Financing the Adoption of Clean Technology[*]

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Abstract

We analyze the adoption of clean technology by heterogeneous firms subject to financing constraints. We develop a model of investment with heterogeneous capital goods, which differ in their associated energy needs and in their age. We show that, in equilibrium, cleaner and newer capital requires a larger down payment. Therefore, 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. Larger firms operate with higher energy efficiency, by investing in cleaner new technologies and operating newer capital, which tends to be more energy efficient. We use a calibrated version of our model to simulate the aggregate transitional dynamics to cleaner technology.

Keywords: Clean Technology; Financial Frictions; Capital Reallocation.

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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 transitional 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 transitional 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. In recent work, Känzig (2022) analyzes the heterogeneous effects of shocks to energy prices on households. Kuhn and Schlattmann

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[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.

(2023) analyze the effects of subsidies on energy-efficient durable goods in a quantitative model of household consumption. Iovino, Martin, and Sauvagnat (2022) 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.[2]

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. De Haas and Popov (2023) show that easier access to external financing stimulates clean growth, consistent with the predictions of our model. Hartzmark and Shue (2023) 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 (2023) 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. 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.

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[2] 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. 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.

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 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 and the case in which firms internalize a private disutility of energy use.

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, $u_c > 0$ 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.[3] The price of energy is $p_e > 0$.[4]

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.[5]

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 can only credibly promise to pay up to a fraction $\theta \in [0, 1)$ of the resale value of capital.[6] In

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[3] 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.

[4] 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.

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

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

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,

$$\begin{aligned} w + b &= d + \sum_{j\in\{C,D\}} q_j k_j + \sum_{j\in\{C,D\}} p_e e_j, & (2)\\ f(x) + \sum_{j\in\{C,D\}} q_j k_j (1-\delta) &= w' + Rb, & (3) \end{aligned}$$

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.[7] 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 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 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

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

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 of 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, and ν_j for the non-negativity constraints on type-j capital, 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 of type-j capital.[8]

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

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[8] 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

$$\lambda' = \mu - \mu' \tag{7}$$

$$\mu = 1 + \phi_d \tag{8}$$

$$\mu' = 1 + (1-\rho)\phi'_d. \tag{9}$$

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 of type j capital must be larger than that of 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 of 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:

$$q_C - q_D < \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta}, \tag{10}$$

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:

$$q_C - q_D > \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta + (1-\theta)(1-\delta)}. \tag{11}$$

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:

$$\begin{aligned} (\gamma_D - \gamma_C)p_e \left(1 + R^{-1}\theta(1-\delta) + R^{-2}\theta^2(1-\delta)^2 + ...\right) &= \frac{(\gamma_D - \gamma_C)p_e}{1 - R^{-1}\theta(1-\delta)} \\ &= \frac{R(\gamma_D - \gamma_C)p_e}{r + \delta + (1-\theta)(1-\delta)}. \end{aligned} \tag{12}$$

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 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.[9]

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 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

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[9] 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.

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.[10] 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 $u_C^e + \frac{\lambda'}{1+(1-\rho)\phi_d'}\wp_C^e = u_D^e + \frac{\lambda'}{1+(1-\rho)\phi_d'}\wp_D^e$. 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 $\bar{R} = R(1 + \frac{u_D^e - u_C^e}{\wp_C^e - \wp_D^e}) > R$ and we can express the investment Euler equations as follows:

$$1 = \bar{R}^{-1}\frac{f_x(x) + (1-\theta)q_j(1-\delta)}{\wp_j^e}. \tag{13}$$

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.*

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 downpayment. This price difference reflects part of the future energy cost savings associated with the clean technology. Because of the higher downpayment, sufficiently financially constrained firms

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

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 to adopt 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 $R_C \leq R_D = R = \beta^{-1}$.[11]

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 the current and next period,

$$w + \sum_{j \in \{C,D\}} b_j = d + \sum_{j \in \{C,D\}} q_j k_j + \sum_{j \in \{C,D\}} p_e e_j, \tag{14}$$

$$f(x) + \sum_{j \in \{C,D\}} q_j k_j (1-\delta) = w' + \sum_{j \in \{C,D\}} R_j b_j, \tag{15}$$

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[11] 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.

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

$$\theta q_j k_j (1-\delta) \geq R_j b_j, \tag{16}$$

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 (16) by $\beta\lambda'_j$, the investment Euler equations can be stated as

$$R_j u^e_j + \frac{\lambda'_j}{\mu'} R_j \wp^e_j \geq f_x(x). \tag{17}$$

In our baseline model, $R_C = R_D = R$, and assuming both types of capital are used in equilibrium, $R_C u^e_C < R_D u^e_D$ whereas $R_C \wp^e_C > R_D \wp^e_D$ (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 $\frac{\partial}{\partial R_C}(R_C u^e_C) > 0$ and on the (scaled) cum-energy down payment $\frac{\partial}{\partial R_C}(R_C \wp^e_C) > 0$. 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—i.e., $\rho = 1$.[12] Thus, the problem of a new firm born with net-worth w is

$$v(w) \equiv \max_{\{d,b,k_j,e_j\} \in \mathbb{R}^2 \times \mathbb{R}^4_+} d - \phi(-d) - \chi \sum_j e_j + R^{-1} w', \tag{18}$$

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:

$$u^e_j + \gamma_j \chi + \lambda' \wp^e_j \geq R^{-1} f_x(x). \tag{19}$$

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 $u^e_j + \gamma_j \chi = R^{-1} q_j (r + \delta) + \gamma_j (p_e + \chi) < R^{-1} q_i (r + \delta) + \gamma_i (p_e + \chi) = u^e_i + \gamma_i \chi$, then $\wp^e_j = R^{-1} q_j (r + \delta) + \gamma_j (p_e + \chi) + R^{-1} (1 - \theta) q_j (1 - \delta) - \gamma_j \chi > R^{-1} q_i (r + \delta) + \gamma_i (p_e + \chi) + R^{-1} (1 - \theta) q_i (1 - \delta) - \gamma_i \chi = \wp^e_i$.

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

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[12] We analyze the general case $\rho \leq 1$ in Appendix A.2.

$\gamma_C < \gamma_D$ 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 $u^e_C = R^{-1}q_C(r + \delta) + \gamma_C p_e > R^{-1}q_D(r + \delta) + \gamma_D p_e = u^e_D$.

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. Financial constraints induce firms with low net worth to invest in dirty capital because of its lower financing needs.

3.6 Effect of Legal Enforcement and Financial Development

We now 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 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 $\lim_{\theta \to 1} \wp^e_j = u^e_j$, 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 $\wp^e_j(\theta)$. Assume that there is an economy with legal enforcement $\theta_0 \in [0, 1)$ for which $u^e_C < u^e_D$ and $\wp^e_C(\theta_0) > \wp^e_D(\theta_0)$ 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 $\wp^e_C(\theta) < \wp^e_D(\theta)$, 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.[13] 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.

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

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[13] To see this, note that the discount rate at which firms are indifferent $\bar{R}(\theta) = R(1+(u^e_D - u^e_C)/(\wp^e_C(\theta) - \wp^e_D(\theta))) = R(1 + (u^e_D - u^e_C)/(u^e_D - u^e_C + R^{-1}(1-\theta)(q_C - q_D)(1-\delta)))$ is increasing in θ.

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:

$$x = g(x_N, x_O) \equiv \left(\sigma_N^{\frac{1}{\epsilon}} x_N^{\frac{\epsilon-1}{\epsilon}} + \sigma_O^{\frac{1}{\epsilon}} x_O^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}, \tag{20}$$

where ϵ denotes the elasticity of substitution between new and 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 resource constraint for old capital is

$$\sum_{j\in\{C,D\}} \int k_{jN} d\pi(w) = \sum_{j\in\{C,D\}} \int k_{jO} d\pi(w), \tag{21}$$

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 $(j, a) \in \mathcal{J} \times \mathcal{A} \equiv \{C, D\} \times \{N, O\}$, to solve

$$v(w) \equiv \max_{\{d,b,k_{ja},e_{ja}\}\in\mathbb{R}^2\times\mathbb{R}^8_+} d - \phi(-d) + \beta\{\rho w' + (1-\rho)v(w')\} \tag{22}$$

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

$$\begin{aligned} w + b &= d + \sum_{(j,a)\in\mathcal{J}\times\mathcal{A}} q_{ja} k_{ja} + \sum_{(j,a)\in\mathcal{J}\times\mathcal{A}} p_e e_{ja}, && (23) \\ f(x) + \sum_{j\in\mathcal{J}} q_{jO} k_{jN} &= w' + Rb, && (24) \end{aligned}$$

and the collateral constraint

$$\theta \sum_{j\in\mathcal{J}} q_{jO} k_{jN} \geq Rb, \tag{25}$$

where $x = \left(\sum_{a\in\mathcal{A}} \sigma_a^{\frac{1}{\epsilon}} x_a^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}}$, $x_a \equiv \sum_{j\in\mathcal{J}} \min\left\{\frac{e_{ja}}{\gamma_j}, k_{ja}\right\}$ for $a \in \mathcal{A}$, and $v(w)$ denotes the value function conditional on continuation and variables next period are denoted with a prime.

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 firm problem in (22) through (25), the distribution is induced by the policy functions, and the market for old capital clears, that is, (21) 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 of them fully depreciate after production, in equilibrium they must have the same cum-energy user cost (and down payment): $u^e_{CO} = u^e_{DO} = \wp^e_{CO} = \wp^e_{DO}$. We will thus denote this cum-energy user cost by u^e_O, which will be determined in equilibrium. This will facilitate the analysis and u^e_O will in turn imply 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

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

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 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, (clean and dirty) old capital as follows:

$$u^e_{jN} + \frac{\lambda'}{1 + (1-\rho)\phi'_d}\wp^e_{jN} \quad \geq \quad R^{-1} f_x(x)\frac{\partial x}{\partial x_N} \tag{26}$$

$$u^e_O\left(1 + \frac{\lambda'}{1 + (1-\rho)\phi'_d}\right) \quad = \quad R^{-1} f_x(x)\frac{\partial x}{\partial x_O}. \tag{27}$$

Inequality (26) holds with equality for either clean or dirty new capital (or both). Following the same arguments developed 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 of new capital for which (26) holds with equality. We can divide both sides of this equation by the corresponding sides of (27) and use to definition of x to obtain the optimal ratio between new and old capital:

$$\frac{x_N}{x_O} = \frac{\sigma_N}{\sigma_O}\left(\frac{u^e_{jN}}{u^e_O}\right)^{-\epsilon}\left(\frac{1 + \frac{\lambda'}{1+(1-\rho)\phi'_d}\frac{\wp^e_{jN}}{u^e_{jN}}}{1 + \frac{\lambda'}{1+(1-\rho)\phi'_d}}\right)^{-\epsilon}. \tag{28}$$

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 invest in a larger share of old capital than unconstrained firms do.

4.3 Higher Energy Efficiency of New Capital

The empirical evidence of Section 5 shows that technological progress is making newer vintages of capital more energy efficient over time. To mimic the effects of this 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 $x_N \equiv \sum_{j\in\{C,D\}} \min\left\{\frac{e_{jN}}{\gamma_j}, k_{jN}\right\}$. Instead, 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 $\kappa > 1$ denotes the 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 follows $u^e_{jO} = \wp^e_{jO} = q_{jO} + \kappa\gamma_j p_e$. 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 (26), (27), and (28). Thus, we still obtain 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.[14] 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 five 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

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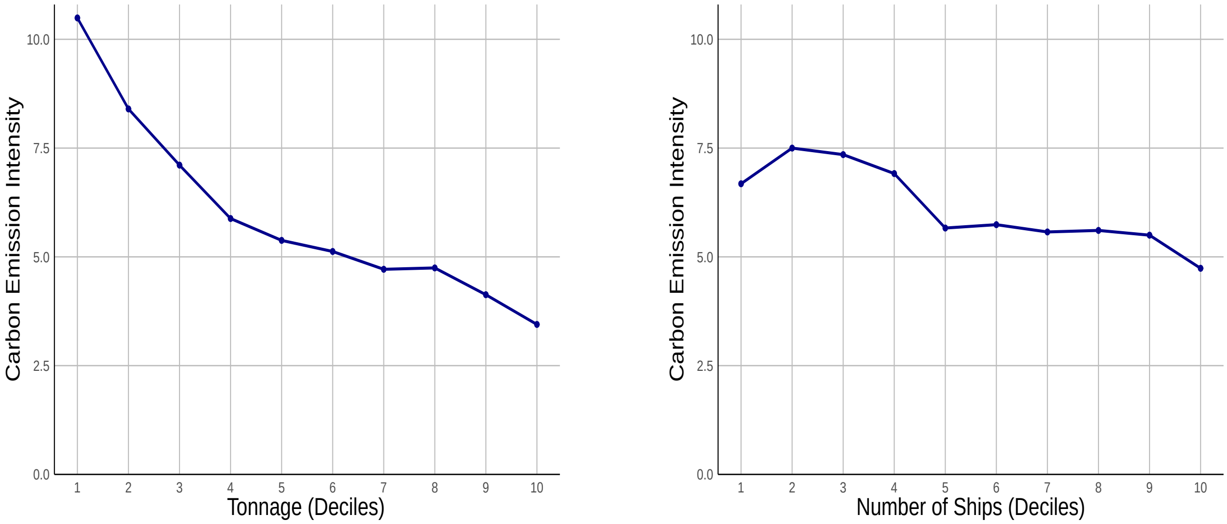
[14] Kalouptsidi (2014) leverages this dataset to estimate a model of entry and exit in bulk shipping.

owners. Moreover, the findings are robust to focusing on specific types of ships, such as 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.

Figure 1: Fleet Size and Carbon Emission Intensity



(a) Tonnage

(b) Number of Ships

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. The analysis focuses on bulkers, container ships, and oil tankers and on fleets with at least five ships.

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 by tonnage is more than double the emission intensity of fleets in the highest decile by tonnage. 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

We now document that 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.

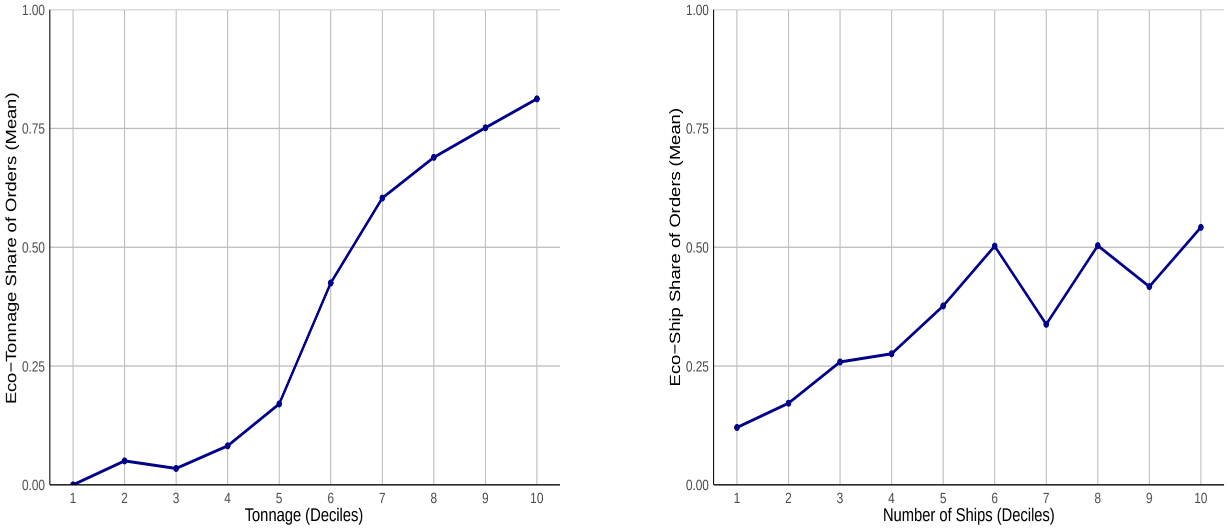
We also test the relationship between fleet size and clean new investment controlling for fixed effects for ship types and confirm this significant relationship (Table B2). For bulkers, a common type of ship with a large share of Eco ships among new orders, increasing fleet size (total tonnage) by one standard deviation relative to the average, the fraction of low-emission new-ship orders goes from 80% to 87%. 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 31% to 36%.

5.4 Larger Firms Operate Newer Capital

We now document 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.

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

Figure 2: Fleet Size and Eco Ship Orders



(a) Fleet Tonnage

(b) Number of Ships

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. The analysis focuses on fleets with at least five ships.

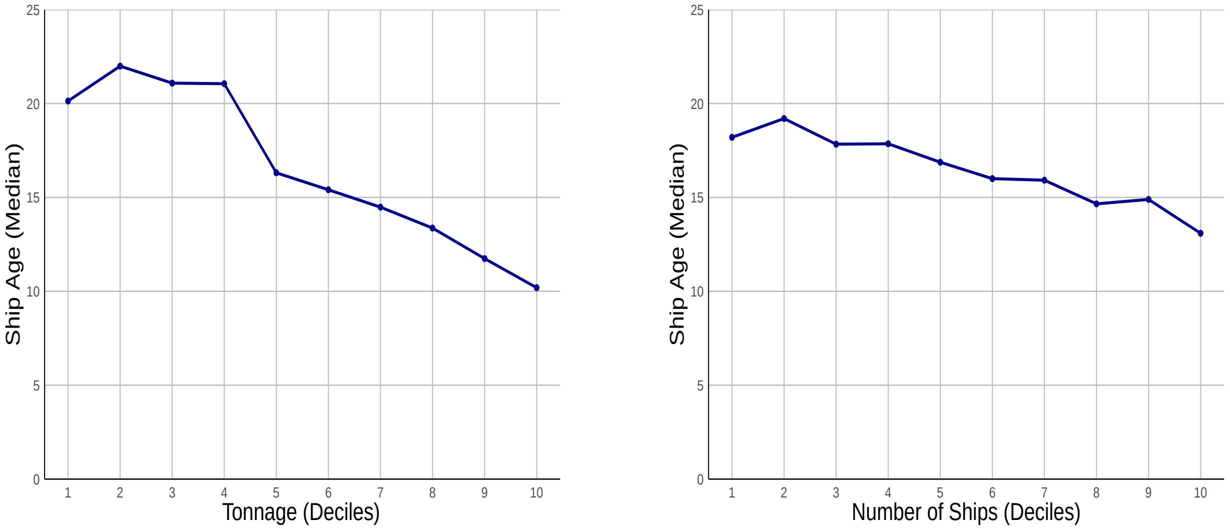
fleet size by one standard deviation relative to the average, average capital age goes from 18 to 14 years (and from 12 to 10 when we restrict attention to bulkers).

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.

Figure 3: Fleet Size and Capital Age



(a) Fleet Tonnage

(b) Number of Ships

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. The analysis focuses on fleets with at least five ships.

6 Transition to Cleaner Technology

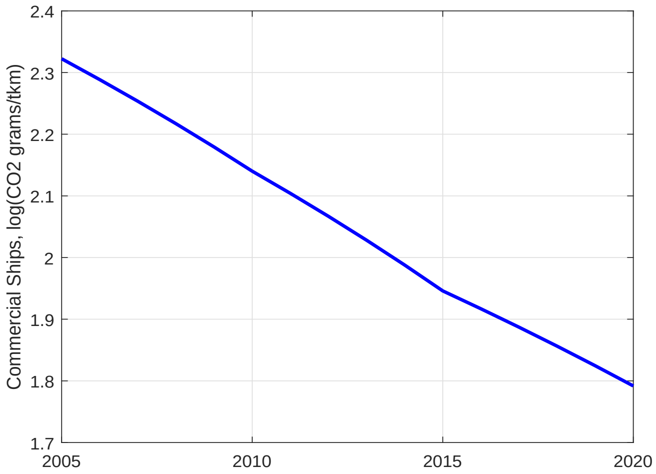
In this section we use the empirical evidence to calibrate our model and analyze its equilibrium transitional dynamics as technological progress may lead to improvements in energy efficiency. This analysis shows that our analytical insights on the role of financing constraints for technology adoption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

$$x_N \equiv \left(\sigma_{CN}^{\frac{1}{\eta}} (k_{CN})^{\frac{\eta-1}{\eta}} + (1-\sigma_{CN})^{\frac{1}{\eta}} (k_{DN})^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}}, \tag{29}$$

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.

where $\eta > 0$ denotes the elasticity of substitution between clean new and dirty new capital. We maintain the assumption from the previous section that clean old and dirty old capital are perfect substitutes to facilitate the computation. We also maintain the assumption that new and old capital are combined in the CES aggregator (20) with elasticity of substitution ϵ. We parameterize both CES aggregators in order to closely replicate the empirical patterns of technology adoption across the firm size distribution that we document in Section 5.

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, in two periods (new and old). We further assume that all firms exit after one period.

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 (i.e., 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 the median are closely matched in model and data.

We parameterize the convex cost of equity issuance as a power function: $\phi(-d) \equiv$

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

$\phi_0(-d)^{\phi_1}$ 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 transitional dynamics.

The top-left panel of Figure 5 displays the exogenous path of the technological parame-

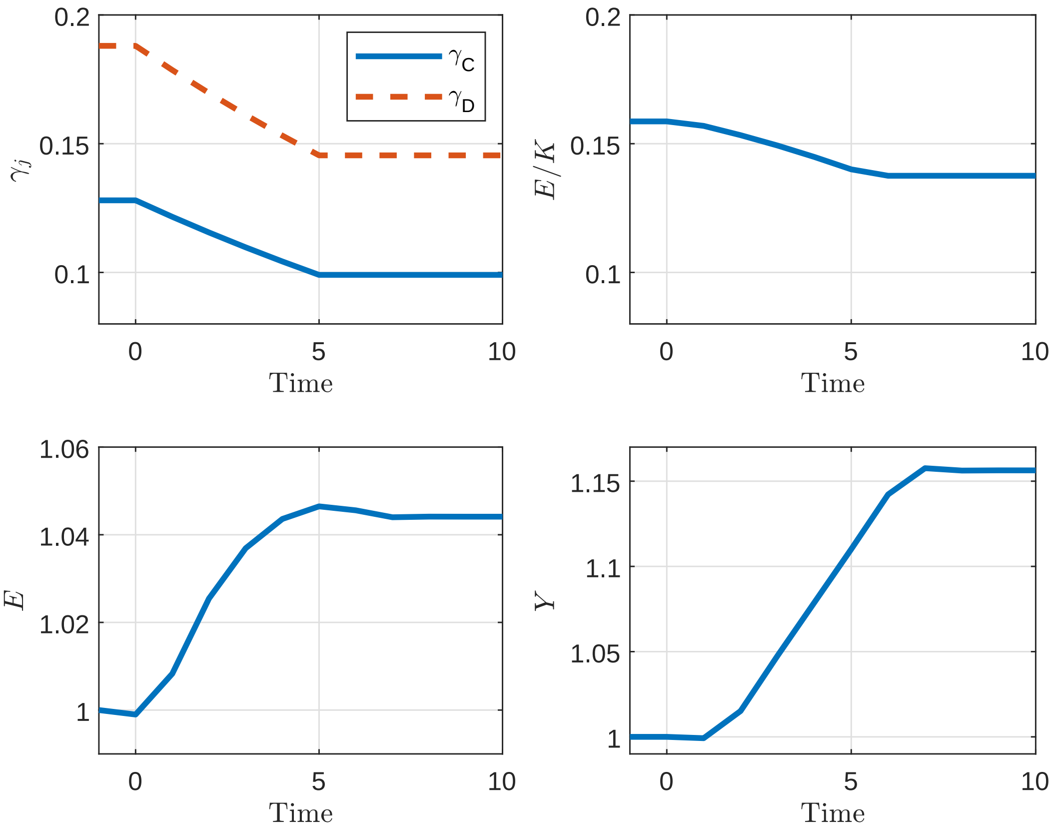


Figure 5: Improvement in Energy Efficiency of Clean and Dirty Capital

Notes: The figure displays the transitional 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.

ters $\gamma_{C,t}$ 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 transitional dynamics of $\gamma_{C,t}$ and $\gamma_{D,t}$, old capital is less energy efficient than new capital, because the lower energy requirements apply to the latest vintage of capital, whereas old capital maintains the energy requirements 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)

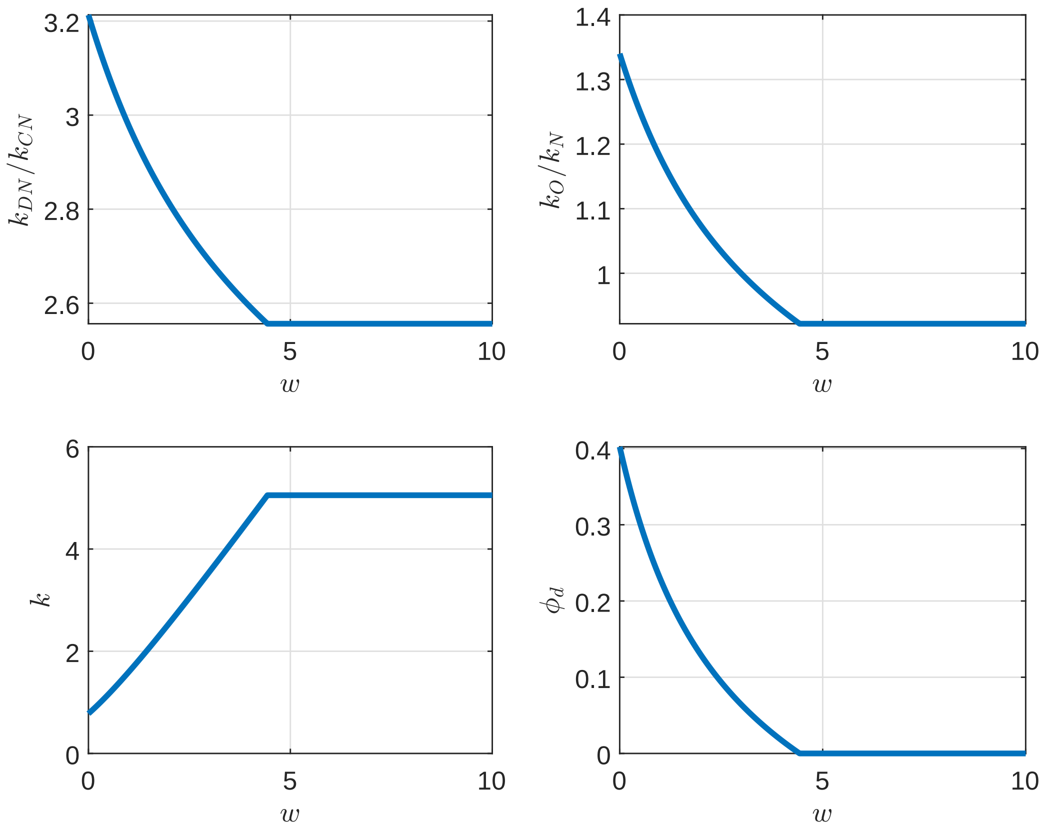


Figure 6: Patterns of Technology Adoption During Transition (γ_C and γ_D)

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transitional 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 $\phi_{d,t}$.

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 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 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 producing 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 during the transition, as firms substitute toward clean capital, aggregate energy use decreases. After the substitution has taken place, however, the economy keeps expanding

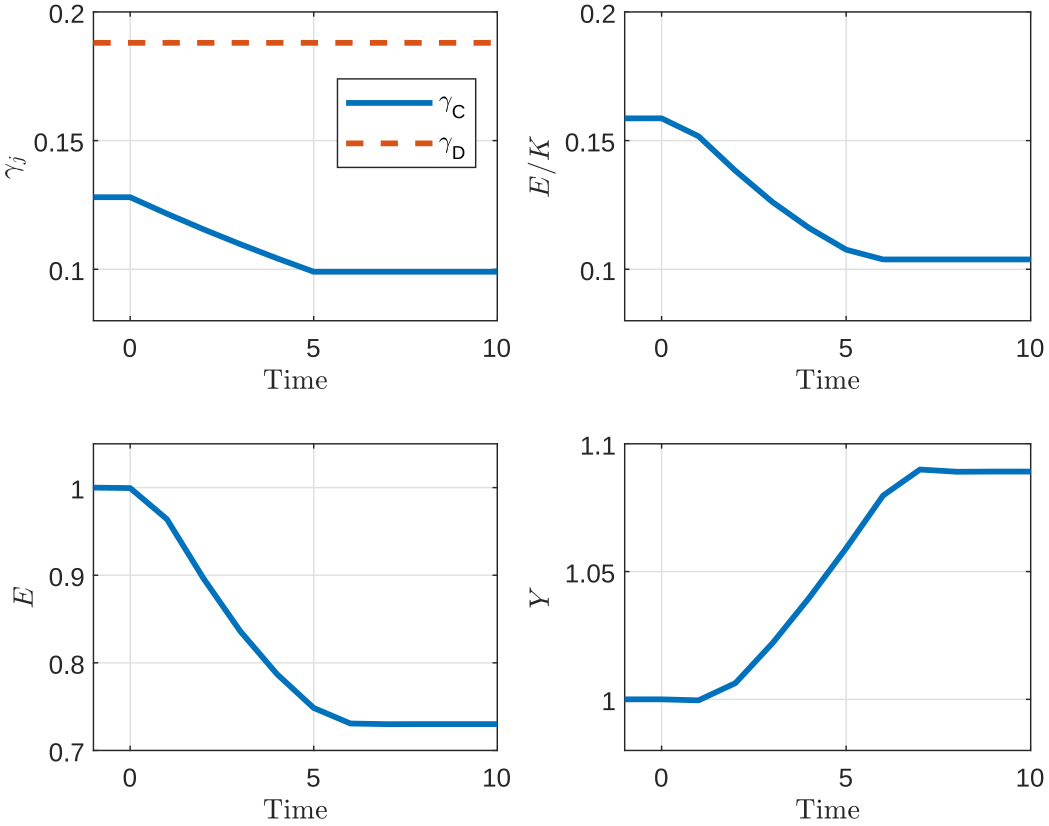


Figure 7: Improvement in Energy Efficiency of Clean Capital

Notes: The figure displays the transitional 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.

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

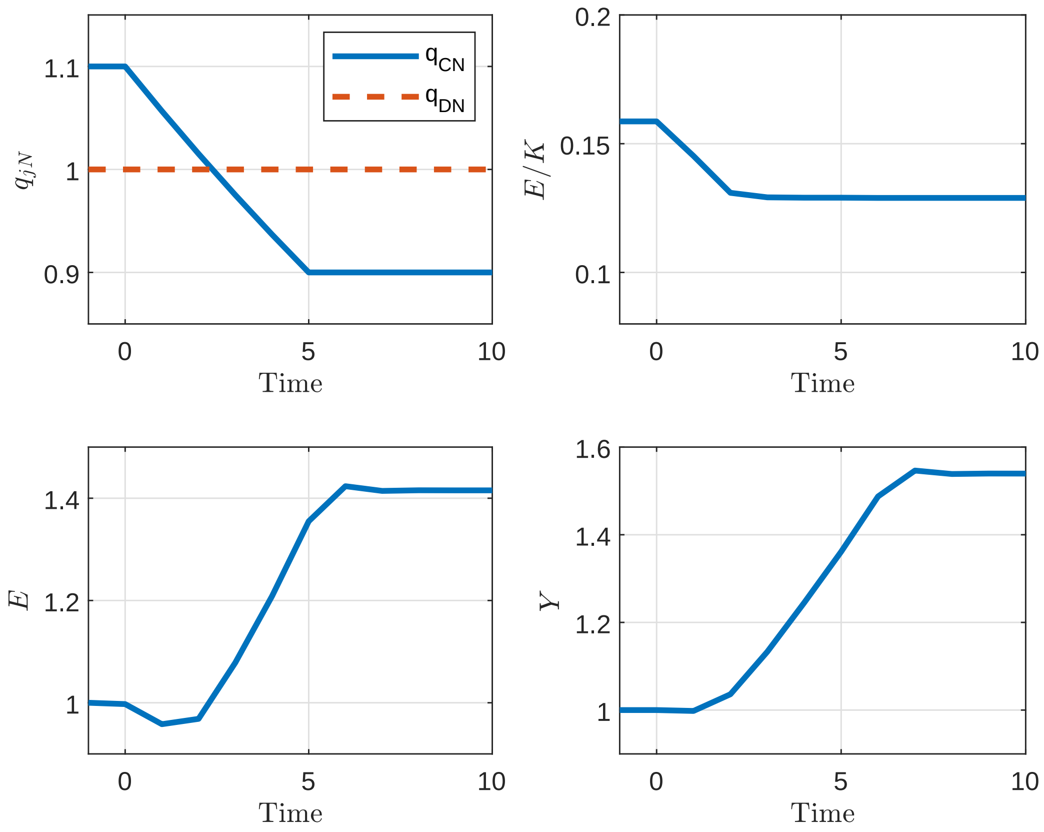


Figure 8: Reduction in Cost of Clean Capital

Notes: The figure displays the transitional 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.

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 requirements 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 heterogeneous capital goods. When both clean and dirty new capital are used in equilibrium, clean capital is more expensive in terms of down payment. Thus, financially constrained firms invest in dirty capital.

Furthermore, new capital is more expensive than old capital in terms of down payment, because new capital has a longer residual life. As a result, financially constrained firms invest 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 in the adoption of clean technology implies that environmental policy has important distributional consequences. Our framework therefore has rich implications for the design of environmental policies, such as a carbon emissions tax or a scrappage subsidy for dirty capital, in the presence of financial constraints, which are left for future work.

Finally, our theory suggests that financial development that improves legal enforcement can both increase aggregate output while decreasing aggregate energy use. The key reason 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.

References

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012): "The Environment and Directed Technical Change," *American Economic Review*, 102(1), 131–166.

Acemoglu, D., U. Akcigit, D. Hanley, and W. Kerr (2016): "Transition to Clean Technology," *Journal of Political Economy*, 124(1), 52–104.

Acemoglu, D., C. Lelarge, and P. Restrepo (2020): "Competing with Robots: Firm-level Evidence from France," *American Economic Review, Papers and Proceedings*, 110, 383–388.

Atkeson, A., and P. J. Kehoe (1999): "Models of Energy Use: Putty-Putty versus Putty-Clay," *American Economic Review*, 89(4), 1028–1043.

Azomahou, T., R. Boucekkine, and P. Nguyen-Van (2012): "Vintage Capital and the Diffusion of Clean Technologies," *International Journal of Economic Theory*, 8(3), 277–300.

Barahona, N., F. A. Gallego, and J.-P. Montero (2020): "Vintage-Specific Driving Restrictions," *Review of Economic Studies*, 87(4), 1646–1682.

Barnett, M., W. Brock, and L. P. Hansen (2020): "Pricing Uncertainty Induced by Climate Change," *Review of Financial Studies*, 33(3), 1024–1066.

Barrage, L. (2020): "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy," *Review of Economic Studies*, 87, 1–39.

Bento, A. M., L. H. Goulder, M. R. Jacobsen, and R. H. von Haefen (2009): "Distributional and Efficiency Impacts of Increased US Gasoline Taxes," *American Economic Review*, 99(3), 667–699.

Berkouwer, S. B., and J. T. Dean (2022): "Credit, Attention, and Externalities in the Adoption of Energy Efficient Technologies by Low-Income Households," *American Economic Review*, 112(10), 3291–3330.

De Haas, R., and A. Popov (2023): "Finance and Green Growth," *The Economic Journal*, 133(650), 637–668.

Eisfeldt, A., and A. A. Rampini (2006): "Capital Reallocation and Liquidity," *Journal of Monetary Economics*, 53(3), 369–399.

——— (2007): "New or Used? Investment with Credit Constraints," *Journal of Monetary Economics*, 54, 2656–2681.

Eisfeldt, A., and Y. Shi (2018): "Capital Reallocation," *Annual Review of Financial Economics*, 10, 361–386.

Gavazza, A., and A. Lanteri (2021): "Credit Shocks and Equilibrium Dynamics in Consumer Durable Goods Markets," *Review of Economic Studies*, 88(6), 2945–2969.

Gentet-Raskopf, C. (2022): "To treat or prevent pollution?," Working Paper.

Gillingham, K., and K. Palmer (2014): "Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence," *Review of Environmental Economics and Policy*, 8(1), 18–38.

Golosov, M., J. Hassler, P. Krusell, and A. Tsyvinski (2014): "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica*, 82(1), 41–88.

Hartzmark, S. M., and K. Shue (2023): "Counterproductive Sustainable Investing: The Impact Elasticity of Brown and Green Firms," Working Paper.

Hassler, J., P. Krusell, and A. A. Smith (2016): "Environmental Macroeconomics," in *Handbook of Macroeconomics, Vol. 2*, ed. by J. B. Taylor, and H. Uhlig, pp. 1893–2008. Chapter 24.

Heinkel, R., A. Kraus, and J. Zechner (2001): "The Effect of Green Investment on Corporate Behavior," *Journal of Financial and Quantitative Analysis*, 36(4), 431–449.

Iovino, L., T. Martin, and J. Sauvagnat (2022): "Corporate Taxation and Carbon Emissions," Working Paper.

Jorgenson, D. W. (1963): "Capital Theory and Investment Behavior," *American Economic Review (Papers and Proceedings)*, 53, 247–259.

Kalouptsidi, M. (2014): "Time to Build and Fluctuations in Bulk Shipping," *American Economic Review*, 104(2), 564–608.

Känzig, D. (2022): "The Unequal Economic Consequences of Carbon Pricing," Working Paper.

Kiyotaki, N., and J. Moore (1997): "Credit Cycles," *Journal of Political Economy*, 105(2), 211–248.

Kuhn, M., and L. Schlattmann (2023): "Distributional Consequences of Climate Policies," CEPR Discussion Paper 18893.

Lanteri, A. (2018): "The Market for Used Capital: Endogenous Irreversibility and Reallocation over the Business Cycle," *American Economic Review*, 108(9), 2383–2419.

Lanteri, A., and A. A. Rampini (2023): "Constrained-Efficient Capital Reallocation," *American Economic Review*, 113(2), 354–395.

Ma, S., J. Murfin, and R. Pratt (2022): "Young Firms, Old Capital," *Journal of Financial Economics*, 146(1), 331–356.

Martinsson, G., L. Sajtos, P. Strömberg, and C. Thomann (2023): "The Effect of Carbon Pricing on Firm Emissions: Evidence from the Swedish CO_2 Tax," Working Paper.

Oehmke, M., and M. Opp (2024): "A Theory of Socially Responsible Investment," Working Paper.

Rampini, A. A. (2019): "Financing Durable Assets," *American Economic Review*, 109(2), 664–701.

Rampini, A. A., and S. Viswanathan (2010): "Collateral, Risk Management, and the Distribution of Debt Capacity," *Journal of Finance*, 65(6), 2293–2322.

——— (2013): "Collateral and Capital Structure," *Journal of Financial Economics*, 109(2), 466–492.

APPENDIX

A Additional Model Analyses

A.1 Energy Cost Paid in Arrears

In this section, we assume that firms pay for energy at the same date 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 present and next period are

$$\begin{aligned} w + b &= d + \sum_{j \in \{C,D\}} q_j k_j, && \text{(A1)} \\ f(x) + \sum_{j \in \{C,D\}} q_j k_j (1 - \delta) &= w' + Rb + \sum_{j \in \{C,D\}} p_e e_j, && \text{(A2)} \end{aligned}$$

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 be expressed as follows:

$$u_j^e + \frac{\lambda'}{1 + (1 - \rho)\phi_d'} \wp_j \geq R^{-1} f_x(x). \tag{A3}$$

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

$$\begin{aligned} q_C - q_D &< \frac{(\gamma_D - \gamma_C) p_e}{r + \delta}, && \text{(A4)} \\ q_C - q_D &> 0. && \text{(A5)} \end{aligned}$$

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

A.2 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:

$$u_j^e + \gamma_j \chi + \frac{\lambda}{\mu'}(\wp_j^e + \gamma_j \chi) - \frac{\mu - 1}{\mu'}\gamma_j \chi \geq R^{-1} f_x(x) \tag{A6}$$

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 (A6) 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 (A6) 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

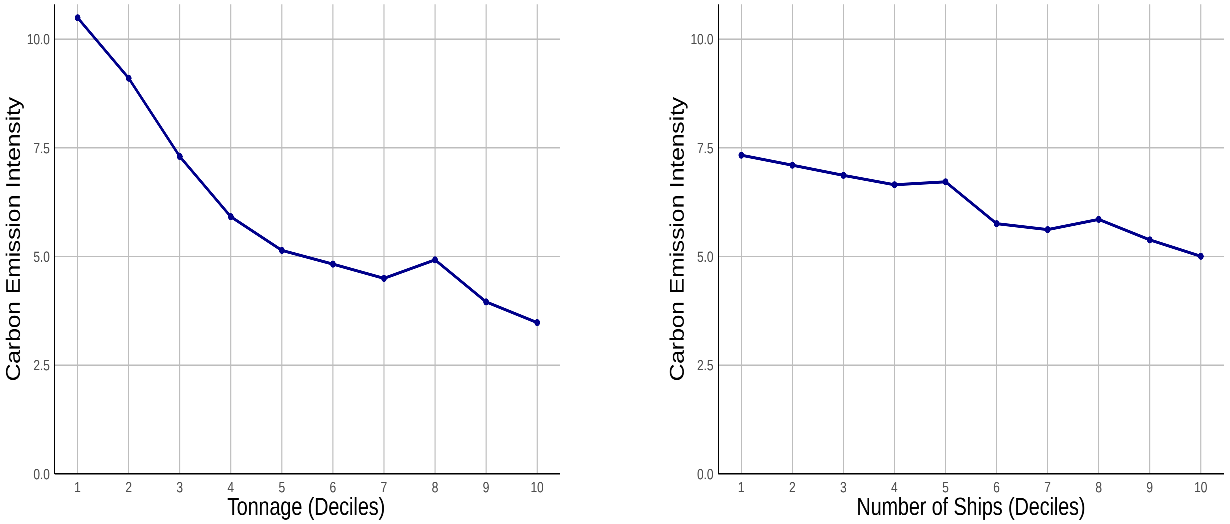
$$\frac{\lambda}{\mu'}\wp_C^e - \frac{\mu' - 1}{\mu'}\gamma_C \chi > \frac{\lambda}{\mu'}\wp_D^e - \frac{\mu' - 1}{\mu'}\gamma_D \chi.$$

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. Operators and owners do not coincide in the case of leased vessels. Figures B4, B5, and B6 document the stylized facts when we focus on a single type of fleet, namely fleets of bulkers (bulk carriers). 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.

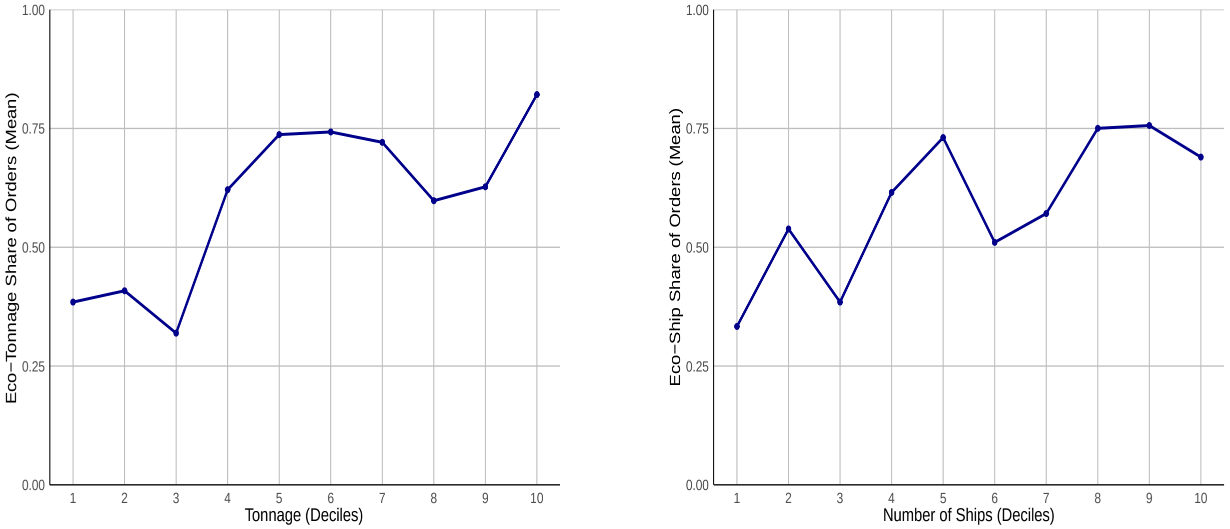
Figure B1: Fleet Size and Carbon Emission Intensity - Fleet Defined by Operator



(a) Tonnage (b) Number of Ships

Notes: The figure displays the relationship between fleet size and carbon emission intensity. A fleet is defined by its operator, instead of its owner as in Figure 1. 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. The analysis focuses on bulkers, container ships, and oil tankers and on fleets with at least five ships.

Figure B2: Fleet Size and Eco Ship Orders - Fleet Defined by Operator

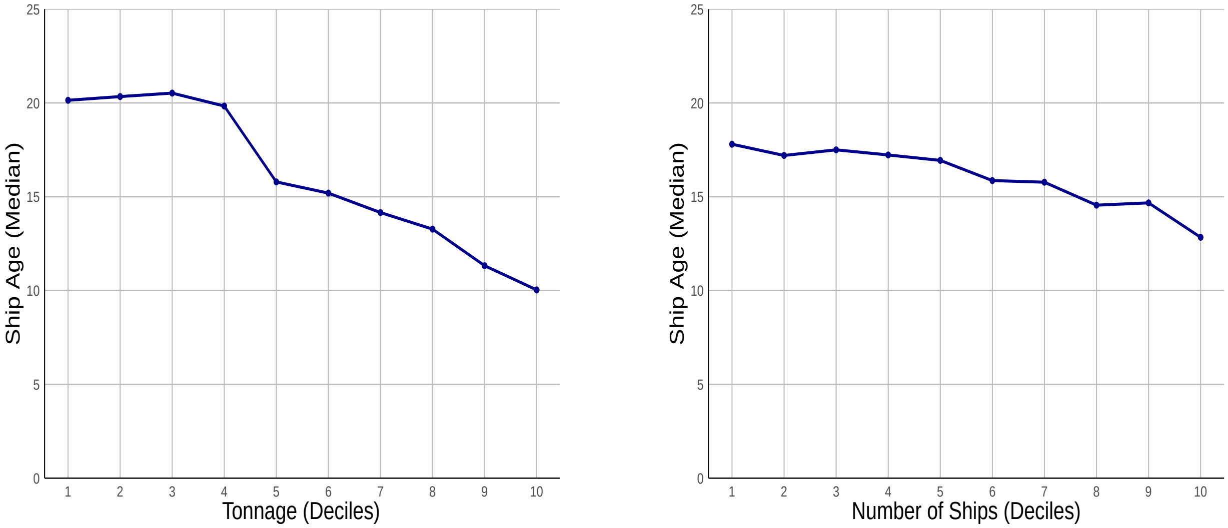


(a) Fleet Tonnage

(b) Number of Ships

Notes: The figure displays the relationship between fleet size and the share of new investment accounted for by Eco (low-emission) Ships. A fleet is defined by its operator, instead of its owner as in Figure 2. 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. The analysis focuses on fleets with at least five ships.

Figure B3: Fleet Size and Capital Age - Fleet Defined by Operator

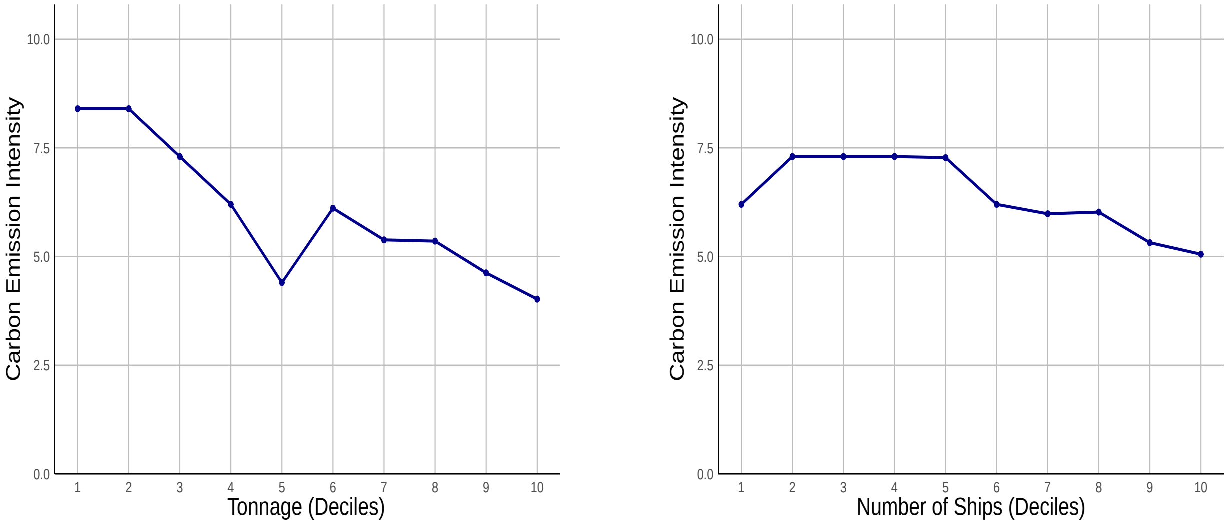


(a) Fleet Tonnage

(b) Number of Ships

Notes: The figure displays the relationship between fleet size and capital age. A fleet is defined by its operator, instead of its owner as in Figure 3. 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. The analysis focuses on fleets with at least five ships.

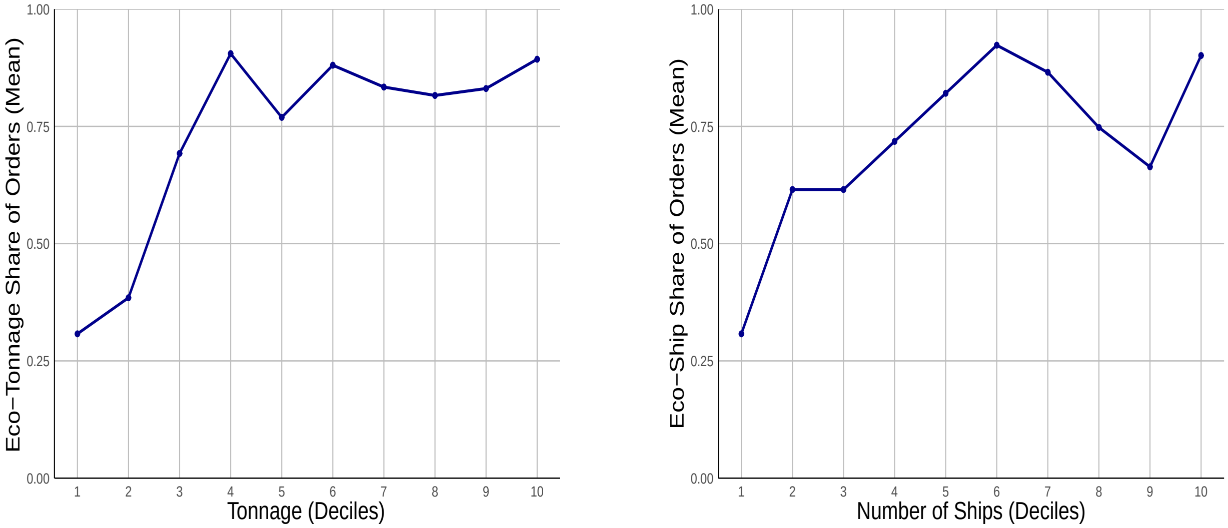
Figure B4: Fleet Size and Carbon Emission Intensity - Bulker Fleets



(a) Tonnage (b) Number of Ships

Notes: The figure displays the relationship between fleet size and carbon emission intensity, focusing on bulker fleets. 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.

Figure B5: Fleet Size and Eco Ship Orders - Bulker Fleets

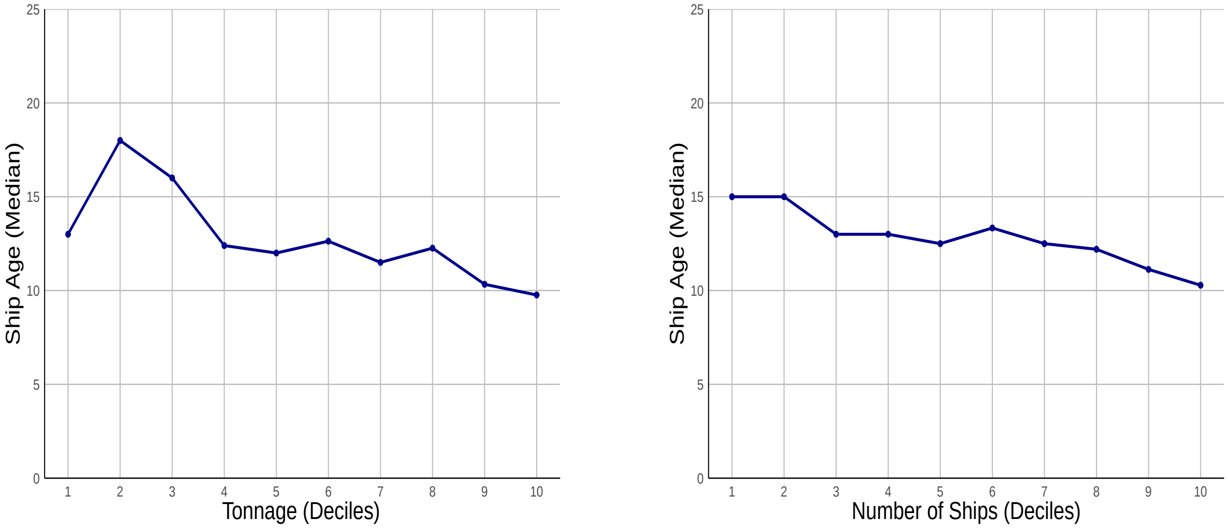


(a) Fleet Tonnage

(b) Number of Ships

Notes: The figure displays the relationship between fleet size and the share of new investment accounted for by Eco (low-emission) Ships, focusing on bulker fleets. 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.

Figure B6: Fleet Size and Capital Age - Bulker Fleets



(a) Fleet Tonnage

(b) Number of Ships

Notes: The figure displays the relationship between fleet size and capital age, focusing on bulker fleets. 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.

Table B1: Fleet Size and Emission Intensity

	Dependent variable:			
	Emission Intensity		Emission Intensity	
	(1)	(2)	(3)	(4)
log(Tonnage)	-1.282^{***}	-0.811^{***}		
	(0.037)	(0.041)		
log(N Ships)			-0.998^{***}	-0.280^{***}
			(0.110)	(0.051)
Constant	22.136^{***}	15.565^{***}	8.922^{***}	5.744^{***}
	(0.458)	(0.606)	(0.267)	(0.244)
Fixed effects	No	Yes	No	Yes
Observations	1,045	1,045	1,045	1,045
R^2	0.541	0.807	0.074	0.828
Adjusted R^2	0.540	0.804	0.073	0.825

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 columns refers to a regression in which we measure fleet size as total tonnage and do not include fixed effects for fleet-type and typical ship size. 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 five 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)	0.124^{***}	0.054^{***}		
	(0.006)	(0.008)		
log(N Ships)			0.135^{***}	0.053^{***}
			(0.020)	(0.014)
Constant	-1.103^{***}	0.060	-0.048	0.618^{***}
	(0.078)	(0.111)	(0.062)	(0.053)
Fixed effects	No	Yes	No	Yes
Observations	575	575	575	575
R^2	0.390	0.617	0.073	0.598
Adjusted R^2	0.389	0.604	0.071	0.584

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 columns 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 five 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)	0.058^{***}	0.050^{***}		
	(0.001)	(0.002)		
log(N Ships)			0.086^{***}	0.062^{***}
			(0.005)	(0.004)
Constant	-0.483^{***}	-0.329^{***}	-0.099^{***}	0.137^{***}
	(0.015)	(0.028)	(0.011)	(0.012)
Fixed effects	No	Yes	No	Yes
Observations	4,367	4,367	4,367	4,367
R^2	0.278	0.322	0.076	0.292
Adjusted R^2	0.278	0.319	0.076	0.289

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 columns 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 five ships.

Table B4: Fleet Size and Capital Age

	Dependent variable:			
	Average Ship Age		Average Ship Age	
	(1)	(2)	(3)	(4)
log(Tonnage)	-2.040^{***}	-1.718^{***}		
	(0.070)	(0.107)		
log(N Ships)			-2.698^{***}	-1.689^{***}
			(0.242)	(0.227)
Constant	39.558^{***}	33.777^{***}	25.841^{***}	16.359^{***}
	(0.744)	(1.420)	(0.589)	(0.682)
Fixed effects	No	Yes	No	Yes
Observations	4,367	4,367	4,367	4,367
R^2	0.162	0.210	0.028	0.193
Adjusted R^2	0.162	0.206	0.027	0.190

Notes: The table reports the estimated coefficients of regressions of the average ship age on measures of fleet size. The first columns 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 five ships.

C Additional Quantitative Results

C.1 Transitional Dynamics: Equilibrium Conditions

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

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

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:

$$\begin{aligned} \left(q_{jN} + \gamma_{j,t} p_e\right) \mu_t &= R^{-1} \left(f_{x,t} g_{jN,t} + q_{jO,t+1}\right) + R^{-1} \theta q_{jO,t+1} \lambda_t \\ u^e_{O,t} \mu_t &= R^{-1} f_{x,t} g_{O,t} \\ \mu_t &= 1 + \phi_{d,t} & \text{(C1)} \\ \mu_t &= 1 + \lambda_t. & \text{(C2)} \end{aligned}$$

The price of type-j old capital at time t, $q_{jO,t}$, satisfies $u^e_{O,t} = q_{jO,t} + \gamma_{j,t-1} p_e$, $j \in \{C, D\}$. The market-clearing conditions for old capital is:

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

C.2 Transitional 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.

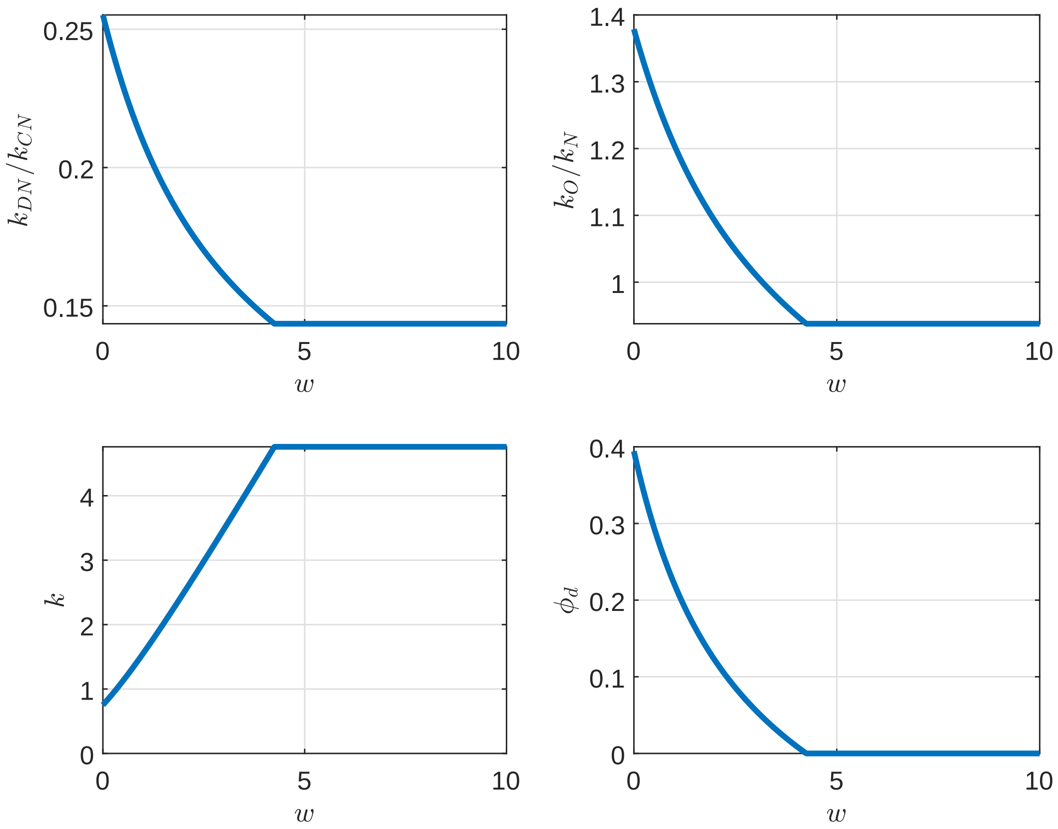


Figure C1: Patterns of Technology Adoption During Transition (γ_C)

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transitional 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 $\phi_{d,t}$.

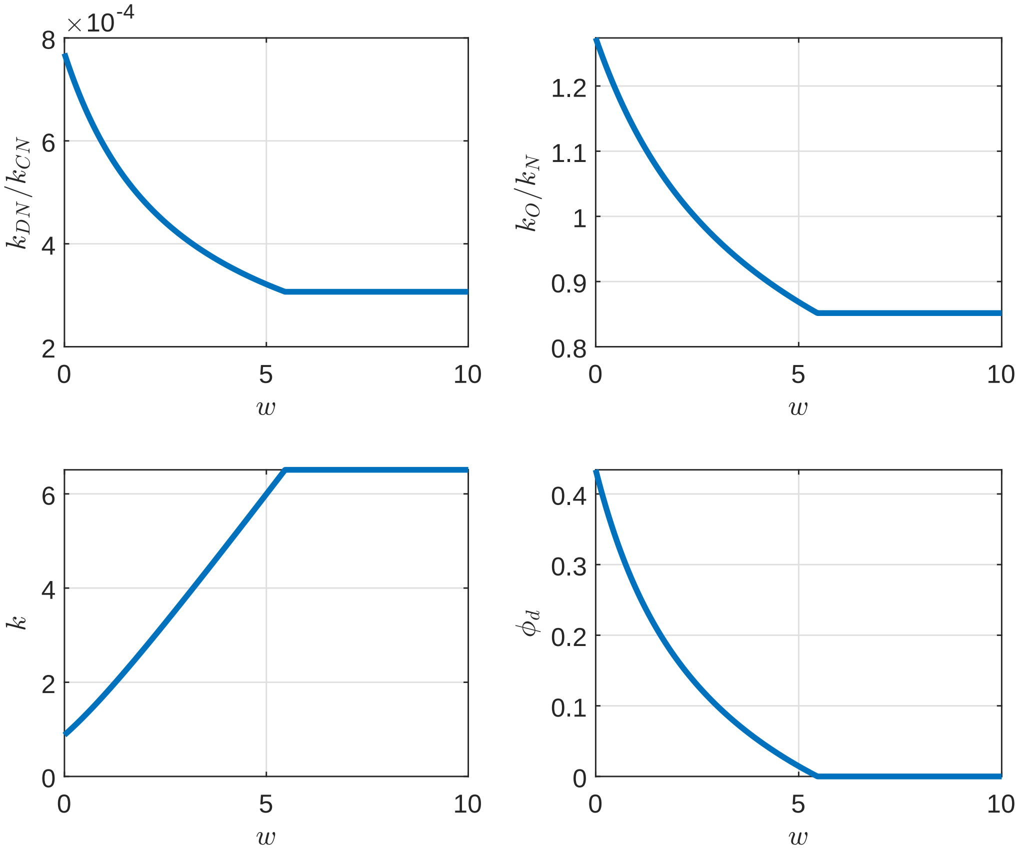


Figure C2: Patterns of Technology Adoption During Transition (q_{CN})

Notes: The figure displays the patterns of investment in an intermediate period ($t = 3$) of the transitional 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 $\phi_{d,t}$.