

Financing the Adoption of Clean Technology*

Andrea Lanteri[§]

Adriano A. Rampini[¶]

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Abstract

We analyze the adoption of clean technology by heterogeneous firms subject to financing constraints. 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. This equilibrium pattern of technology adoption implies that environmental policy has important distributional consequences.

Keywords: Clean Technology; Financial Frictions; Capital Reallocation.

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[§]Duke University; andrea.lanteri@duke.edu

[¶]Duke University; rampini@duke.edu

1 Introduction

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

What are the equilibrium patterns of clean-technology adoption when firms are heterogeneous in their financial resources? This paper addresses this question by providing empirical evidence on investment in energy-efficient capital and 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.

We begin our analysis by leveraging a rich dataset on commercial ships to provide empirical evidence 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. 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.

Our main contribution is to develop a new theory in which the presence of financial constraints accounts for all of these empirical findings. The 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 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.

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. 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. Indeed, 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.

Our framework provides a natural laboratory to analyze the effects of environmental policy when the planner takes into account heterogeneity and thus the equilibrium distributional effects of policy incentives for clean-technology adoption, such as taxes on carbon emissions or subsidies for the scrapping of polluting capital.

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 note that 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. We abstract from these considerations to focus squarely on the implications of financing constraints for the distributional patterns in clean technology adoption.

The rest of the paper proceeds as follows. Section 2 describes the most relevant related literature. Section 3 discusses the empirical evidence. Section 4 considers a model with two types of capital, in which clean capital is more energy efficient than dirty capital, but more expensive. Section 5 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 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 environmental macroeconomics. The paper is also related to the literature on heterogeneity in macroeconomics, especially the recent work on the heterogeneous effects of policies, the literature on innovation, technology adoption, and growth, and the macro-finance literature, but for brevity we will not discuss these relations further here.

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

¹Lanteri (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.

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. Hassler, Krusell, and Smith (2016) emphasizes 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. Iovino, Martin, and Sauvagnat (2022) focuses 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.²

3 Stylized Facts

We begin our analysis by leveraging rich micro data on commercial shipping to provide evidence on the distribution of energy efficiency across heterogeneous firms.

²Relatedly, 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).

3.1 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 2022.³ We complement the dataset with information on the average energy efficiency of different types of ships.

3.2 Fact 1: Larger Firms Operate Cleaner Capital

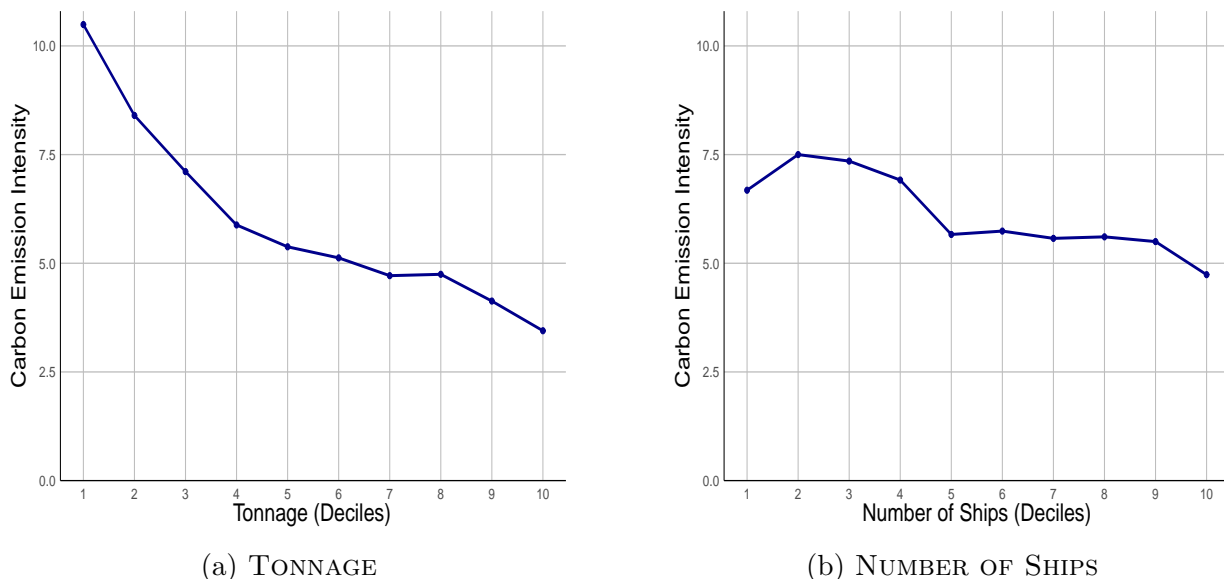
To perform our empirical analysis, we first aggregate information about ships at the owner level to measure our variables of interest at the firm (fleet) level. In this analysis, we focus on commercial shipping fleets with at least five ships, to reduce the noise due to the fact that most fleets are 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 owners. Moreover, the findings are robust to alternative cutoffs for firm size.

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

³Kalouptsidei (2014) leverages this dataset to estimate a model of entry and exit in bulk shipping.

Figure 1: Fleet Size and Carbon Emission Intensity



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

controlling for fixed effects for fleet type and typical vessel size and confirm this significant relationship (Table A1). Next, we proceed to analyze the drivers of the negative correlation between fleet size and emission intensity.

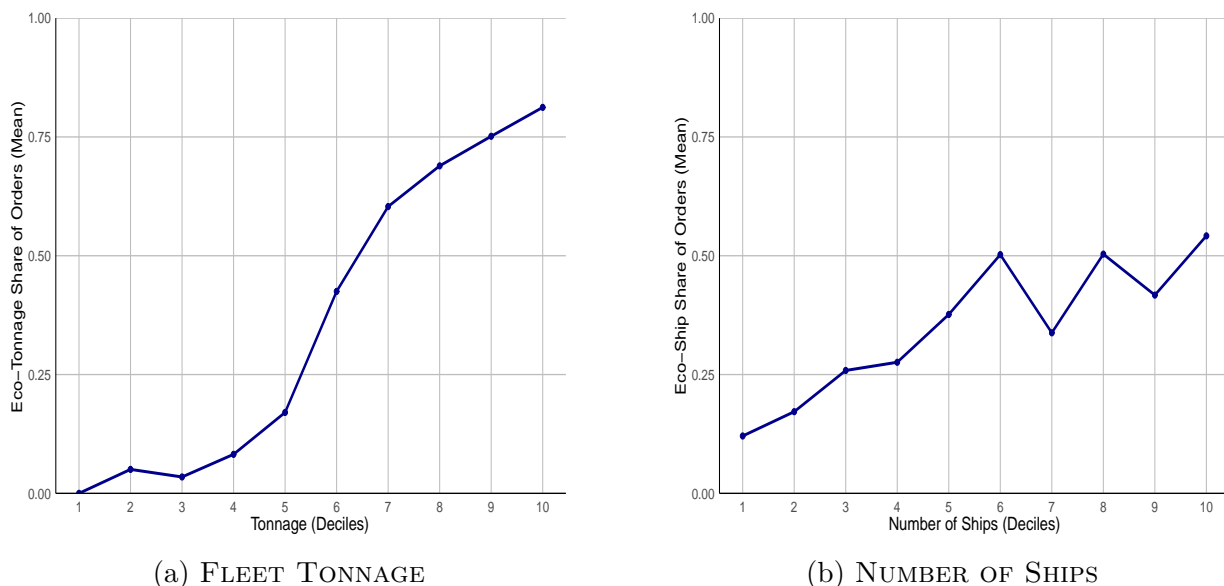
3.3 Fact 1(a): Larger Firms Invest in Cleaner New Capital

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

Figure 2: Fleet Size and Eco Ship Orders



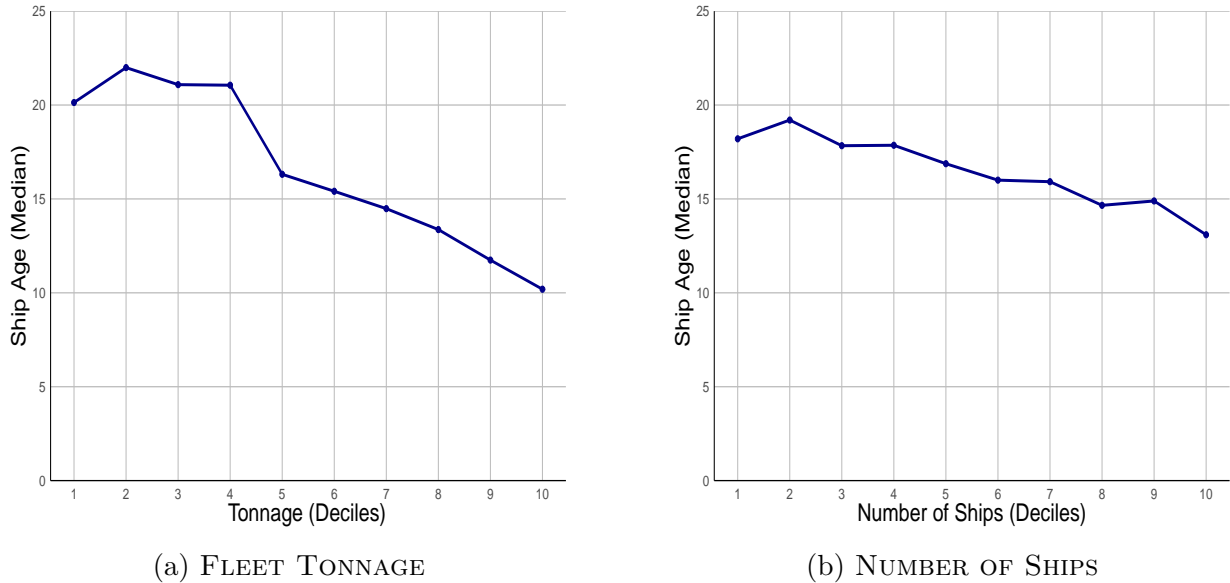
Notes: The figure displays the relationship between fleet size and the share of new investment accounted for by Eco (low-emission) Ships. Specifically, the left panel reports the share of new-ship orders accounted for by Eco Ships on the y-axis for all deciles of fleet size, measured by total tonnage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

fixed effects for ship types and confirm this significant relationship (Table A2). 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 A3). 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%.

3.4 Fact 1(b): 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.

Figure 3: Fleet Size and Capital Age



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

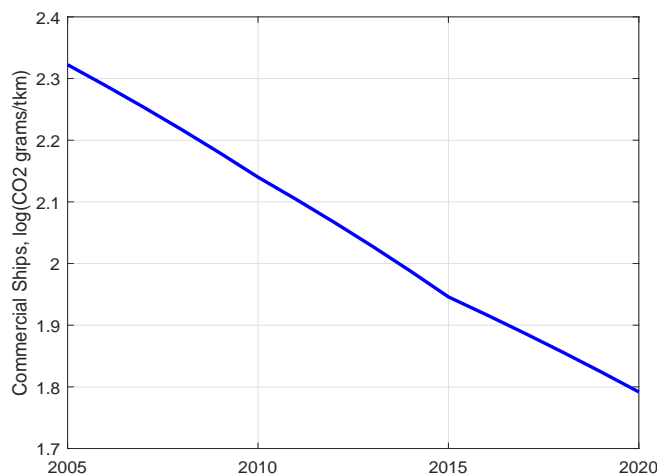
To buttress this finding, we regress average ship age on our measures of fleet size, controlling for fixed effects for ship types. Table A4 shows that, across several specifications, there is a significant negative relationship between fleet size and average ship age. Increasing fleet size by one standard deviation relative to the average, average capital age goes from 18 to 14 years (and from 12 to 10 when we restrict attention to bulkers).

3.5 Fact 1(c): 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 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.

4 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.

4.1 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 $f(0) = 0$, $\lim_{x \rightarrow 0} f_x(x) = +\infty$, and $\lim_{x \rightarrow \infty} f_x(x) = 0$.

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 $\min\{\frac{e_j}{\gamma_j}, k_j\}$, where e_j is energy used for type- j capital. Assume that clean capital is more energy efficient than dirty capital.⁴

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 $x \equiv \sum_{j \in \mathcal{J}} \min\{\frac{e_j}{\gamma_j}, k_j\}$. 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.

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. The price of energy is $p_e > 0$.⁵

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

⁴For simplicity we abstract from embodied energy, that is, energy needed to produce each type of capital.

⁵The 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.

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.⁶

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.⁷ In a stationary equilibrium, the marginal utility of consumption of the representative agent is constant and hence we treat firms as risk-neutral with the rate of time preference $\beta \in (0, 1)$, subject to the financial constraints on equity and debt finance described above.

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

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

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

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

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

and the collateral constraint

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

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.⁸ At an optimum, firms match

⁶We could alternatively assume that dividends have to be non-negative without affecting our conclusions.

⁷Rampini and Viswanathan (2010, 2013) derive such collateral constraints in an environment with limited enforcement without exclusion.

⁸The constraint set is convex, and the value function that solves the Bellman equation is unique, strictly increasing, and concave.

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 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

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

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

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

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

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

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.

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

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.

4.2 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, $u_j^e < u_i^e$, then the cum-energy down payment of type j capital must be larger than that of type i capital, $\wp_j^e > \wp_i^e$, 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 $u_j^e = R^{-1}q_j(r + \delta) + \gamma_j p_e < R^{-1}q_i(r + \delta) + \gamma_i p_e = u_i^e$, then, as argued above, $\wp_j^e = R^{-1}q_j(r + \delta) + \gamma_j p_e + R^{-1}(1 - \theta)q_j(1 - \delta) > R^{-1}q_i(r + \delta) + \gamma_i p_e + R^{-1}(1 - \theta)q_i(1 - \delta) = \wp_i^e$; 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: $u_C^e < u_D^e$.*

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:

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

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 $\wp_C^e > \wp_D^e$ implies the following lower bound on the difference in the price of clean and dirty capital:

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

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:

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

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 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. To see this, note that as w goes to 0, so must x , and therefore equation (5) implies that $\mu'/\mu \rightarrow 0$. Using the first-order condition for debt (7), $\lambda'/\mu' \rightarrow +\infty$, 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.

⁹Notice 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.

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

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 $R^D \equiv \frac{R(1+\phi_d)}{1+(1-\rho)\phi'_d}$. Using the indifference condition between clean and dirty capital, we have $R^D = R(1 + \frac{u_D^e - u_C^e}{\wp_C^e - \wp_D^e}) > R$ and we can express the investment Euler equations as follows:

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

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.*

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

To consider the effect of legal enforcement we take all the technological parameters as given, and make the dependence of the cum-energy down payment on legal enforcement explicit by writing $\wp_j^e(\theta)$. Assume that there is an economy with legal enforcement $\theta_0 \in [0, 1)$ for which $u_C^e < u_D^e$ and $\wp_C^e(\theta_0) > \wp_D^e(\theta_0)$ as we have assumed throughout. Then there exists a $\underline{\theta} \in (\theta_0, 1)$ for $\underline{\theta}$ suitably defined, such that for sufficiently strong legal enforcement, that is, for $\theta \geq \underline{\theta}$, we have $\wp_C^e(\theta) < \wp_D^e(\theta)$, and thus clean capital dominates dirty capital. This means that there may be types of dirty capital that are dominated in strong legal

enforcement economies, but nevertheless used in weak legal enforcement economies. Firms in such weak legal enforcement economies may choose this type of dirty capital, because of its lower financing need. In addition, when neither type of capital is dominated, the threshold level of net worth at which firms switch from dirty to clean capital decreases with legal enforcement.¹¹ 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, $\gamma_C < \bar{\gamma}_C$, for $\bar{\gamma}_C > 0$ 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.

5 Clean Technology and Capital Age

In this section, we introduce a choice of capital age, on top of the choice between clean and dirty capital. This allows us to account for the empirical evidence that capital age is decreasing in firm size, as well as the patterns of investment in clean and dirty capital discussed in the previous section.

¹¹To see this, note that the discount rate at which firms are indifferent $R^D(\theta) = R(1 + (u_D^e - u_C^e) / (\varphi_C^e(\theta) - \varphi_D^e(\theta))) = R(1 + (u_D^e - u_C^e) / (u_D^e - u_C^e + R^{-1}(1 - \theta)(q_C - q_D)(1 - \delta)))$ is increasing in θ .

5.1 Model with Clean vs. Dirty Technology and Capital Age

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

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

$$x = g(x_N, x_O) \equiv \left(\sigma_N^{\frac{1}{\epsilon}} x_N^{\frac{\epsilon-1}{\epsilon}} + \sigma_O^{\frac{1}{\epsilon}} x_O^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}, \quad (14)$$

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

$$\sum_{j \in \{C, D\}} \int k_{jN} d\pi(w) = \sum_{j \in \{C, D\}} \int k_{jO} d\pi(w), \quad (15)$$

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

$$v(w) \equiv \max_{\{d, b, k_{ja}, e_{ja}\} \in \mathbb{R}^2 \times \mathbb{R}_+^8} d - \phi(-d) + \beta \{ \rho w' + (1 - \rho) v(w') \} \quad (16)$$

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

$$w + b = d + \sum_{(j,a) \in \mathcal{J} \times \mathcal{A}} q_{ja} k_{ja} + \sum_{(j,a) \in \mathcal{J} \times \mathcal{A}} p_e e_{ja}, \quad (17)$$

$$f(x) + \sum_{j \in \mathcal{J}} q_{jO} k_{jN} = w' + Rb, \quad (18)$$

and the collateral constraint

$$\theta \sum_{j \in \mathcal{J}} q_{jO} k_{jN} \geq Rb, \quad (19)$$

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.

5.2 Determinants of Clean Technology and Vintage Adoption

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

Note that we have $\varphi_{jN}^e > u_{jN}^e$ and $\varphi_{jO}^e = u_{jO}^e$, 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): $u_{CO}^e = u_{DO}^e = \varphi_{CO}^e = \varphi_{DO}^e$. We will thus denote this cum-energy user cost by u_O^e , which will be determined in equilibrium. This will facilitate the analysis and u_O^e 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 $u_{CN}^e < u_{DN}^e$ and $\varphi_{CN}^e > \varphi_{DN}^e$. These inequalities imply that

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

As before, the upper bound on the difference in price is given by the present value of the energy savings associated with clean capital, whereas the lower bound is given by the present value of the pledgeable fraction of these savings. As is evident, limited collateralizability, that is, $\theta < 1$, is 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:

$$u_{jN}^e + \frac{\lambda'}{1 + (1 - \rho)\phi'_d} \wp_{jN}^e \geq R^{-1} f_x(x) \frac{\partial x}{\partial x_N} \quad (20)$$

$$u_O^e \left(1 + \frac{\lambda'}{1 + (1 - \rho)\phi'_d} \right) = R^{-1} f_x(x) \frac{\partial x}{\partial x_O}. \quad (21)$$

Inequality (20) 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 (20) holds with equality. We can divide both sides of this equation by the corresponding sides of (21) and use the definition of x to obtain the optimal ratio between new and old capital:

$$\frac{x_N}{x_O} = \frac{\sigma_N}{\sigma_O} \left(\frac{u_{jN}^e}{u_O^e} \right)^{-\epsilon} \left(\frac{1 + \frac{\lambda'}{1 + (1 - \rho)\phi'_d} \frac{\wp_{jN}^e}{u_{jN}^e}}{1 + \frac{\lambda'}{1 + (1 - \rho)\phi'_d}} \right)^{-\epsilon}. \quad (22)$$

For financially unconstrained firms ($\lambda' = 0$), this ratio equals $\frac{\sigma_N}{\sigma_O} \left(\frac{u_{jN}^e}{u_O^e} \right)^{-\epsilon}$. 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 $\frac{\wp_{jN}^e}{u_{jN}^e} > 1$, 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.

5.3 Higher Energy Efficiency of New Capital

The empirical evidence of Section 3 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 $u_{jO}^e = \wp_{jO}^e = q_{jO} + \kappa \gamma_j p_e$. Clean and dirty old capital must have the same user cost to be both used in equilibrium, so $u_O^e \equiv u_{CO}^e = u_{DO}^e$. 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 (20), (21), and (22). 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.

6 Transition to Cleaner Technology

In this section we calibrate our model to analyze its equilibrium transitional dynamics as technological progress leads to improvements in energy efficiency. This analysis shows that our analytical insights on the cross-sectional patterns of technology adoption in stationary

equilibrium are also relevant to understand technology adoption as the economy experiences 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:

$$x_N \equiv \left(\sigma_{CN}^{\frac{1}{\eta}} (k_{CN})^{\frac{\eta-1}{\eta}} + (1 - \sigma_{CN})^{\frac{1}{\eta}} (k_{DN})^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}}, \quad (23)$$

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 (14) 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 3.

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. The distribution of net worth is thus exogenous and we assume it to be uniform in an interval $[w_{min}, w_{max}]$. We parameterize the convex cost of equity issuance as a power function: $\phi(-d) \equiv \phi_0(-d)^{\phi_1}$ for $d < 0$, with $\phi_0 > 0$ and $\phi_1 > 1$. We calibrate these parameters to obtain a distribution of marginal cost of equity issuance similar to the one in Lanteri and Rampini (2023). We assume that half of the resale value of capital is pledgeable as collateral.

6.2 Effect 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 compute the aggregate equilibrium dynamics and analyze the heterogeneous patterns of technology adoption during this transition. Appendix B reports the model equilibrium conditions along the transitional dynamics.

Table 1: Parameter Values

| | | Parameter | Value | |
|------------------------|--------------------------------------|---------------------|--------------------|-----|
| Preferences | Discount factor | β | 0.96 ¹⁰ | |
| Life cycle | Death probability | ρ | 1 | |
| Technology | Returns to scale | α | 0.6 | |
| | TFP | A | 1.91 | |
| | Elasticity of subst. Clean/Dirty New | η | 50 | |
| | Clean New share | σ_{CN} | 0.75 | |
| | Elasticity of subst. New/Old | ϵ | 5 | |
| | New share | σ_N | 0.75 | |
| | Price Clean New | q_{CN} | 1.1 | |
| | Price Dirty New | q_{DN} | 1 | |
| | Energy input Clean | γ_C | 0.5 | |
| | Energy input Dirty | γ_D | 0.75 | |
| | Energy price | p_e | 0.2 | |
| | Financial constraints | Collateralizability | θ | 0.5 |
| | | Equity cost | ϕ_0 | 0.3 |
| Equity cost | | ϕ_1 | 2 | |
| Net worth distribution | | w_{min} | 0.1 | |
| Net worth distribution | | w_{max} | 1.1 | |

The top-left panel of Figure 5 displays the exogenous path of the technological parameters $\gamma_{C,t}$ and $\gamma_{D,t}$. Starting from the initial stationary equilibrium, both parameters decline at a common constant rate for 50 years (5 periods in the model), after which the economy reaches a new stationary equilibrium. In each period during the 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 top-right panel displays the endogenous dynamics of the cum-energy user cost of old capital $u_{O,t}^e$, which we compute by imposing the market-clearing condition for old capital at each period. As the figure shows, the exogenous decline in the required energy inputs induces a steady decline in the cum-energy user cost of old capital. The bottom panels show that the economy experiences growth in aggregate output (bottom left) and at the same time reduces its energy intensity (bottom right).

We use the simulated transition path to investigate firms' heterogeneous patterns of technology adoption. Figure 6 shows that, consistent with the analytical results of the

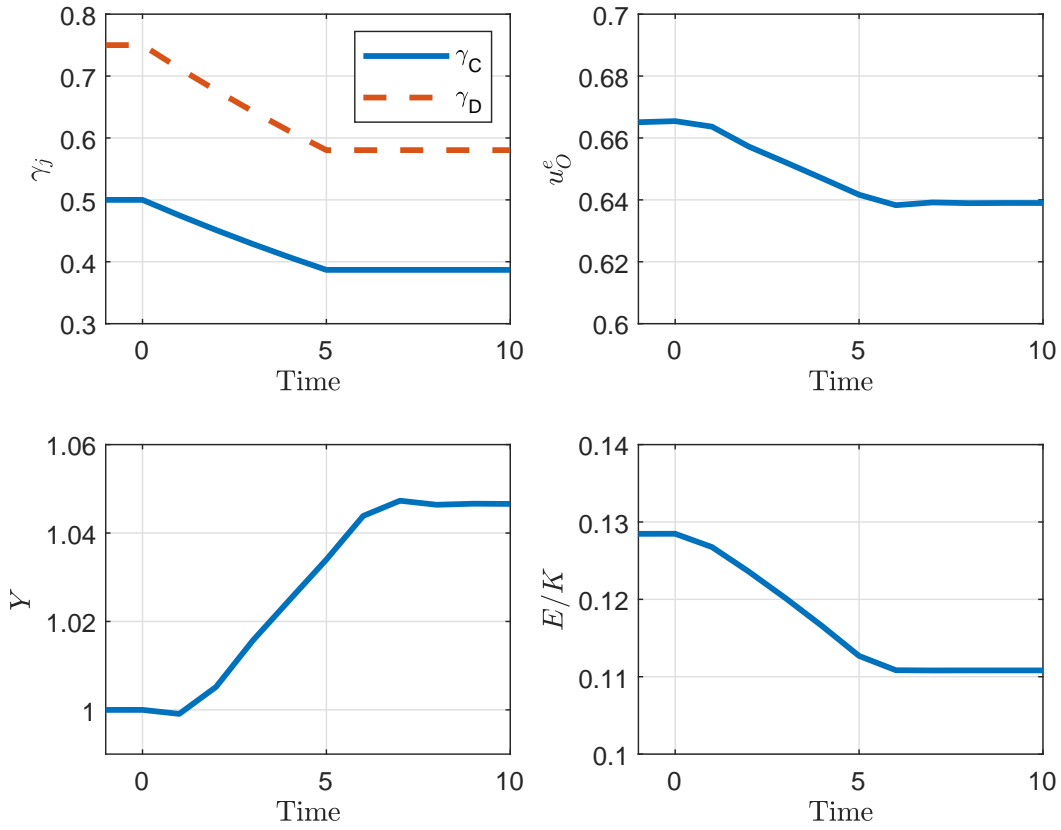


Figure 5: Improvement in Energy Efficiency of Clean and Dirty Capital

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 equilibrium dynamics of the cum-energy user cost of old capital $u_{O,t}^e$; the bottom-left panel displays the path of aggregate output; the bottom-right panel displays the path of aggregate energy intensity, defined as aggregate energy consumption divided by the aggregate capital stock.

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

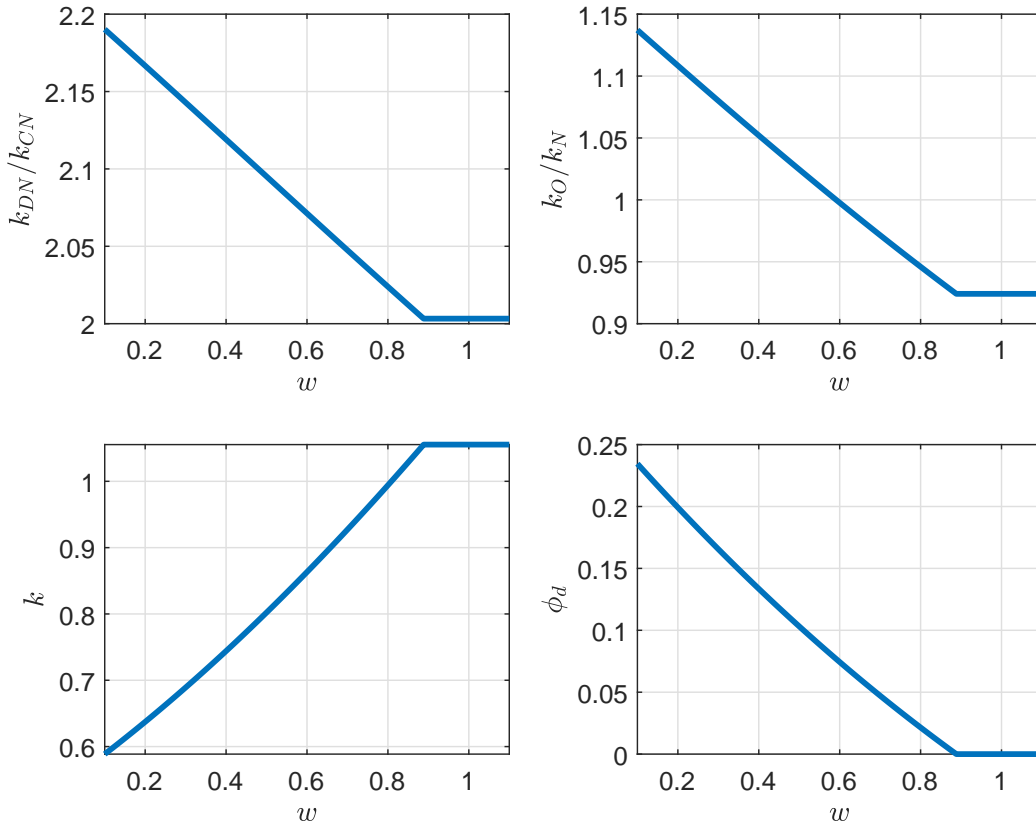


Figure 6: Patterns of Technology Adoption During Transition (γ_C and γ_D)

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 $\phi_{d,t}$.

toward clean capital, aggregate output increases, while the energy intensity of the economy decreases.

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. 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. Instead, when

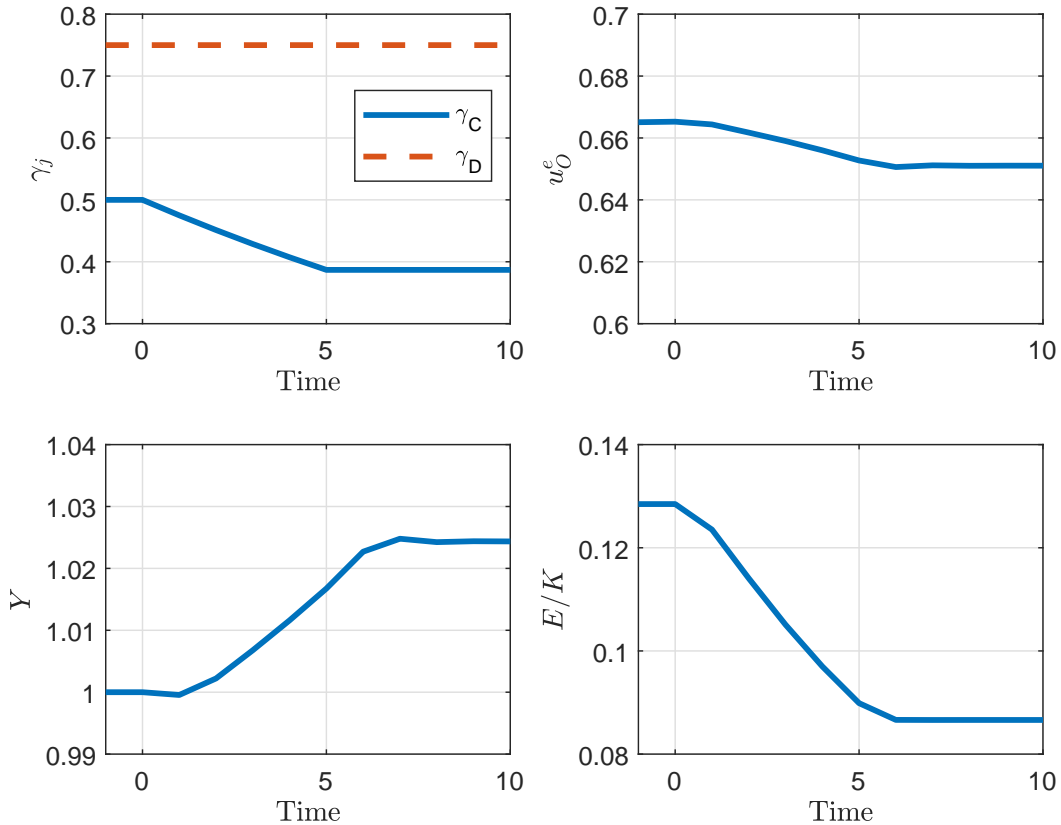


Figure 7: Improvement in Energy Efficiency of Clean Capital

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 γ_D over time; the top-right panel displays the equilibrium dynamics of the cum-energy user cost of old capital $u_{O,t}^e$; the bottom-left panel displays the path of aggregate output; the bottom-right panel displays the path of aggregate energy intensity, defined as aggregate energy consumption divided by the aggregate capital stock.

only $\gamma_{C,t}$ decreases, the difference in energy requirement ($\gamma_D - \gamma_{C,t}$) increases over time, inducing substitution toward clean capital, which speeds up the aggregate improvements in energy efficiency.

Despite this difference at the aggregate level, Figure 8 shows that the cross-sectional patterns of technology adoption are similar across the two experiments. During the transition, the early adopters of cleaner technology are financially unconstrained firms. In contrast, firms with low net worth invest in a larger share of dirty and old capital.

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

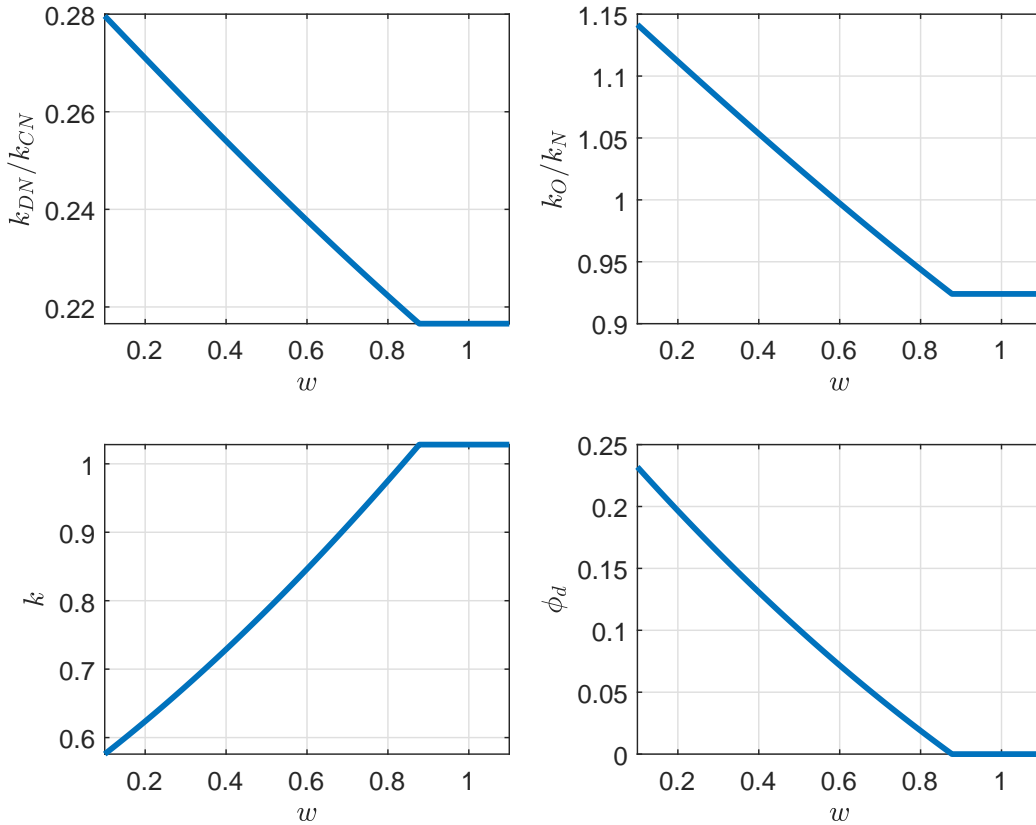


Figure 8: Patterns of Technology Adoption During Transition (γ_C)

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 $\phi_{d,t}$.

ing clean capital. Beyond the context of clean-technology adoption in commercial shipping, this experiment 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 9. 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. Furthermore, Figure 10 confirms that net worth plays an important role for the adoption of

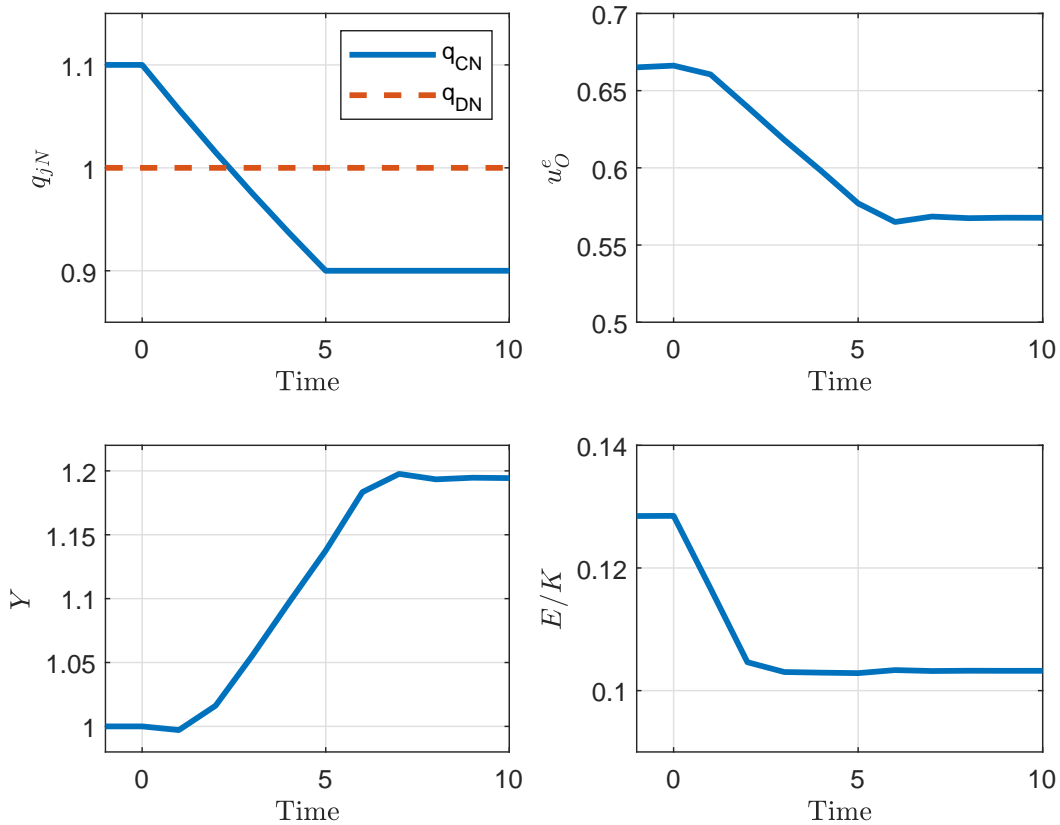


Figure 9: Reduction in Cost of Clean Capital

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 equilibrium dynamics of the cum-energy user cost of old capital $u_{O,t}^e$; the bottom-left panel displays the path of aggregate output; the bottom-right panel displays the path of aggregate energy intensity, defined as aggregate energy consumption divided by the aggregate capital stock.

clean and new capital during the transition, because the shares of dirty and old capital remain decreasing in net worth, as in the previous experiments.

Overall, these numerical results confirm that our main analytical insights on the patterns of technology adoption across heterogeneous firms are highly relevant to understand the global transition to cleaner technology, as capital becomes more energy efficient and clean technologies become more affordable.

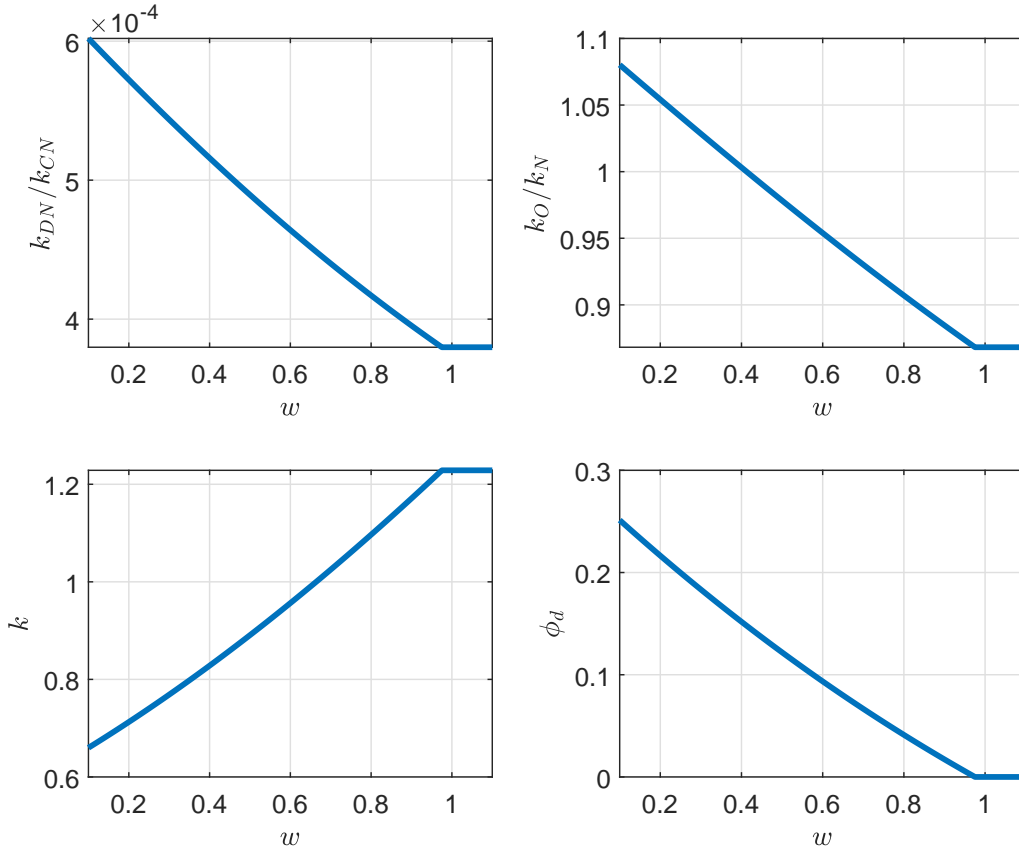


Figure 10: Patterns of Technology Adoption During Transition (q_{CN})

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 $\phi_{d,t}$.

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 evidence from 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.

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APPENDIX

A Additional Empirical Evidence

Table A1: Fleet Size and Emission Intensity

| | <i>Dependent variable:</i> | | | |
|-------------------------|----------------------------|----------------------|----------------------|----------------------|
| | Emission Intensity | | Emission Intensity | |
| | (1) | (2) | (3) | (4) |
| log(Tonnage) | -1.282*** (0.037) | -0.811*** (0.041) | | |
| log(N Ships) | | | -0.998*** (0.110) | -0.280*** (0.051) |
| Constant | 22.136*** (0.458) | 15.565*** (0.606) | 8.922*** (0.267) | 5.744*** (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 column 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 A2: Fleet Size and Share of Eco-Ship Orders

| | <i>Dependent variable:</i> | | | |
|-------------------------|----------------------------|---------------------|---------------------|---------------------|
| | Share of Eco Ships | | Share of Eco Ships | |
| | (1) | (2) | (3) | (4) |
| log(Tonnage) | 0.124*** (0.006) | 0.054*** (0.008) | | |
| log(N Ships) | | | 0.135*** (0.020) | 0.053*** (0.014) |
| Constant | -1.103*** (0.078) | 0.060 (0.111) | -0.048 (0.062) | 0.618*** (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 column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least five ships.

Table A3: Fleet Size and Share of Eco Ships

| | <i>Dependent variable:</i> | | | |
|-------------------------|----------------------------|----------------------|----------------------|---------------------|
| | Share of Eco Ships | | Share of Eco Ships | |
| | (1) | (2) | (3) | (4) |
| log(Tonnage) | 0.058*** (0.001) | 0.050*** (0.002) | | |
| log(N Ships) | | | 0.086*** (0.005) | 0.062*** (0.004) |
| Constant | -0.483*** (0.015) | -0.329*** (0.028) | -0.099*** (0.011) | 0.137*** (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 column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least five ships.

Table A4: Fleet Size and Capital Age

| | <i>Dependent variable:</i> | | | |
|-------------------------|----------------------------|----------------------|----------------------|----------------------|
| | Average Ship Age | | Average Ship Age | |
| | (1) | (2) | (3) | (4) |
| log(Tonnage) | -2.040*** (0.070) | -1.718*** (0.107) | | |
| log(N Ships) | | | -2.698*** (0.242) | -1.689*** (0.227) |
| Constant | 39.558*** (0.744) | 33.777*** (1.420) | 25.841*** (0.589) | 16.359*** (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 column refers to a regression in which we measure fleet size as total tonnage and do not control for fleet-type (e.g., container ships, bulkers, etc.) fixed effects. The second column includes fleet-type fixed effects. The third column refers to a regression in which we measure fleet size as the number of ships; this regression does not include fleet-type fixed effects. The fourth column includes fleet-type fixed effects. The analysis focuses on fleets with at least five ships.

B Additional Model Details

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

$$w_t + b_t = d_t + \sum_{j \in \{C, D\}} (q_{jN} + \gamma_{j,t} p_e) k_{jN,t} + u_{O,t}^e k_{O,t}$$

$$f(x_t) + \sum_{j \in \{C, D\}} q_{jO,t+1} k_{jN,t} = w_{t+1} + Rb_t,$$

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:

$$(q_{jN} + \gamma_{j,t} p_e) \mu_t = R^{-1} (f_{x,t} g_{jN,t} + q_{jO,t+1}) + R^{-1} \theta q_{jO,t+1} \lambda_t$$

$$u_{O,t}^e \mu_t = R^{-1} f_{x,t} g_{O,t}$$

$$\mu_t = 1 + \phi_{d,t} \tag{B1}$$

$$\mu_t = 1 + \lambda_t. \tag{B2}$$

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

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