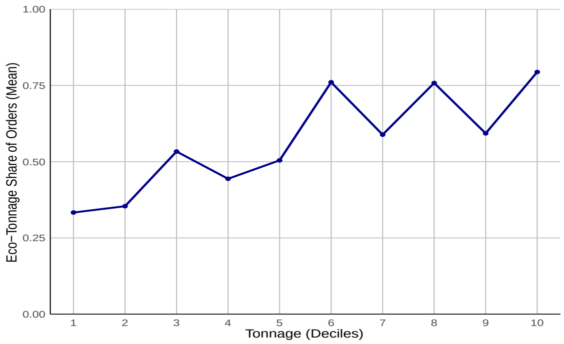
(e) Oil Tankers - Tonnage



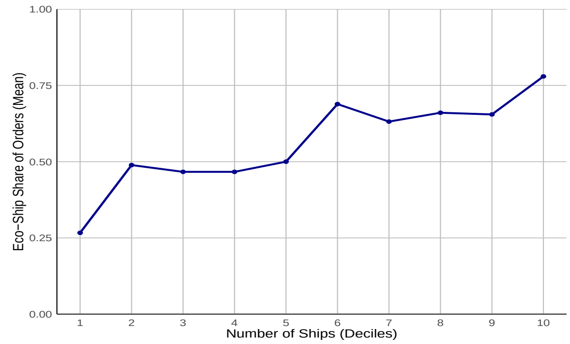
(f) Oil Tankers - Number of Ships

Figure B1: Fleet Size and Carbon Emission Intensity - Robustness

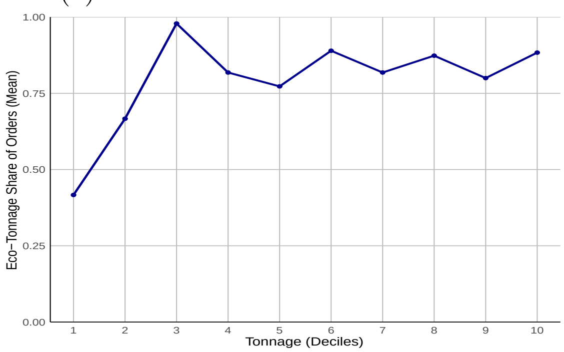
Notes: The figure displays the relationship between fleet size and carbon emission intensity (as in Figure 1) in three alternative samples. In the top panels, a fleet is defined by its operator, instead of its owner. In the middle panels, we focus on bulker fleets. In the bottom panels, we focus on oil tanker fleets. Left panels report the Annual Efficiency Ratio (AER, a measure of carbon emission intensity expressed in grams of CO_2 per deadweight tonnage and distance travelled) on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. Right panels report the same measure of emission intensity for all deciles of fleet size, measured by number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on fleets with at least three ships.



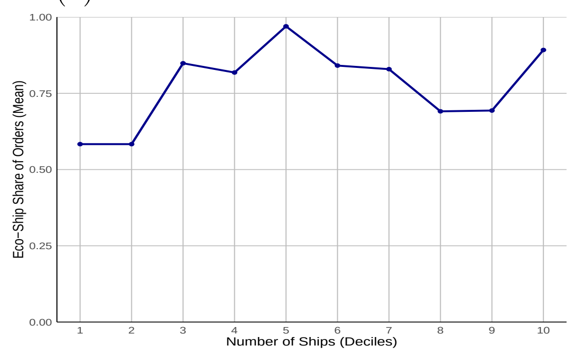
(a) Operator - Fleet Tonnage



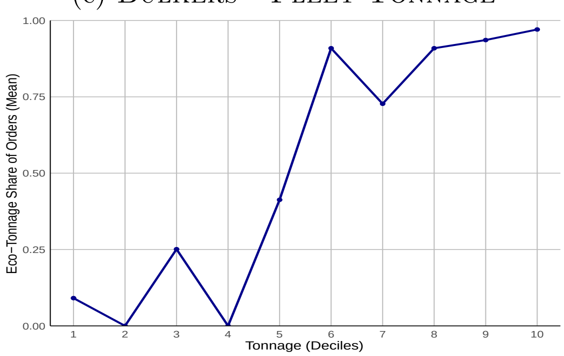
(b) Operator - Number of Ships



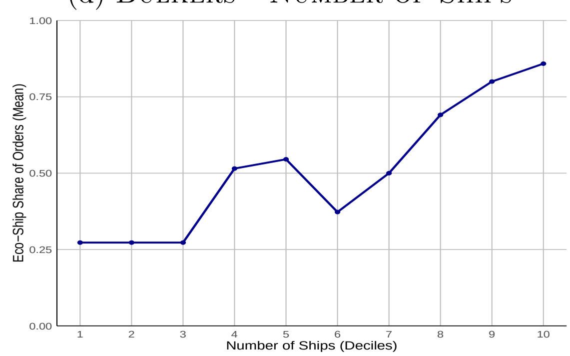
(c) Bulkers - Fleet Tonnage



(d) Bulkers - Number of Ships



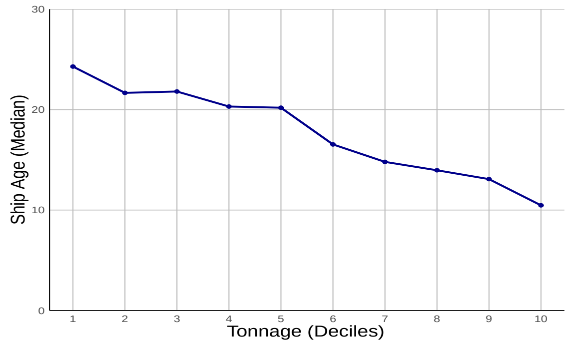
(e) Oil Tankers - Fleet Tonnage



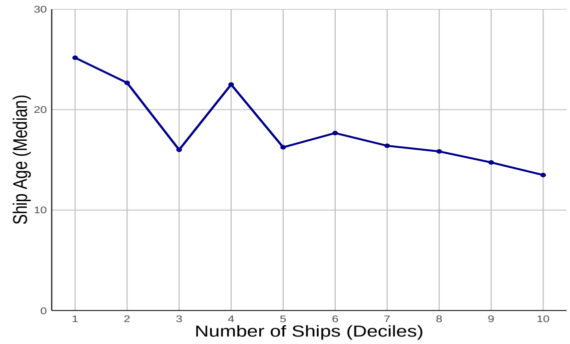
(f) Oil Tankers - Number of Ships

Figure B2: Fleet Size and Eco Ship Orders - Robustness

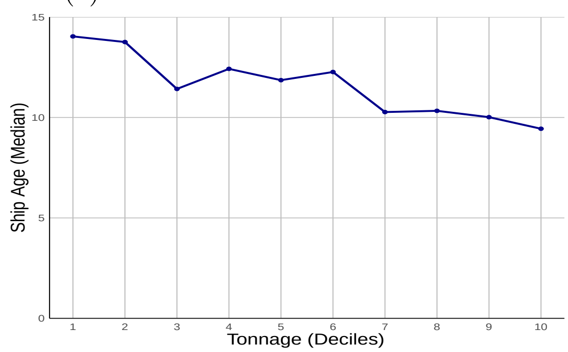
Notes: The figure displays the relationship between fleet size and the share of new investment accounted for by Eco (low-emission) Ships (as in Figure 2) in three alternative samples. In the top panels, a fleet is defined by its operator, instead of its owner. In the middle panels, we focus on bulker fleets. In the bottom panels, we focus on oil tanker fleets. Left panels report the share of new-ship orders accounted for by Eco Ships on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. Right panels report the share of new-ship orders accounted for by Eco Ships for all deciles of fleet size, measured by the number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on fleets with at least three ships.



(a) Operator - Fleet Tonnage



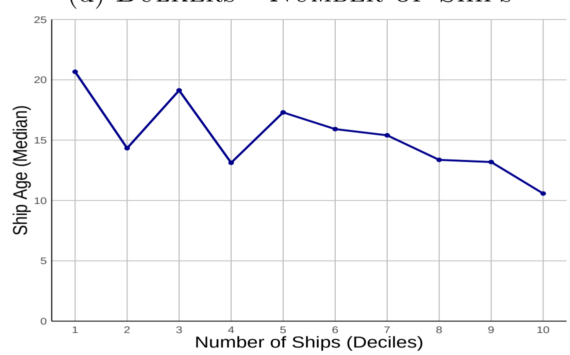
(b) Operator - Number of Ships



(c) Bulkers - Fleet Tonnage

(d) Bulkers - Number of Ships

(e) Oil Tankers - Fleet Tonnage



(f) Oil Tankers - Number of Ships

Figure B3: Fleet Size and Capital Age - Robustness

Notes: The figure displays the relationship between fleet size and capital age (as in Figure 3) in three alternative samples. In the top panels, a fleet is defined by its operator, instead of its owner. In the middle panels, we focus on bulker fleets. In the bottom panels, we focus on oil tanker fleets. Left panels report median ship age on the y-axis for all deciles of fleet size, measured by total tonnage, on the x-axis. Right panels report median ship age for all deciles of fleet size, measured by the number of ships, on the x-axis. Fleets with the same number of ships are ranked by tonnage. The analysis focuses on fleets with at least three ships.

Table B1: Fleet Size and Emission Intensity

	Dependent variable:			
	Emission Intensity		Emission Intensity	
	(1)	(2)	(3)	(4)
log(Tonnage)	-1.079^{***}	-0.949^{***}		
	(0.052)	(0.037)		
log(N Ships)			-0.536^{***}	-0.490^{***}
			(0.083)	(0.058)
Constant	19.024^{***}	16.850^{***}	6.944^{***}	6.313^{***}
	(0.656)	(0.466)	(0.179)	(0.127)
Fixed effects	No	Yes	No	Yes
Observations	1,252	1,252	1,252	1,252
R^2	0.253	0.651	0.032	0.536
Adjusted R^2	0.252	0.650	0.032	0.534

Notes: The table reports the estimated coefficients of regressions of the average carbon-emission intensity (Annual Efficiency Ratio) on measures of fleet size. The first column refers to a regression in which we measure fleet size as total tonnage and do not include fixed effects for fleet type (e.g., container ships, bulkers, etc.). The second column includes fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fixed effects. The fourth column includes fixed effects. The analysis focuses on fleets with at least three ships.

Table B2: Fleet Size and Share of Eco-Ship Orders

	Dependent variable:			
	Share of Eco Ships		Share of Eco Ships	
	(1)	(2)	(3)	(4)
log(Tonnage)	0.116***	0.052***		
	(0.006)	(0.007)		
log(N Ships)			0.124***	0.046***
			(0.016)	(0.012)
Constant	−0.991***	0.081	−0.011	0.631***
	(0.066)	(0.094)	(0.048)	(0.045)
Fixed effects	No	Yes	No	Yes
Observations	665	665	665	665
R^2	0.388	0.621	0.080	0.598
Adjusted R^2	0.388	0.610	0.078	0.586

Notes: The table reports the estimated coefficients of regressions of the share of Eco (i.e., low-emission) ships among new-ship orders on measures of fleet size. The first column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least three ships.

Table B3: Fleet Size and Share of Eco Ships

	Dependent variable:			
	Share of Eco Ships		Share of Eco Ships	
	(1)	(2)	(3)	(4)
log(Tonnage)	0.047***	0.040***		
	(0.001)	(0.001)		
log(N Ships)			0.068***	0.048***
			(0.003)	(0.003)
Constant	−0.361***	−0.221***	−0.050***	0.156***
	(0.010)	(0.019)	(0.006)	(0.008)
Fixed effects	No	Yes	No	Yes
Observations	7,649	7,649	7,649	7,649
R^2	0.228	0.266	0.070	0.238
Adjusted R^2	0.228	0.264	0.069	0.236

Notes: The table reports the estimated coefficients of regressions of the share of Eco (i.e., low-emission) ships on measures of fleet size. The first column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least three ships.

Table B4: Fleet Size and Capital Age

	Dependent variable:			
	Average Ship Age		Average Ship Age	
	(1)	(2)	(3)	(4)
log(Tonnage)	-2.215^{***}	-1.879^{***}		
	(0.060)	(0.089)		
log(N Ships)			-3.127^{***}	-1.986^{***}
			(0.187)	(0.179)
Constant	41.483^{***}	35.581^{***}	27.013^{***}	16.873^{***}
	(0.591)	(1.159)	(0.375)	(0.529)
Fixed effects	No	Yes	No	Yes
Observations	7,649	7,649	7,649	7,649
R^2	0.151	0.191	0.035	0.168
Adjusted R^2	0.151	0.189	0.035	0.166

Notes: The table reports the estimated coefficients of regressions of the average ship age on measures of fleet size. The first column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least three ships.

C Additional Quantitative Results

C.1 Transition Dynamics: Equilibrium Conditions

We report here the equilibrium conditions along the transition to cleaner technology discussed in Section 6. The firms' budget constraints are

$$\begin{aligned} w_t + b_t &= d_t + \sum_{j\in\{C,D\}} \left(q_{jN,t} + \gamma_{j,t} p_e\right) k_{jN,t} + u^e_{O,t} k_{O,t} \\ f(x_t) + \sum_{j\in\{C,D\}} q_{jO,t+1} k_{jN,t} &= w_{t+1} + R b_t, \end{aligned}$$

and the collateral constraint reads $\theta \sum_{j\in\{C,D\}} q_{jO,t+1} k_{jN,t} \geq Rb_t$. The optimality conditions for investment in type-j new capital, investment in old capital, dividends, and debt financing are:

$$\begin{aligned} \left(q_{jN,t} + \gamma_{j,t} p_e\right) \mu_t &= R^{-1} \left(f_{x,t} g_{jN,t} + q_{jO,t+1}\right) + R^{-1} \theta q_{jO,t+1} \lambda_t \\ u^e_{O,t} \mu_t &= R^{-1} f_{x,t} g_{O,t} \\ \mu_t &= 1 + \phi_{d,t} \\ \mu_t &= 1 + \lambda_t. \end{aligned}$$

The price of type-j old capital at time t, $q_{jO,t}$, satisfies $u^e_{O,t} = q_{jO,t} + \gamma_{j,t-1} p_e$, $j \in \{C, D\}$. Given the assumption that clean old and dirty old capital are perfect substitutes, the market-clearing condition for old capital simplifies to:

$$\sum_{j\in\{C,D\}} \int k_{jN,t-1} d\pi_{t-1}(w) = \int k_{O,t} d\pi_t(w).$$

C.2 Transition Dynamics: Additional Results

Figures C1 and C2 complement the results in Section 6. The two figures display the cross-sectional patterns of technology adoption during a transition induced by an exogenous decrease in γ_C and q_{CN}, respectively.

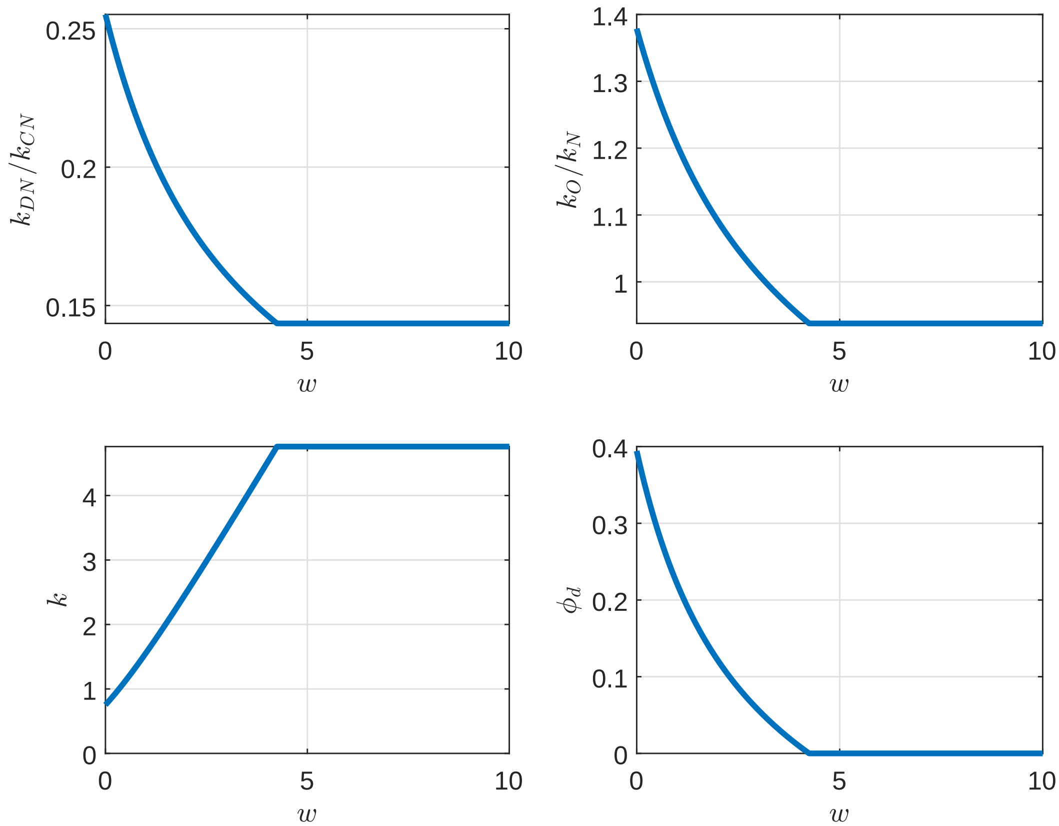


Figure C1: Patterns of Technology Adoption During Transition (γ_C)

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transition dynamics associated with an exogenous, gradual decrease in $\gamma_{C,t}$ only. The x-axis is net worth w in all panels. The top-left panel displays the ratio of dirty-new capital to clean-new capital $k_{DN,t}/k_{CN,t}$; the top-right panel displays the ratio of old capital to new capital $k_{O,t}/k_{N,t}$; the bottom-left panel displays total capital; the bottom-right panel displays the marginal cost of equity issuance $\phi_{d,t}$.

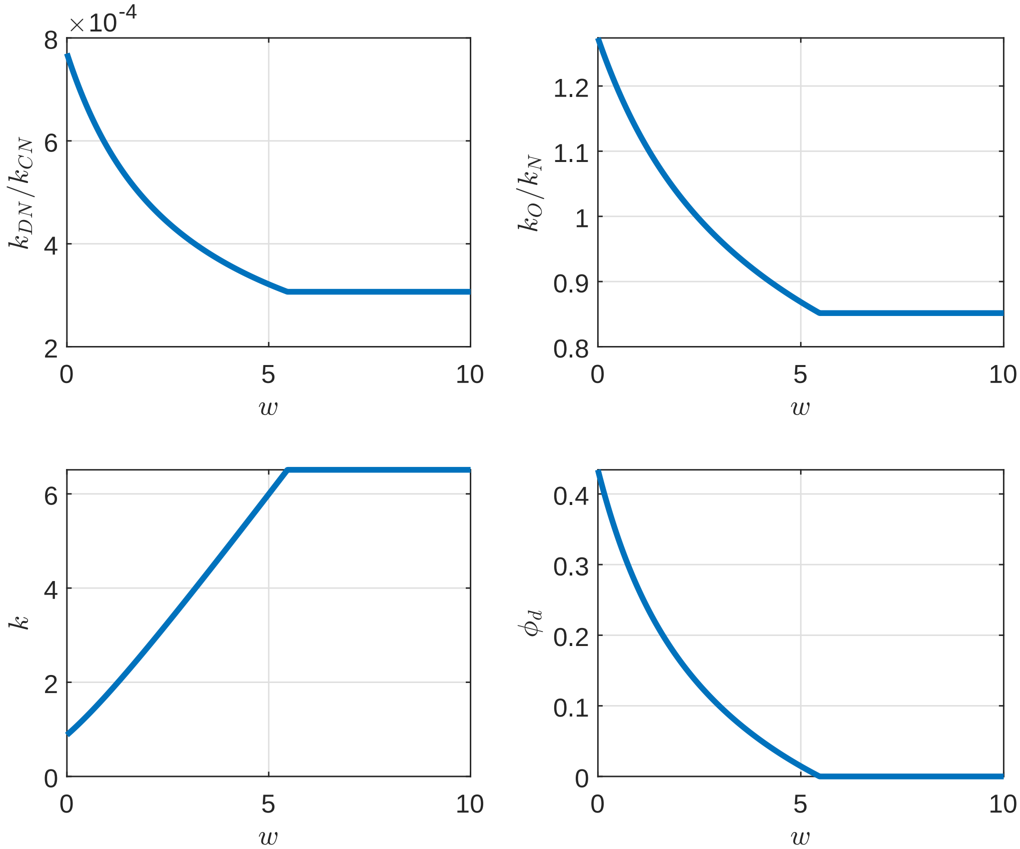


Figure C2: Patterns of Technology Adoption During Transition (q_{CN})

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transition dynamics associated with an exogenous, gradual decrease in $q_{CN,t}$. The x-axis is net worth w in all panels. The top-left panel displays the ratio of dirty-new capital to clean-new capital $k_{DN,t}/k_{CN,t}$; the top-right panel displays the ratio of old capital to new capital $k_{O,t}/k_{N,t}$; the bottom-left panel displays total capital; the bottom-right panel displays the marginal cost of equity issuance $\phi_{d,t}$.