Investment-Goods Market Power and Capital Accumulation*

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Abstract

We develop a model of capital accumulation in an economy that sources investment goods from large firms with market power. We model investment-goods producers as a dynamic oligopoly with increasing marginal cost and characterize the equilibrium with a dynamic markup rule. We use this characterization to analyze the dynamics of investment and prices. The markup on investment goods acts as an endogenous adjustment cost, which decreases as the economy grows but permanently distorts the steady state. We calibrate the model to simulate the post-2020 shocks to demand for equipment and semiconductors. The calibrated model attributes the observed increase in the price of equipment mainly to increasing marginal costs and to a smaller extent to increasing markups. We then analyze the effects of policy interventions to expand capacity and address market power. Finally, we extend the model to investment-specific technological progress due to learning by doing.

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1 Introduction

The post-2020 global recovery has been a stark reminder of the dependence of the macroeconomy on the supply of critical inputs produced by highly concentrated industries, such as semiconductors.[1] These goods are necessary inputs in the production of equipment investment. When demand for durable goods surged during the recovery, semiconductor prices soared, dampening capital accumulation, contributing to inflation, and prompting ambitious policy responses.[2]

More broadly, for many critical types of investment goods–such as commercial aircraft, ships, electric vehicles, and construction machinery–a relatively small number of large global producers supply the world economy.

The goal of this paper is to analyze the role of market power in investment-goods markets for the dynamics of prices, capital accumulation, and output. To this end, we develop a general framework that combines a neoclassical growth model of capital accumulation with a dynamic oligopoly model of investment-goods producers. We characterize the equilibrium interactions between investment and markups. We then apply this framework to analyze quantitatively the role of market power in the semiconductor industry for post-2020 equipment price dynamics and the related policy interventions.

Figure 1 portrays the dynamics of the US Producer Price Index of semiconductors (solid line) and of machinery and equipment (dashed line), both deflated using the GDP deflator. Starting in 2020, semiconductor prices increased dramatically, reaching a 20% deviation from their trend in 2023. Over the same period, the overall price of equipment goods, which require semiconductors as inputs, also increased significantly and was 7% higher than its trend in 2023.[3]

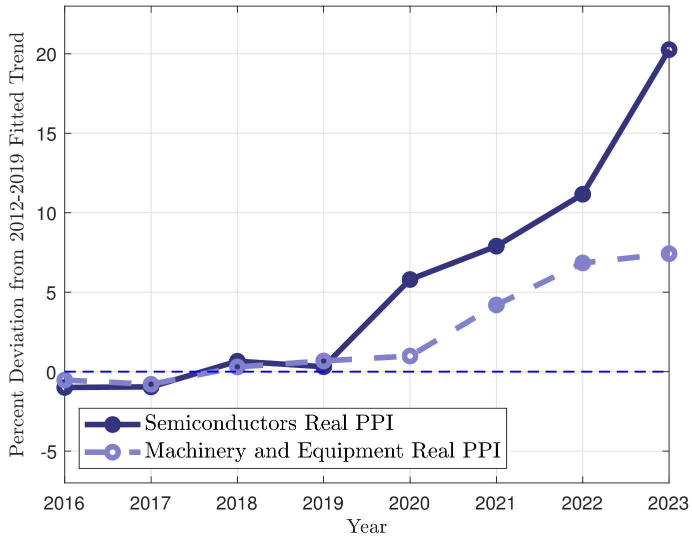
Given the high concentration of the semiconductor industry, it is natural to ask to what extent these price increases were driven by higher marginal costs—e.g., due to capacity constraints—or higher markups. Moreover, understanding the macroeconomic role of these markets is paramount because it is likely that future economic growth will increasingly rely on semiconductors. Motivated by these questions, our framework allows us to shed lights more generally on the macroeconomic role of market concentration in durable-goods markets, both in response to shocks and in the long run.

[1] In 2021, the two largest semiconductor manufacturers—TSMC and Samsung—jointly accounted for approximately 70% of global sales.

[2] In the US, the CHIPS and Science Act of 2022 aimed at generating hundreds of billions of dollars of investment in semiconductor manufacturing to rebalance the global patterns of production of semiconductors, which is concentrated in Asia.

[3] In Appendix A.1 we provide additional empirical evidence on these price series and on the dynamics of semiconductor and equipment markets during the recovery.

Figure 1: Semiconductor and Equipment Price Dynamics



Notes: The figure displays the US Producer Price Index of Semiconductors (FRED series `PCU334413334413A`) and the US Producer Price Index of Machinery and Equipment (FRED series `WPU11`) during 2016-2023. Both series are deflated using the US GDP deflator (FRED series `A191RD3A086NBEA`) and displayed in percent deviations from a linear trend fitted during 2012-2019.

In our model, an economy accumulates capital by importing investment goods according to a standard investment Euler equation. Investment requires an input produced by an oligopolistic industry. Foreign producers of this input face a convex cost function and maximize the present discounted value of profits, internalizing the effects of their production decisions on prices through the Euler equation. We analyze a Markov Perfect Equilibrium, in which strategies depend on a natural state variable, namely the level of capital in the domestic economy.

Because of the durable nature of capital, investment-goods producers effectively compete with the undepreciated stock of capital—equivalently, the secondary market for investment goods—, as well as among themselves, and choose the level of production trading off current and future profits. By focusing on differentiable policy functions, we characterize the optimal trade-off with a Generalized Euler Equation, which relates the markup to the derivatives of the equilibrium policy functions. These derivatives encode each producer's strategic interactions with future selves and other competitors. We then express the equilibrium price with a dynamic markup rule that provides insights on the role of the price elasticity of investment and on a dynamic notion of marginal cost that includes a foregone future markup.

To perform a quantitative exploration of the role of market power for the dynamics of investment, we calibrate the model interpreting the foreign oligopoly as the semiconductor manufacturing industry. When the level of capital in the domestic economy is low, the price of investment and the markup are high. Then, as the domestic economy accumulates capital toward its steady state, prices and markups decline over time. This mechanism generates a state-dependent capital adjustment cost, as endogenous markups contribute to slow convergence to steady state and permanently distort the steady-state level of capital. Notably, our quantification suggests that foregone future markups due to durability, a typically unmeasured component of the marginal cost, account for the bulk of the steady-state markup distortion.

Using our calibration, we disentangle the roles of different features of our framework, such as the capital-accumulation model on the demand side and the technological assumptions on the supply side, for the evolution of markups. We show that the price elasticity of investment demand is low when capital in the domestic economy is low, which accounts for a markup that is initially high and then declines during the transition. Furthermore, the presence of convex costs of producing investment goods strengthens producers' market power.

We also analyze a version of the model in which investment-goods producers commit to future production plans. In this case, the internalization of competition with past undepreciated production leads to markups that are higher in levels and do not decrease as the economy grows. This comparison sheds light on the nature of time inconsistency in our model and its macroeconomic implications.

We apply these insights on the transitional dynamics of the model to understand the response of the economy to macroeconomic shocks. Specifically, we perform several experiments in the calibrated model to reproduce salient features of the post-2020 global recovery, which featured strong demand for durable goods. We proxy a rise in demand for investment goods with a positive Total Factor Productivity (TFP) shock in the domestic economy. One interpretation of this shock is the significant expansion in work from home, which led to higher demand for computing and communication equipment.

We find that markups increase in response to the shock and then decrease over time, consistent with empirical evidence on the profitability of semiconductor producers in the recent recovery. Despite the endogenous increase in markups, however, the calibrated model suggests that the equilibrium price increase is predominantly driven by increasing marginal costs. In our baseline scenario, as the price of semiconductor increases by 20% as in the data, the marginal cost increases by 17%.

We also analyze the effects of shocks to the production of investment goods and then extend our model to stochastic, persistent productivity shocks and perform simulations that confirm the main insights of our parsimonious baseline model in a richer business-cycle framework.

The experience of the recent recovery has motivated several policy interventions that may reduce the concentration of some critical sectors, such as semiconductors, and expand their productive capacity. We use our model to simulate the effects of entry of one additional large producer. Marginal costs decrease because the production of investment goods is spread across more units, and, critically, long-run markup distortions decrease because of enhanced competition pressure. In contrast, we find that a relaxation of capacity constraints that does not affect the number of producers has a smaller impact on equilibrium prices. We conclude our policy analysis by characterizing the constrained-efficient allocation in the presence of market power.

Finally, we analyze the interactions between investment-goods market power and endogenous investment-specific technological progress due to learning by doing. When producers internalize learning by doing, they have an incentive to accelerate the path of production to reduce future cost, thereby reducing equilibrium markups early in the transition.

The rest of the paper is organized as follows. Section 2 discusses our contributions to the literature. Section 3 presents the model environment. Section 4 characterizes the dynamic oligopoly in investment goods. Section 5 presents the quantitative analysis of the role of market power for capital accumulation. Section 6 discusses the effects of aggregate shocks. Section 7 analyzes the effects of policy interventions. Section 8 extends the model to feature learning by doing. Section 9 concludes.

2 Related Literature

This paper contributes to several strands of the literature. A growing body of work in macroeconomics analyzes the aggregate effects of producer market power. De Loecker, Eeckhout, and Unger (2020) study the evolution of markups over time in the US economy. Edmond, Midrigan, and Xu (2023) provide a quantitative analysis of the social cost of markups. While many studies focus on imperfect competition and price dynamics in output markets (e.g., Mongey, 2021; Wang and Werning, 2022; Burstein, Carvalho, and Grassi, 2023), several recent paper focus on market power and firm granularity in input markets, such as the labor market (e.g., Berger, Herkenhoff, and Mongey, 2022; Jarosch, Nimczik, and Sorkin, 2023), and the credit market (Villa, 2023). Our contribution is to focus on market power in the production of durable inputs such as investment goods. We develop a framework to analyze the effects of market power on capital accumulation.

The literature on investment dynamics typically focuses on frictions on the demand side of the market for investment goods, such as adjustment costs at the firm level (e.g., Cooper and Haltiwanger, 2006; Khan and Thomas, 2008; Baley and Blanco, 2021; Winberry, 2021) or financing constraints (e.g., Buera and Shin, 2013; Moll, 2014; Lanteri and Rampini, 2023), as well as on the role of firm heterogeneity. We explore a complementary approach and analyze distortions stemming from the supply side of investment goods—namely, market power of producers. Caplin and Leahy (2006) and Fiori (2012) analyze the supply side of investment goods in models with fixed adjustment costs. Our focus on the production side of investment-goods markets is related to the contribution of Bertolotti and Lanteri (2024), which models endogenous product innovation, but without strategic interactions.

This paper also contributes to the literature on international trade, market structure, and macroeconomic dynamics (e.g. Ghironi and Melitz, 2005; Atkeson and Burstein, 2008). We focus on the role of market power in the production of durable goods. Since the work of Eaton and Kortum (2001), the literature has emphasized the high degree of geographic concentration in the global production of investment goods. Restuccia and Urrutia (2001) and Hsieh and Klenow (2007) study the effects of investment prices on growth across countries.[4] Our paper contributes to this body of work by analyzing market power in investment-goods markets as a source of friction in capital accumulation. Our quantitative application on demand for investment goods and capacity constraints during the recent recovery is related to the analyses of Comin, Johnson, and Jones (2023), Fornaro and Romei (2023) and Darmouni and Sutherland (2024).

Our methodology combines a neoclassical growth model with a model of dynamic oligopoly in durable-goods markets and we analyze a Markov Perfect Equilibrium (Maskin and Tirole, 2001). A large theoretical literature in industrial organization investigates monopoly pricing for durable goods with and without commitment (e.g., Coase, 1972; Stokey, 1981; Bond and Samuelson, 1984; Kahn, 1986; Suslow, 1986). Several papers leverage the insights of this literature to provide quantitative analyses of durable-good oligopolies (e.g., Esteban and Shum, 2007; Goettler and Gordon, 2011). Fabinger, Itskhoki, and Gopinath (2012) performs a theoretical analysis of the dynamics of durable-good prices across multiple market structures (monopoly, oligopoly, and monopolistic competition) assuming a linear technology; in the oligopoly case, it shows that a Markov Perfect Equilibrium must satisfy a Generalized Euler Equation similar to the one we obtain and then focuses on analytical solutions assuming demand is also linear. To analyze the macroeconomic role of market power for the dynamics of investment prices, we assume a convex cost function, which we also endogenize with learning by doing. We formalize a dynamic markup

[4] Engel and Wang (2011) emphasizes the critical role of trade in durable goods for the comovement between aggregate activity and trade flows. Burstein, Cravino, and Vogel (2013) focuses on the effects of investment-goods imports on wages. Lanteri, Medina, and Tan (2023) analyzes the effects of trade shocks on capital reallocation in a small open economy.

rule in our main theoretical result and then perform a quantitative analysis of the model focusing on semiconductors and equipment investment. Consistent with the insights of this literature, our assumptions on discounting, depreciation, and convex costs of production ensure that investment-goods producers exert market power, despite the durability of their output. Following the approach of Villa (2023), which analyzes a financial-intermediary oligopoly with dynamic demand, we solve the model using the Generalized Euler Equation, a tool introduced in the literature on optimal fiscal policy (Klein, Krusell, and Ríos-Rull, 2008). We also consider the case of commitment to future production, which we solve recursively using the multiplier on the investment Euler equation as a state variable (Marcet and Marimon, 2019).

3 Model

In this section, we present our model of an economy that accumulates capital by importing investment goods from a finite number of large producers. We then characterize the efficient allocation. We focus on a deterministic model to sharpen the analysis and extend the model to stochastic shocks in Section 6.3.

3.1 Investment Demand

We begin by describing the demand side of the market for investment goods. A deterministic open economy is populated by a representative household with utility function

$$\sum_{t=0}^{\infty} \beta^t u(C_t),$$

where $\beta \in (0,1)$ denotes the discount factor, C_t is aggregate consumption, and $u_c > 0$, $u_{cc} \leq 0$, where subscripts denote first and second derivative respectively.

The budget constraint of the household reads

$$C_t + P_t^I I_t + B_t = W_t L + R_t^K K_{t-1} + R B_{t-1} + D_t,$$

where P_t^I is the price of investment I_t, B_t are bonds that offer the exogenous world gross interest rate R, W_t is the wage, L is a constant endowment of labor, R_t^K denotes the rental rate of capital K_{t-1}, and D_t are profits obtained from ownership of domestic firms. We assume that the household is subject to the natural debt limit.

Investment adds to the capital stock, which depreciates at rate δ:

$$K_t = (1-\delta)K_{t-1} + I_t. \tag{1}$$

We assume that investment has to be non-negative and restrict attention to a region of the parameter space where this constraint is not binding.

The first-order conditions of the utility maximization problem with respect to bonds and investment are

$$1 = \beta \frac{u_c(C_{t+1})}{u_c(C_t)} R \tag{2}$$

$$P_t^I = \beta \frac{u_c(C_{t+1})}{u_c(C_t)} \left(R_{t+1}^K + (1-\delta) P_{t+1}^I \right). \tag{3}$$

We assume that the interest rate satisfies $R = \beta^{-1}$. Equation (2) then implies that consumption converges to its steady-state value in one period.

A representative firm rents capital from the representative household and hires labor to produce output with a constant-returns to scale production function:

$$Y_t = F(K_{t-1}, L). \tag{4}$$

The first-order conditions of the profit maximization problem are

$$\begin{aligned} F_K(K_{t-1}, L) &= R_t^K \\ F_L(K_{t-1}, L) &= W_t. \end{aligned} \tag{5}$$

For notational convenience, we define $f(K_{t-1}) \equiv F(K_{t-1}, L)$. Because of constant returns to scale, the representative firm makes zero profits in equilibrium—i.e., $D_t = 0$.

By combining the household and firm optimality conditions (2), (3), and (5), we obtain the following investment Euler equation that describes optimal capital accumulation in the open economy:

$$P_t^I = R^{-1} \left(f_k(K_t) + (1-\delta) P_{t+1}^I \right). \tag{6}$$

Equation (6) implicitly expresses the demand for investment goods I_t as a function of the capital stock K_{t-1} as well as current and future investment prices P_t and P_{t+1}.

We stress that our assumptions on consumers and ownership of the capital stock are not critical for this condition. We can equivalently derive equation (6) assuming that firms accumulate capital instead of households. Indeed, this condition holds also in a partial-equilibrium model in which competitive firms with discount rate R^{-1} choose investment optimally to maximize their present discounted value of profits.[5]

We also highlight that the open economy is *small* in the sense that the world interest rate is exogenous. We make this assumption to focus squarely on the determination of the price of investment goods, which is instead endogenous and affected by the path of capital accumulation in the open economy. The exogeneity of the interest rate allows us to abstract from the internalization of changes in the world real interest rate by investment-goods producers, which is unlikely to be a force of first-order importance and would make the analysis more cumbersome.

3.2 Investment-Goods Production

We now describe the supply side of the market for investment goods.

Assembly of investment. A perfectly competitive representative firm combines an amount Q_t of imported investment goods and an amount X_t of output good to assemble domestic investment with a Leontief production function:

$$I_t = \min \left\{ \frac{Q_t}{\theta}, \frac{X_t}{1-\theta} \right\},$$

where $\theta \in [0, 1]$ denotes the share of imported investment goods, which trade at price P_t. Profit maximization implies $\frac{Q_t}{\theta} = \frac{X_t}{1-\theta}$ and the equilibrium investment price must satisfy

$$P_t^I = \theta P_t + 1 - \theta, \tag{7}$$

which implies that the investment assembling firm makes zero profits. It is thus immaterial whether this technology is owned by domestic or foreign investors. Notice that our model nests a standard small-open-economy neoclassical growth model when $\theta = 0$.

Production of imported investment goods. We assume that there is an integer number $N \geq 1$ of identical producers of a homogeneous good, which we refer to as "investment-good producers." Equivalently, there is a fixed cost of entering the industry and the level of this cost is such that entry is profitable for N firms, but would yield negative profits with a larger number of entrants. We analyze the effects of firm entry in Section 6. These firms are owned by foreign investors.

The production of investment requires output goods. Specifically, each investment-good producer has a cost function $c(q_t)$, where q_t is the quantity produced at date t and

[5] We obtain the same investment Euler equation (6) in general equilibrium if the representative household has linear preferences.

we assume $c_q > 0$ and $c_{qq} \geq 0$. In Section 8 we analyze a more general formulation of the cost function with endogenous technological progress in the form of learning by doing, which renders the marginal cost increasing in the quantity produced in the short run but decreasing over time.

Static profits at date t are given by $\pi_t \equiv P_t q_t - c(q_t)$. We will consider several alternative assumptions on competition and strategic interactions. Across all of these assumptions, we maintain that the objective of investment-good producers is to maximize the present discounted value of profits:

$$\sum_{t=0}^{\infty} R^{-t} \pi_t. \tag{8}$$

Maintaining this assumption on the objective function, it is straightforward to consider the case of domestic investment-goods producers. In that case, profits would be rebated to domestic consumers and the allocation would be otherwise identical to the one we will obtain. However, the objective function (8) may not coincide with the objective of the firm owner—i.e., domestic households—when firms do not take prices as given.[6]

3.3 First Best

Before analyzing the effects of market power, we briefly introduce the competitive benchmark. In a competitive equilibrium without market power, investment-goods producers choose a sequence of production levels $\{q_t\}_{t=0}^{\infty}$ to maximize (8) *taking as given* the sequence of prices $\{P_t\}_{t=0}^{\infty}$. Thus, the equilibrium price satisfies $P_t = c_q\left(\frac{\theta I_t}{N}\right)$ and optimal capital accumulation satisfies

$$\theta c_q\left(\frac{\theta I_t}{N}\right) + 1 - \theta = R^{-1}\left(f_k(K_t) + (1-\delta)\left(\theta c_q\left(\frac{\theta I_{t+1}}{N}\right) + 1 - \theta\right)\right). \tag{9}$$

If the cost function c is convex, the first-best allocation coincides with the outcome of a standard model of capital accumulation with convex capital adjustment costs. Furthermore, convexity implies that it is efficient to produce the same amount in all of the investment-goods firms, which motivates our focus on symmetric equilibria in the remainder of the paper.

This outcome is also the solution to the problem of a planner that maximizes household welfare in the domestic economy subject to an aggregate resource constraint that includes

[6]For an analysis of common ownership in oligopoly in general equilibrium models, see Azar and Vives (2021), which highlights that there is no simple objective function for firms that are not price takers and share a common owner; solving this issue in our dynamic context with durable goods is beyond the scope of this paper.

the cost of producing investment goods. We formulate this problem in Appendix B.1.[7]

4 Investment-Goods Oligopoly

We now analyze the case of investment-goods producers that act as oligopolists. We describe the Markov Perfect Equilibrium, derive the optimality conditions of the investment-goods producers, and formalize a dynamic markup rule. We then use this characterization to relate markups and capital accumulation. Finally, we contrast this problem with the case of commitment to future production.

4.1 Markov Perfect Equilibrium and Generalized Euler Equation

To focus on time-consistent decisions in the absence of commitment to future production levels, we analyze a symmetric Markov Perfect Equilibrium with Cournot competition, in which quantities produced are functions of a single natural state variable, the capital stock in the domestic economy. To obtain a sharper characterization, we further restrict attention to differentiable decision rules.

Combining equations (6) and (7) and using recursive notation, we can express the investment Euler equation—i.e., the demand curve for investment goods—as follows:

$$P = R^{-1}\left(\theta^{-1} f_k(K') + (1-\delta)P(K')\right) - \kappa, \tag{10}$$

where $\kappa \equiv \theta^{-1}(1-\theta)\left(1 - R^{-1}(1-\delta)\right)$.

For a generic investment-goods producer, we denote by $q_{-}(K)$ the quantity produced by each other producer as a function of the capital stock K. Furthermore, investment-good producers anticipate the equilibrium price function $P(K')$ and the continuation value function $V(K')$, encoding the present discounted value of profits (8). Each producer solves the following problem:

$$\max_{P,q,K'} Pq - c\left(q\right) + R^{-1}V(K'),$$

subject to the Euler equation (10) and the law of motion for capital

$$K' = (1-\delta)K + \theta^{-1}\left((N-1)q_{-}(K) + q\right), \tag{11}$$

[7] In Appendix B.2 we also show that this planning problem coincides with one in which the planner is subject to a participation constraint that requires investment-good producers to earn a minimum level of profits, as long as there are lump-sum transfers between the domestic economy and foreign firms. We also consider the "constrained efficiency" case without lump-sum transfers in Section 7.3.

where we used the market-clearing condition $(N-1)q_{-}(K)+q=Q=\theta I$ to express aggregate production of the investment good.

We stress two important differences between this problem and several other macroeconomic models of strategic interactions in pricing (e.g. Atkeson and Burstein, 2008). First, the durability of investment in our framework implies that each firm competes with the existing stock of undepreciated capital, as well as with the other $N-1$ firms, as equation (11) illustrates.[8] Second, investment-good producers in our model are *large* players with respect to *aggregate variables* and internalize the effects of their actions on the evolution of the economy, including the aggregate price of investment.

The optimality condition for the production level can be represented as the following Generalized Euler Equation (GEE):

$$\theta P-\theta c_q(q)+qR^{-1}\left(\theta^{-1}f_{kk}(K')+(1-\delta)P_k(K')\right)+R^{-1}V_k(K')=0. \tag{12}$$

This is a functional equation that involves the derivative of the future price with respect to the capital stock, reflecting the fact that investment-good producers cannot commit to future actions, but internalize the effect of current production on future equilibrium outcomes.

In a symmetric equilibrium, the maximum value of this problem coincides with $V(K)$. Thus, the envelope condition reads:

$$V_k(K)=-\theta\left(1-\delta+\left(\frac{N-1}{N}\right)I_k(K)\right)\left(P-c_q\left(\frac{\theta I(K)}{N}\right)\right), \tag{13}$$

where $I(K)$ denotes aggregate investment and we have used the fact that in a symmetric equilibrium each firm produces a fraction $1/N$ of the total amount of imported investment goods—i.e., $q(K)=q_{-}(K)=\frac{\theta I(K)}{N}$. The term $I_k(K)$ encodes the strategic interactions among oligopolistic firms, which, in a Markov Perfect Equilibrium, are mediated by changes in the state variable: Each firm internalizes the effect of its current production on future competitors' production through changes in the level of capital in the open economy.

To gain intuition on the GEE (12), consider a marginal increase in future capital K'—and the associated increase in the level of production q. This increase in K' has three effects on the present discounted value of profits. First, it yields additional profits equal to the current markup $P-c_q(q)$ for the share θ of oligopolistic input in investment.

[8] As a relevant example of the importance of dynamic competition with the undepreciated stock in the case of semiconductor producers, in 2022 TSMC warned investors that the past high volume of production during 2020-21 would lead to lower demand in the future. Source: https://asia.nikkei.com/Business/Tech/Semiconductors/Chip-giant-TSMC-warns-of-excessive-inventory-at-clients.

Second, an increase in K' moves the market equilibrium along the demand curve, reducing the market-clearing price. The corresponding effect on profits—i.e., the term $qR^{-1}\left(\theta^{-1}f_{kk}(K') + (1-\delta)P_k(K')\right)$—is encoded in the derivative of the right-hand side of the investment Euler equation, and thus depends on changes in the marginal product of capital and in the future value of capital.

Third, an increase in K' shifts downward the future residual demand curve, with an effect on future profits given by $R^{-1}V_k(K')$, which the envelope condition (13) relates to the future markup. This last term highlights that oligopolistic firms producing a durable good internalize that their future production will compete with the undepreciated fraction $(1-\delta)$ of the current production, as well as with their competitors' output, as indicated by the term $\left(\frac{N-1}{N}\right) I_k(K)$ in equation (13).

Overall, the GEE (12) describes the optimal trade-off between current and future markup. We summarize the equilibrium conditions of the Markov Perfect Equilibrium in the following definition.

Definition 1 *A* ***Symmetric Markov Perfect Equilibrium*** *is a set of functions mapping the capital stock K to the present discounted value of profits for each oligopolist $V(K)$, the quantity produced $q(K)$, the associated level of aggregate investment $I(K) = \frac{Nq(K)}{\theta}$, and the price $P(K)$ that satisfy the investment Euler equation* (10)*, the capital accumulation equation* (11)*, the Generalized Euler Equation* (12)*, and the envelope condition* (13)*.*

We leverage this definition to solve the model numerically in Section 5.

4.2 Dynamic Markup Rule and Static Markup

We now characterize the equilibrium price and express it in terms of a markup and an appropriate notion of marginal cost. Formally, we prove the following result.

Proposition 1 *In a Symmetric Markov Perfect Equilibrium, the price satisfies the following markup rule:*

$$P = \underbrace{\frac{N}{N-\eta}}_{\text{Dynamic Markup}} \cdot \underbrace{\left(c_q(q) - R^{-1}\theta^{-1}V_k(K')\right)}_{\text{Dynamic Marginal Cost}}, \tag{14}$$

where η is the inverse price elasticity of investment demand, defined as

$$\eta \equiv -\frac{Q}{P}\frac{dP}{dQ} = -\frac{Q}{P}\theta^{-1}R^{-1}\left(\theta^{-1}f_{kk}(K') + (1-\delta)P_k(K')\right), \tag{15}$$

and the marginal value $V_k(K)$ is given by equation (13)*.*

To prove this result, we first rewrite the GEE (12) as follows:

$$P\left(1+\frac{\theta^{-1}q}{P}\cdot\underbrace{R^{-1}\left(\theta^{-1}f_{kk}(K')+(1-\delta)P_k(K')\right)}_{\frac{dP}{dK'}}\right)=c_q(q)-R^{-1}\theta^{-1}V_k(K').$$

We then observe that $\frac{dP}{dQ}=\frac{dP}{dK'}\frac{dK'}{dQ}=\theta^{-1}\frac{dP}{dK'}$, as one additional unit of output of the oligopolistic industry translates into θ^{-1} additional unit of future capital. Thus, using the definition of η in equation (15) and the fact that $q=\frac{Q}{N}$, we get equation (14), which expresses the price as a *dynamic markup* rule.

The rule calls for applying the Cournot oligopoly markup $\frac{N}{N-\eta}$ to a dynamic notion of marginal cost. This notion of marginal cost is composed of two terms. First, we have the "static" marginal cost $c_q(q)$, which is the physical cost of producing one additional unit at the current date. Second, because of the dynamic nature of the oligopolist problem, we have the discounted future marginal value, which encodes the loss in future profit due to the fact that one additional unit will shift residual demand in the future.

We define the dynamic markup *rate* as a share of the dynamic marginal cost, $\mu^D\equiv\frac{N}{N-\eta}-1=\frac{\eta}{N-\eta}$, where the superscript D stands for "dynamic." We highlight that the inverse elasticity η is an equilibrium object that varies with the level of aggregate capital K, and so does the markup rate μ^D. Using the envelope condition (13), we can also express the static markup rate μ^S as follows:

$$\mu^S\equiv\frac{P-c_q(q)}{c_q(q)}=\mu^D\left(1-\frac{NR^{-1}\theta^{-1}V_k(K')}{\eta c_q(q)}\right). \tag{16}$$

This static markup is the object that is typically estimated in empirical analyses of market power. Proposition 1 allows us to decompose this measured markup into a Cournot markup term that depends only on market structure and demand elasticity and an "unmeasured cost" encoded in the future marginal continuation value. Specifically, in equation (16), the term in parenthesis on the right-hand side adjusts the dynamic markup to account for the effect of future competition on the dynamic marginal cost.

We stress that the dynamic markup rule of Proposition 1 (equation (14)) is robust to an important generalization of our model, namely the introduction of endogenous technological progress in investment production due to learning by doing. The addition of this channel only modifies the expression for the envelope term, as we explain in detail in Section 8.

4.3 Prices and Markups Around Steady State

We now obtain some analytical insights on the effect of the level of capital on the equilibrium price and on the role of the production function f—i.e., the demand side of the model—for this price mapping. We investigate these relationships quantitatively in Section 5.3.

Let us define the equilibrium law of motion of capital, $g(K) \equiv K(1-\delta) + I(K)$. We proceed under the regularity condition that a stable steady-state level of capital exists and capital converges to it monotonically from below (at least locally). In a neighborhood of the steady state, we then have $0 \leq g_k(K) = 1 - \delta + I_k(K) < 1$. We verify this condition in our numerical solution. A steady-state level of capital and price satisfy

$$(\theta P + 1 - \theta)(R - 1 + \delta) = f_k(K).$$

Differentiating the Euler equation (6) with respect to K, we obtain

$$\begin{aligned} P_k(K_{t-1}) &= \left(R^{-1}\theta^{-1} f_{kk}(K_t) + R^{-1}(1-\delta)P_k(K_t)\right) g_k(K_{t-1}) \\ &= \sum_{s=0}^{\infty} R^{-s-1}(1-\delta)^s \left(\Pi_{\tau=t-1}^{t-1+s} g_k(K_\tau)\right) \theta^{-1} f_{kk}(K_{t+s}), \end{aligned} \tag{17}$$

which expresses the slope of the equilibrium price function as a present discounted value of the second derivatives of the production function moving forward in time along the equilibrium capital accumulation path.

In steady state, equation (17) becomes

$$P_k(K) = \frac{R^{-1}\theta^{-1} f_{kk}(K) g_k(K)}{1 - R^{-1}(1-\delta) g_k(K)}. \tag{18}$$

The numerator of (18) is negative by concavity of the production function. The denominator is positive. Hence the equilibrium price is decreasing in the level of capital, $P_k < 0$, in a neighborhood of a steady state. This result, together with $f_{kk} < 0$, ensures that the inverse elasticity η is positive in a neighborhood of a steady state. Therefore, the properties of the production function—which determines investment demand in our model—are critical for both price dynamics and market power.

Furthermore, in steady state we can use the envelope condition (13) together with equation (16) to relate the static markup to the demand elasticity and investment policy function as follows:

$$\mu^S = \frac{\mu^D}{1 - \frac{N}{N-\eta} R^{-1}\left(1 - \delta + \left(\frac{N-1}{N}\right) I_k(K)\right)}.$$

4.4 Capital Level and Price Elasticity of Investment

We now investigate the relation between the level of capital and the price elasticity of investment, which is a key determinant of the markup on new investment goods. Whereas it is necessary to examine this relation numerically in our model, we can make analytical progress in a simplified setting.

Consider the limiting case of full depreciation, $\delta = 1$, and assume there is a monopoly, i.e. $N = 1$ and that $\theta = 1$. Moreover, assume the economy has an endowment of capital K_0 that is not purchased from the monopolist. This endowed capital acts as stand-in for undepreciated capital from the past in our model with partial depreciation and shifts the demand for investment.

In this case, taking logs of the investment Euler equation, we can write

$$\log(P) = -\log(R) + \log\left(f_k(K_0 + I)\right).$$

Thus, the inverse price elasticity is

$$\eta = -\frac{f_{kk}(K_0 + I)I}{f_k(K_0 + I)}.$$

Assume further that the production function is Cobb-Douglas, $f(K) = AK^\alpha$ with $\alpha \in (0, 1)$, as we will maintain in our quantitative analysis. Then,

$$\eta = (1 - \alpha)\frac{I}{K_0 + I},$$

which is decreasing in K_0 for a given level of quantity demanded I. Hence, investment demand is less elastic with respect to the price for low K_0 and the optimal markup is decreasing in K_0.

More in general, the sign of the derivative of the inverse elasticity with respect to K_0 depends on the the first three derivatives of the production function:

$$\frac{\partial \eta}{\partial K_0} = I\left(\frac{(f_{kk})^2 - f_{kkk}f_k}{(f_k)^2}\right),$$

and is negative when $f_{kk}^2 - f_{kkk}f_k < 0$. Intuitively, the first derivative of the production function appears in the Euler equation, which is the demand schedule for investment goods. Thus, the second derivative determines the price elasticity. Finally, the third derivative is a determinant of the slope of the elasticity with respect to the predetermined level of capital.

Leveraging the analytical insights in the simplified setting of this section, we analyze quantitatively the relationship between capital level and markup in Section 5.4.

4.5 Commitment to Future Production

So far we have proceeded under the assumption that investment-good producers cannot commit to future actions. In the literature on durable-good pricing it is well understood that assumptions on commitment may have important consequences for prices and markups. Hence, to analyze the role of commitment to a future production plan in our model, we now consider the following setup.

At $t = 0$, each investment-good producer commits to an infinite sequence of production levels $\{q_t\}_{t=0}^{\infty}$ taking as given a sequence of competitors' production levels $\{q_{-,t}\}_{t=0}^{\infty}$. We then impose symmetry across investment-goods producers in equilibrium. We interpret this setup as the limiting case of a world with long-lived managers that formulate production plans and face high costs of deviating from them, for instance because of large costs of changing the production capacity.[9]

The oligopolist's maximization problem is

$$\max_{\{P_t, q_t, K_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} R^{-t} \left(P_t q_t - c\left(q_t\right)\right)$$

subject to the demand schedule or, using the terminology of Ramsey-optimal policy, "implementability constraint"

$$P_t = R^{-1}\left(\theta^{-1} f_k(K_t) + (1-\delta) P_{t+1}\right) - \kappa$$

for $t = 0, 1, ..,$ with multiplier $R^{-t}\gamma_t$, and the law of motion

$$K_t = (1-\delta)K_{t-1} + \theta^{-1}\left((N-1)q_{-,t} + q_t\right).$$

The first-order conditions of this problem are:

$$q_t - \gamma_t + \gamma_{t-1}(1-\delta) = 0 \tag{19}$$

$$\theta P_t - \theta c_q(q_t) + \gamma_t R^{-1}\theta^{-1} f_{kk}(K_t) - R^{-1}\theta(1-\delta)\left(P_{t+1} - c_q(q_{t+1})\right) = 0, \tag{20}$$

with initial condition on the multiplier $\gamma_{-1} = 0$. These optimality conditions trade off

[9] In this formulation, we assume that investment-goods producers cannot collude because of coordination costs that we do not explicitly model. In Appendix B.3 we consider the case of collusion with commitment, in which case the objective is to maximize the present discounted value of total profits. The two problems coincide if $N = 1$.

present and future profits, similar to the GEE (12). However, we highlight two important differences between the dynamics under commitment and the ones we obtained in a Markov Perfect Equilibrium.

First, equation (19) reveals the nature of the time inconsistency of the optimal production plan under commitment. A higher price at t relaxes the *past* implementability constraint allowing a higher price at $t-1$. However, at $t=0$, the producer is not bound by any past commitment. Then, over time, past commitments, encoded in the multiplier γ_t, accumulate, thereby making it increasingly costly to reduce prices. In contrast, in a Markov Perfect Equilibrium, firms always disregard the competition with their past selves and only internalize future equilibrium decision rules.

Second, because under commitment we assume that firms take as given the whole path of competitors' decisions, they do not internalize the effect of their production levels on future competitors' production, which accounts for the term $I_k(K')$, which is present in the envelope condition (13) but absent in equation (20).

We define a symmetric equilibrium with commitment as follows.

Definition 2 *A **Symmetric Equilibrium with Commitment** is a sequence of allocations, prices, and multipliers on the investment Euler equation $\{K_t, q_t, I_t, P_t, \gamma_t\}_{t=0}^{\infty}$ that satisfy the investment Euler equation, the capital accumulation equation, and the oligopoly first-order conditions* (19) *and* (20).

As in the case without commitment, we can use the optimality conditions (19) and (20) to express the price in terms of the marginal cost and a markup rate. To this end, we first rewrite equation (20) as follows:

$$P_t\left(1+\frac{\theta^{-1}\left(q_t+(1-\delta)\gamma_{t-1}\right)}{P_t}\cdot\underbrace{R^{-1}\theta^{-1}f_{kk}(K_t)}_{\frac{dP_t}{dK_t}}\right)=c_q(q_t)+R^{-1}(1-\delta)\left(P_{t+1}-c_q(q_{t+1})\right).$$

We then observe that $\frac{dP_t}{dQ_t}=\theta^{-1}\frac{dP_t}{dK_t}$. Thus, defining the inverse price elasticity of demand

$$\eta^{FC}\equiv-\frac{Q}{P}\frac{dP_t}{dQ_t}=-\frac{Q}{P}R^{-1}\theta^{-2}f_{kk}(K_t), \tag{21}$$

we obtain the following formal result.

Proposition 2 *In a Symmetric Equilibrium with Commitment, the price satisfies the fol-*

lowing markup rule:

$$P_t = \underbrace{\frac{N}{N - \left(1 + \frac{N(1-\delta)\gamma_{t-1}}{Q_t}\right)\eta^{FC}}}_{\text{Dynamic Markup}} \cdot \underbrace{\left(c_q(q_t) + R^{-1}(1-\delta)\left(P_{t+1} - c_q(q_{t+1})\right)\right)}_{\text{Dynamic Marginal Cost}}, \tag{22}$$

where the inverse price elasticity η^{FC} is given by equation (21).

Equation (22) expresses the price as a dynamic markup rule that is both forward looking and backward looking. In particular, the commitment problem features the backward-looking term $\frac{N(1-\delta)\gamma_{t-1}}{Q_t}$ that was not present in the Markov Perfect Equilibrium. This term captures the fact that the firm internalizes that a marginal increase in price at time t has an effect on the demand schedule at time $t-1$. Notice also that the appropriate notion of marginal cost is composed of two terms. First, we have the "static" marginal cost $c_q(q_t)$, which is the cost of producing one additional unit at the current date. Second, because of the dynamic nature of the oligopolist problem, we have the discounted future markup. Similarly to the case without commitment, we can also define the dynamic markup rate under commitment as a fraction of the marginal cost.

5 Quantitative Analysis

In this section, we leverage our equilibrium definitions and characterization to solve the model numerically. We calibrate the model and explore the implications of market power in investment-goods markets for capital accumulation. We focus on the dynamics of markups along the transition path to steady state in the domestic economy and disentangle the roles of demand, technology, and commitment.

5.1 Solution Method

We begin this section by briefly discussing our global solution method. Appendix C.1 provides additional details.

Markov Perfect Equilibrium. We approximate the Markov Perfect Equilibrium (Definition 1) using a version of the time-iteration algorithm to approximate the policy functions $I(K)$ and $P(K)$. Specifically, we guess a polynomial approximation for $I(K)$. Given this candidate policy function, we obtain an associated guess for $P(K)$ by doing time iteration on equation (6), recursively solving for the left-hand side on a grid for K and then plugging the obtained price function in the right-hand side. Once we obtain a converged price function, we use it to numerically approximate the derivative $P_k(K)$. Then, to update $I(K)$, we apply time iteration to the GEE (12) substituting in it the envelope condition (13) with an approximation of the derivative $I_k(K)$. We repeat these steps until all policy functions converge.

Commitment. To approximate the equilibrium with commitment (Definition 2), we solve the model recursively by adding the multiplier on the past investment Euler equation as a state variable. We then use a time-iteration algorithm on equations (19) and (20) to approximate the policy functions $I(K, \gamma)$ and $\gamma'(K, \gamma)$ with polynomials.

5.2 Calibration

We proceed to describe our choices of functional forms and parameter values, which we report in Table 1. The length of a period is one year. We assume that the production function in the domestic economy is Cobb-Douglas: $F(K_{t-1}, L) \equiv AK_{t-1}^{\alpha}L^{1-\alpha}$ and normalize the labor endowment $L = 1$. We interpret capital as the stock of nonresidential private equipment in the US. We set the capital share in the production function and the depreciation rate to match the ratio of the stock of equipment to GDP and the average depreciation rate of equipment using data from the NIPA Asset Tables. In Appendix C.3 we provide our main results based on an alternative calibration, which refers to a broader definition of capital, including structures, as in standard real-business-cycle models.

We calibrate the share of imported investment goods in total investment using US data on investment-goods prices as follows. We first deflate the Producer Price Index of semiconductors and the Producer Price Index of machinery and equipment using the GDP deflator. We fit a linear trend in both series during 2012-2019. We then match the pass-through of the cumulative increase in the real price of semiconductors to the real price of machinery and equipment during 2019-2023. Relative to trend, we observe a 20% increase in the real price of semiconductors and a 7% increase in the real price of machinery and equipment (Figure 1). In Appendix C.4 we provide our main results based on an alternative calibration, which interprets the imported oligopolistic input more narrowly as wafers, a key component in the production of semiconductors, for which we can use detailed data on production and unit margins. We analyze these data in Appendix A.2.

Given our focus on symmetric equilibrium, we set the number of foreign investment-goods producers to approximate the highly concentrated market structure in semiconductor manufacturing, where the two largest players (TSMC and Samsung) account for over 70% of sales. We then experiment with a change in market structure in Section 7.1.

We assume that the cost function to produce investment goods is quadratic: $c(q) = c_1 q + \frac{c_2}{2} q^2$. We view this functional form assumption as a parsimonious approximation of

Table 1: Parameters Values

	Parameter	Symbol	Value
Investment Demand	Discount Factor	β	0.96
	Depreciation	δ	0.1354
	Capital Share	α	0.0645
	Oligopolistic Capital Share	θ	0.366
	Total Factor Productivity	A	2.743
Investment Supply	Number of Producers	N	3
	Marginal Cost (Intercept)	c_1	0.6369
	Marginal Cost (Slope)	c_2	22

Notes: The table reports the parameter values used in the quantitative analysis.

more general technologies with decreasing returns to scale. In Appendix C.5 we explicitly consider a richer specification of the cost function that approximates capacity constraints that become active in response to large increases in production relative to steady state.

We set the intercept c_1 to normalize the marginal cost of investment to one in the first-best steady state. To quantify the degree of decreasing returns to scale, we calibrate c_2 so that the ratio of profits to sales in steady state closely matches the ratio of operating income (EBIT) to sales in balance-sheet data for the major semiconductor manufacturers. Specifically, using ORBIS data on TSMC and Samsung, we obtain a ratio of approximately 30%. This calibration strategy implies that the steady-state elasticity of the marginal cost with respect to the quantity produced is equal to 0.35%.

5.3 Capital Accumulation, Prices, and Markups

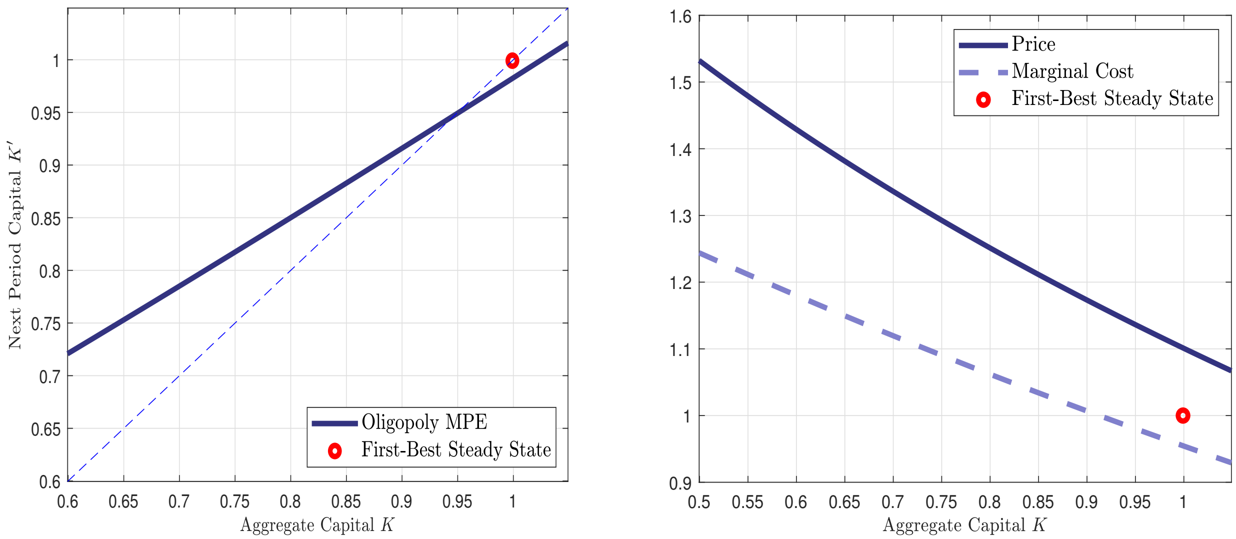
Figure 2 illustrates the main properties of the Markov Perfect Equilibrium. The left panel portrays the law of motion of aggregate capital and the right panel the equilibrium price (solid line) and the marginal cost (dashed line) as functions of the level of capital.

In the Markov Perfect Equilibrium, the steady-state level of capital is approximately 5% lower than in first best (red circle) because of the presence of a markup, which induces a long-run distortion. The steady-state static markup rate is approximately equal to 16%.

Moreover, as the domestic economy grows toward its steady state, the marginal cost is initially high to accommodate a high level of investment, and then declines during the transition. The price of investment also declines, and more so than the marginal cost, which implies that the static markup is decreasing in the level of capital. As a consequence, capital accumulation is slower in the presence of market power than in the first-best allocation.

Weaker competition among investment-goods suppliers dampens capital accumulation and growth.

Figure 2: Markov Perfect Equilibrium: Capital Accumulation, Price, and Marginal Cost



(a) Capital Accumulation

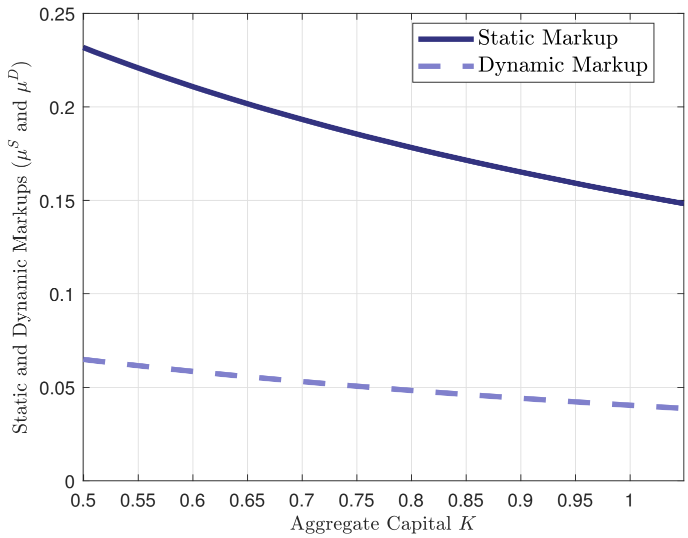
(b) Price and Marginal Cost

Notes: The figure displays capital accumulation and prices in the Markov Perfect Equilibrium (MPE). Panel (a) illustrates the law of motion of capital in the domestic economy. The solid line represents next-period capital (y-axis) as a function of current capital (x-axis). Its intersection with the 45-degree dashed line identifies the steady-state MPE. The red circle marks the equilibrium capital stock in the first-best steady state. Panel (b) displays price P (solid line) and marginal cost $c_q(q)$ (dashed line) as functions of the aggregate capital stock. The red circle marks the equilibrium price in the first-best steady state.

Figure 3 displays the dynamics of markups. We distinguish between the static markup μ_t^S (solid line) and the dynamic markup μ_t^D, which we defined in Section 4.2. The static markup is larger than the dynamic markup because it has to cover the part of the dynamic marginal cost due to competition with the future undepreciated capital stock. Notably, this dynamic component of the marginal cost accounts for the bulk of the steady-state distortion. Furthermore, we find that both markup rates decline as aggregate capital increases.

Quantitatively, our results imply that when the level of capital is approximately half of its steady-state target, the price of investment and the static markup rate are approximately 35% and 45% higher than in steady state, respectively. In the next subsections we dissect the roles of different forces in our model for these results on capital accumulation, prices, and market power.

Figure 3: Static and Dynamic Markup Rates



Notes: The figure illustrates the static markup rate μ^S (solid line) and the dynamic markup rate μ^D in the Markov Perfect Equilibrium as functions of the aggregate capital stock K.

5.4 Role of Demand

We first analyze the role of the demand side—i.e., the neoclassical growth model in the domestic economy—for the dynamics of markups displayed in Figure 3. Given our calibration, investment demand in the domestic economy is highly elastic. In steady state, the inverse elasticity η is approximately equal to 0.12, which implies a dynamic markup rate $\mu^D = 0.045$.

Consistent with the analytical characterization of Section 4.4, investment demand is less elastic when the level of capital is low and becomes more elastic as the domestic economy approaches its steady state. For instance, when the level of capital is approximately half of its steady-state value, the inverse elasticity is approximately equal to 0.35. Accordingly, Figure 3 shows that investment-good producers extract a higher dynamic markup early in the transition and the dynamic markup rate is decreasing in the level of capital.

Furthermore, a low level of capital, combined with low elasticity, implies that investment-goods producers can extract rents from the domestic economy for a relatively long time, while capital accumulates toward the steady state and demand is relatively inelastic. These large anticipated markups decline as the economy approaches the steady state, which accounts for the decreasing gap between μ^S and μ^D in the figure, consistent with equation (16). Thus, both the price elasticity and the anticipation of future markups (the dynamic component of the marginal cost) contribute to generate a larger distortion for lower levels of capital. This mechanism is related to the one that arises in the presence of dynamic oligopoly in the credit market, which Villa (2023) analyzes.

To buttress these findings on the role of demand forces, we develop a formal decomposition of markups along the equilibrium capital-accumulation path, leveraging our characterization of equilibrium. We reformulate the GEE (12) along the transition path in terms of future sequences of three objects: (i) quantities produced, normalized by the current level of the marginal cost; (ii) slopes of the demand function

$$\frac{dP_t}{dQ_t} \equiv \theta^{-1} R^{-1} \left(\theta^{-1} f_{kk}(K_t) + (1-\delta) P_k(K_t) \right);$$

and (iii) an endogenous discount factor, which we define recursively as follows: $B_{t,t} = 1$, $B_{t,t+1} = R^{-1}(1-\delta+(\frac{N-1}{N})I_k(K_t))$, and $B_{t,t+s} = B_{t,t+s-1}R^{-1}(1-\delta+(\frac{N-1}{N})I_k(K_{t+s-1}))$. We then express the static markup rate—as follows:

$$\mu_t^S = -\sum_{s=0}^{\infty} B_{t,t+s} \frac{q_{t+s}}{c_q(q_t)} \frac{dP_{t+s}}{dQ_{t+s}}. \tag{23}$$

To quantify the role of each factor for the dynamics of markups, we compute counterfactual markups using steady-state values for two of the three determinants and letting the remaining one vary according to the equilibrium path.

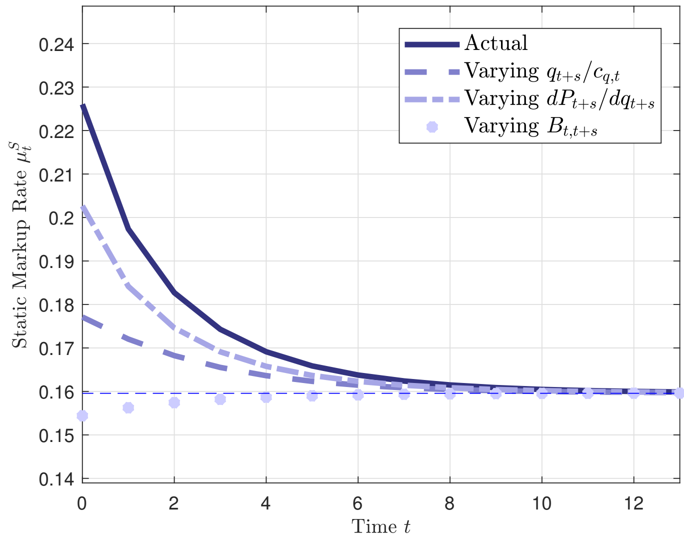
Figure 4 shows that rotations in the demand curve—consistent with an increasing elasticity—largely account for the steep decline in markups. Moreover, the quantity produced declines over time because investment is initially high and then decreases as the domestic economy approaches steady state. This path amplifies the decline in markups over time. Finally, variations in the discounting term $B_{t,t+s}$ play a negligible role.

5.5 Role of Investment-good Technology

Next, we investigate the role of our assumptions on the investment-good technology. We find that the slope of the marginal-cost function c_2—a proxy for the tightness of capacity constraints in our main calibration—plays an important role in sustaining the equilibrium level of markups and the associated profitability of investment-goods producers.

Given our calibrated value $c_2 = 22$, the steady-state static markup rate equals 0.16 and the ratio of profits to sales equals 0.29, which is our empirical target for semiconductor manufacturers. To assess the role of this parameter, we compute the Markov Perfect Equilibrium in counterfactual economies with different values—and re-calibrate c_1 so that all economies have the same level of capital and prices in the first-best steady state. When the marginal cost is flatter ($c_2 = 10$), the static markup rate equals 0.11 and the profit-

Figure 4: Static Markup Decomposition



Notes: The figure displays a decomposition of the evolution of the static markup rate $\mu_t^S = (P_t - c_{q,t})/c_{q,t}$ over the transition of the economy to steady state in the Markov Perfect Equilibrium. The figure disentangles the variation in the static markup rate (solid line) driven by: (i) quantities $q_{t+s}/c_{q,t}$ produced by each oligopolist, divided by the marginal cost (dashed line); (ii) derivatives of inverse demand with respect to aggregate quantity dP_{t+s}/dQ_{t+s} (dash-dotted line); and (iii) discount factor $B_{t,t+s}$ defined in the text (dotted line).

sales ratio equals 0.17. With a steeper marginal cost ($c_2 = 35$), the static markup rate equals 0.2 and the profit-to-sales ratio equals 0.4. Accordingly, equilibrium distortions in the steady-state capital level are increasing in the value of c_2.

This quantitative finding is consistent with the related theoretical literature in Industrial Organization (e.g. Stokey, 1981), which stresses that a durable-good monopolist with a constant marginal cost and without commitment behaves similarly to a competitive producer (Coase, 1972), whereas an increasing marginal cost leads to larger distortions due to market power.

Absent commitment, at every date an investment-good producer disregards the negative effect of a high current production on past prices. If buyers are sufficiently patient, they wait for a low equilibrium price, and thus the equilibrium quickly converges to one with a high volume of production and a competitive price. However, this outcome requires the producer to be willing to quickly produce a large quantity. An increasing marginal cost (or a capacity constraint) ensures that it is not optimal for producers to scale up production quickly. This force sustains higher markups and an effective price discrimination across periods. Consistent with this insight, in Appendix C.5 we find that capacity constraints reinforce the quantitative role of market power for price dynamics in response to shocks.

We also perform a comparative static of the equilibrium with respect to the depreciation rate δ, an inverse measure of the durability of the investment good. A positive depreciation rate is a further departure of our model from the theoretical model that Stokey (1981) analyzes. Durability affects market power through multiple channels. On the one hand, a more durable good implies that competition between current and future production is stronger. On the other hand, higher durability also affects the level of investment demand, potentially reducing the volume of production. In our calibrated model, we find that as the depreciation rate increases in a neighborhood of the baseline value, the steady-state markup rate increases slightly.

5.6 Role of Commitment

Finally, we investigate the role of our assumptions about commitment to future production. To this end, we contrast the Markov Perfect Equilibrium with the case of full commitment (Section 4.5). Figure 5 displays the transitional dynamics to the steady-state equilibrium for aggregate capital, multiplier on the investment Euler equation (γ_t), price of investment, and static markup.[10] The figure compares the Markov Perfect Equilibrium (solid lines) with the case of commitment (dashed lines).

First, we notice that in the presence of commitment the price of investment and the markup are substantially higher than in the Markov Perfect Equilibrium. As a result, capital converges to a lower steady-state level. In steady state, the static markup rate is approximately 130% with commitment and 16% in the Markov Perfect Equilibrium. Accordingly, in the presence of commitment, the welfare cost of oligopoly relative to first best equals 2.3% of permanent consumption, whereas in the Markov Perfect Equilibrium it equals 0.3% of permanent consumption.

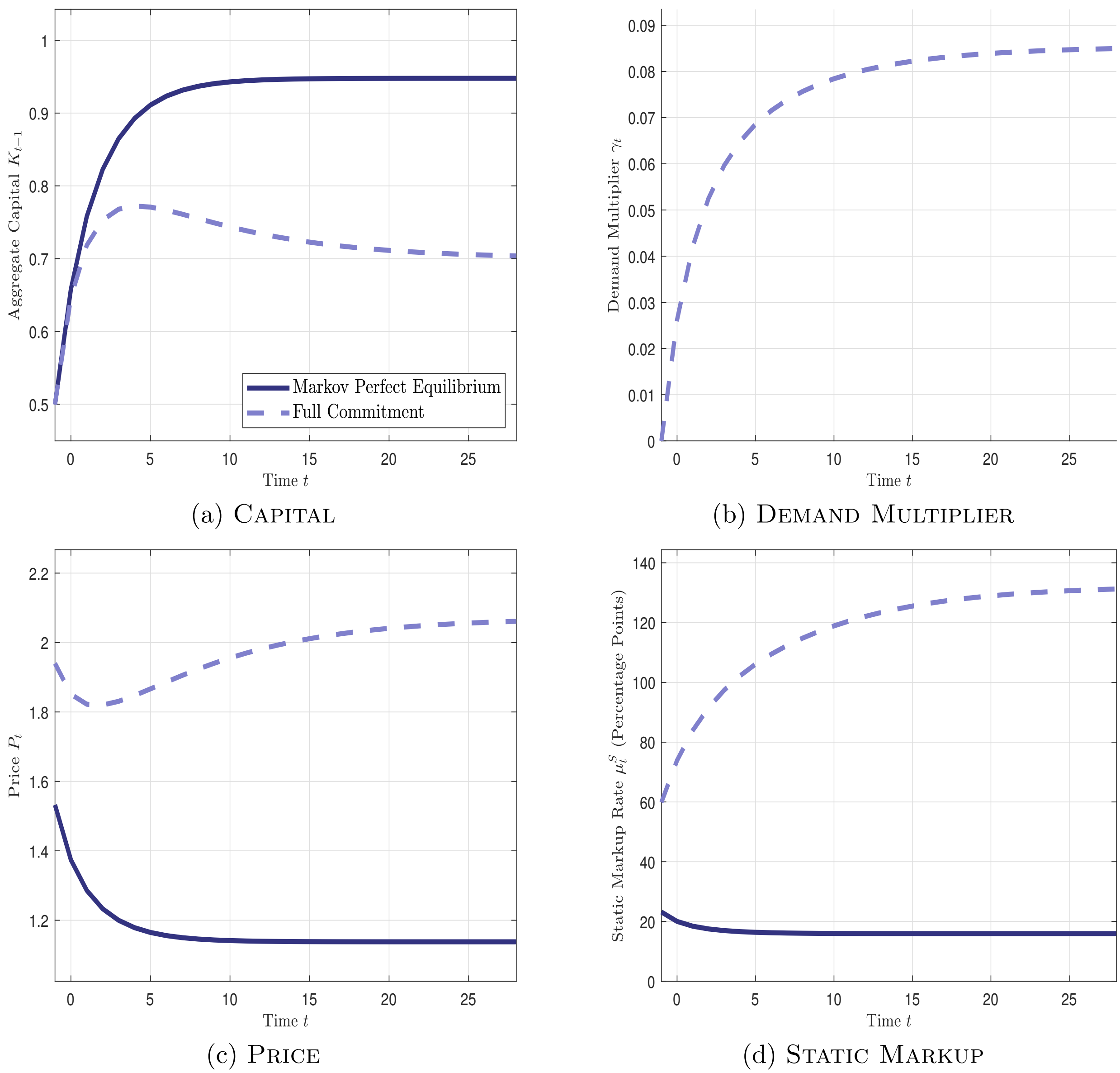
Second, by comparing the transition dynamics in the two regimes, we uncover the source of time inconsistency of the commitment plan. Under full commitment, at the beginning of the transition, when the multiplier is zero, each oligopolist has an incentive to set a relatively high level of production and, accordingly, a lower price than in the long run. As a consequence the domestic economy experiences an investment boom and overshoots its long-run level of capital. Over time, as the promise-keeping multiplier accumulates, the producer internalizes the effects of current prices on past prices through the investment Euler equation. Thus, markups grow, and the economy reverts to its steady-state level of capital. To confirm the crucial role of this multiplier, we perform again a decomposition of the difference between price and marginal cost as in Section 5.4. We report the results in

[10] We assume that the initial capital level equals half of the first-best steady state and that the initial multiplier on the investment Euler equation equals zero.

Appendix C.2.

These dynamics display a sharp contrast with the outcome in the absence of commitment, which, as we have seen, features decreasing price and markup as capital accumulates to the steady state.

Figure 5: Role of Commitment



(a) Capital (b) Demand Multiplier (c) Price (d) Static Markup

Notes: The figure compares the transition of the economy to the steady-state equilibrium without commitment (Markov Perfect Equilibrium, solid lines) and with full commitment (dashed lines). In both settings, we assume that the initial level of capital equals half of the first-best steady-state value. Panels (a), (b), (c), and (d) plot the transitions of aggregate capital K_{t-1}, demand schedule multiplier γ_t, price P_t, and static markup rate μ_t^S, respectively.

6 Shocks, Marginal Costs, and Markups

In this section, we analyze the effects of aggregate shocks, such as the ones experienced in the post-2020 global recovery. We first simulate an increase in the demand for investment goods, which accounts for an increase in both investment-goods prices and quantities produced. We leverage our analyses of the main forces in the model to quantify the roles of increasing marginal costs—akin to capacity constraints—and market power for the transitional dynamics of investment and prices. We then simulate the effects of an investment-cost shock. Finally, we analyze a stochastic version of our model with persistent business-cycle shocks.

6.1 Investment-Demand Shock

We now use the model to gain insight into the dynamics of the post-2020 recovery, when a rise in demand for durable goods—and thus for semiconductors—led to a dramatic increase in the price of equipment. Two factors likely contributed to this pattern. First, producers of semiconductors as well as other manufacturers overall experienced capacity constraints and other sources of increasing marginal costs. Second, these producers could exert market power and extract profits from the period of high demand. The calibrated model allows us to decompose these channels.

To this end, we simulate a positive unexpected shock to the demand for investment goods. Given our parsimonious model of the demand side—which features a production function with equipment as the only variable input—we proxy this increase in investment demand with a permanent increase in the level of TFP in the domestic economy. We calibrate this shock to match a 20% increase in the price of semiconductors during 2019-2023.

Figure 6 displays the aggregate dynamics in the model. The increase in productivity stimulates capital accumulation toward a higher steady-state level. Hence, the analysis of the main forces in the model of Section 5 is highly relevant to understand the results. On impact, the price of investment goods jumps and overshoots its long-run value. Quantitatively, price dynamics are predominantly accounted for by changes in the marginal cost, which increases by approximately 17% to accommodate the initially high level of production of investment goods. We also verify that the first-best equilibrium features similar price dynamics in response to the same shock, which confirms our finding on the predominant role of marginal costs.[11]

[11]In the first-best equilibrium the increase in aggregate capital is 0.3 percentage points larger than in the Markov Perfect Equilibrium.

At the same time, in the Markov Perfect Equilibrium, markups also increase on impact, although moderately, by approximately 2.5 percentage points. Consistent with our analysis of the transition to steady state in Section 5, the inverse elasticity of demand is initially high, as the domestic economy desires to exploit its high marginal return from capital, which justifies the higher markup. Then, markups decline as the domestic economy converges to the new steady state.

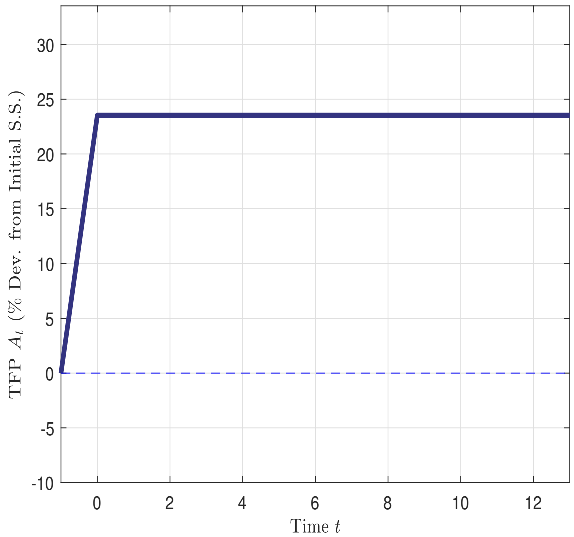
Overall, this analysis shows that in spite of the presence of market power and endogenous markups, the increase in the post-2020 relative price of equipment is driven to a large extent by technological features, such as increasing marginal costs. We obtain similar results in two alternative calibrations of the model: a broader definition of capital including structures, as in standard business-cycle models (Appendix C.3); and a narrower interpretation of oligopolistic investment goods as wafers (Appendix C.4).

Motivated by this finding, we further investigate the role of capacity constraints in the semiconductor industry in Appendix C.5. To this end, we generalize our specification of the cost function to allow for changes in the slope of marginal costs in response to large shocks. In the presence of capacity constraints, the increase in markups accounts for approximately one fourth of the equilibrium price increase after a demand shock. This finding confirms the importance of the convexity of the cost function for the determination of prices and markups in our model.

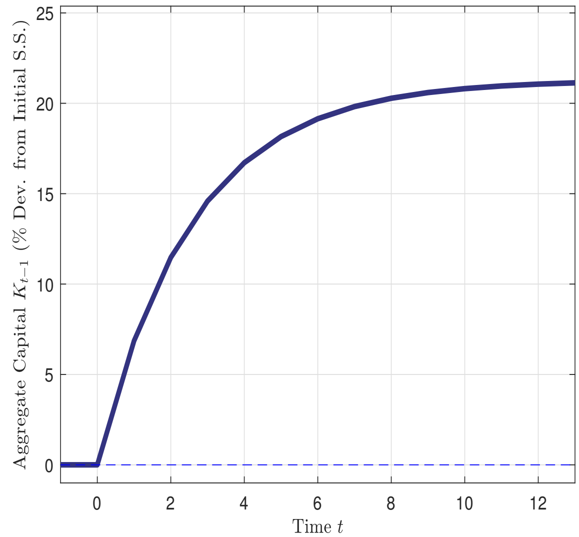
Because of decreasing returns to scale, our baseline model predicts that average—i.e., per unit sold—profits of investment-goods producers also increase significantly in response to the shock, despite a moderate increase in markups. All of these patterns are consistent with empirical evidence on production levels and profitability of semiconductor manufacturers during the post-2020 recovery, which we document in Appendix A. Specifically, we show that there was positive comovement of prices, quantities, and profit margins both using a broader notion of semiconductors and using more detailed data on a narrower category, namely wafers (for which we have more detailed data and perform a separate model calibration in Appendix C.4). This positive comovement of prices and production volumes confirms the important role of demand shocks in the recovery.

Finally, we analyze the effects of the investment-demand shock when investment-goods producers have full commitment. We report the results in Appendix C.6. In the presence of full commitment, markups decline in response to the shock. This scenario confirms that increasing marginal costs play a major role for the increase in the price of equipment.

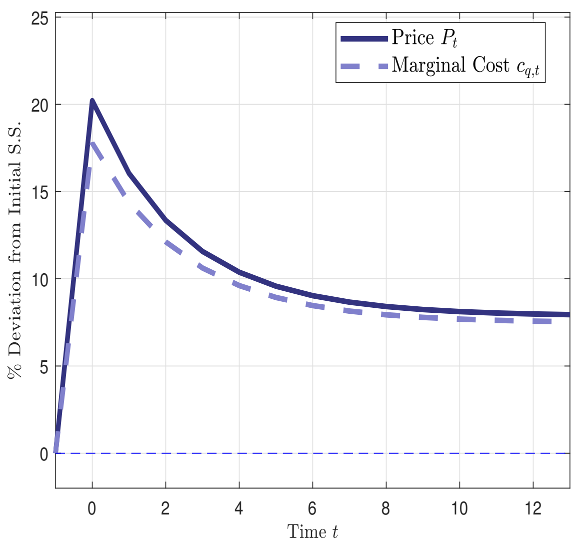
Figure 6: Investment-Demand Shock



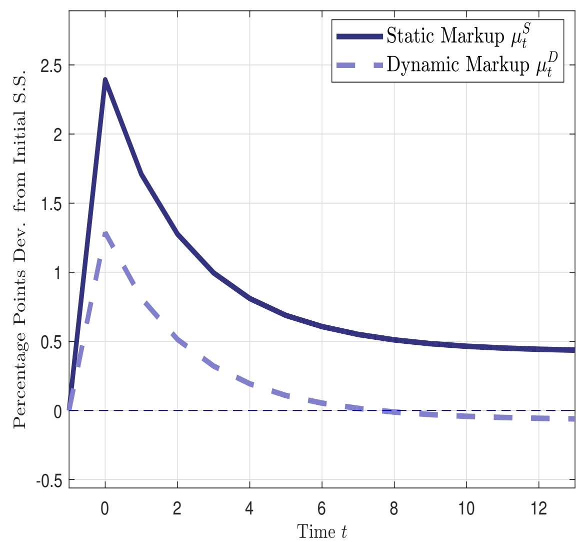
(a) TFP



(b) Capital



(c) Price and Marginal Cost



(d) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent increase in TFP in the Markov Perfect Equilibrium. Panel (a) plots the exogenous change in TFP A_t. Panel (b) plots the transition of aggregate capital K_{t-1} to the new steady state in the domestic economy. Panel (c) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (d) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

6.2 Investment-Cost Shock

Next, we investigate the effects of a shock that hits the production side of investment goods in the model. Specifically, we assume that the cost function is $Z_t c(q_{jt})$, with $Z_t = 1$ in the initial steady state. We then calibrate an increase in Z_t to match the same equilibrium price increase as in the previous subsection.

Figure 7 displays the aggregate effects of this shock in the model. The increase in the cost of producing investment goods induces a decline in the level of capital in the domestic economy. As the price of investment goods increases, markups decline, suggesting that the increase in cost reduces profitability at the margin. Nevertheless, the model predicts that average profits increase. Overall, we find that the demand shock better accounts for the empirical dynamics in the semiconductor industry during the post-2020 recovery, because both prices and quantities produced increased.

We also consider the contemporaneous occurrence of an investment-demand shock and an investment-cost shock. Because both shocks have a positive effect on prices, shocks of a smaller magnitude are needed to account for the large increase in the price of semiconductors we observe in the data. Most notably, in the presence of both shocks the model can quantitatively account for both the price increase and the increase in the volume of production of semiconductors during the post-2020 recovery.

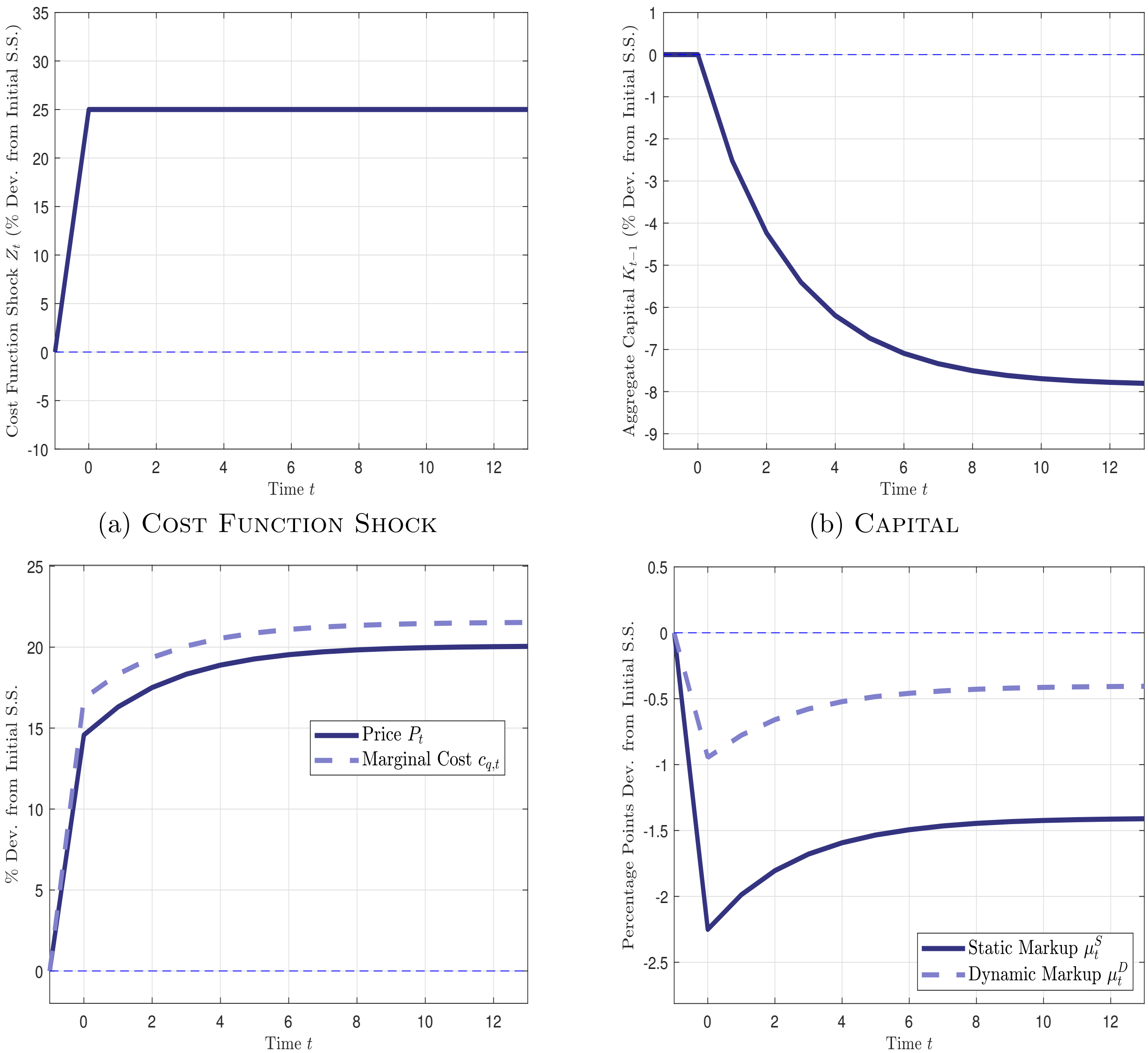
6.3 Business Cycles

Our model provides a microfoundation for capital adjustment costs and thus contributes broadly to the quantitative literature on investment over the business cycle, beyond the focus on the post-2020 recovery. To explore the business-cycle implications of our theory, we now extend our model to include stochastic productivity shocks in the domestic economy.

We assume that the production function is $Y_t = A_t K_{t-1}^{\alpha} L^{1-\alpha}$ and that productivity follows an AR(1) process in logs: $\log(A_t) = (1-\rho)\mu_A + \rho \log(A_{t-1}) + \varepsilon_t$. We parameterize the autocorrelation and standard deviation of innovations following the calibration of TFP shocks for the US economy in Khan and Thomas (2013)—i.e., $\rho = 0.909$ and $\sigma_\varepsilon = 0.014$. We provide all derivations of the stochastic model in Appendix B.4. In the presence of stochastic shocks, the GEE of a generic investment-goods producer becomes:

$$\theta P - \theta c_q(q) + qR^{-1}\mathbb{E}\left[\theta^{-1} f_{kk}(A', K') + (1-\delta)P_k(K', s')|s\right] + R^{-1}\mathbb{E}[V_k(K', s')|s] = 0,$$

Figure 7: Investment-Cost Shock



(a) Cost Function Shock (b) Capital (c) Price and Marginal Cost (d) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent 25% increase in the cost function coefficient Z. Panel (a) plots the exogenous change in Z_t. Panel (b) plots the transition of aggregate capital K_{t-1} to the new steady state in the domestic economy. Panels (c) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (d) plots the transition of static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

whereas the optimality conditions with commitment become:

$$q_t - \gamma_t + \gamma_{t-1}(1-\delta) = 0$$

$$\theta P_t - \theta c_q(q_t) + \gamma_t R^{-1} \mathbb{E}_t \left[\theta^{-1} f_{kk}(A_{t+1}, K_t)\right] - R^{-1}\theta(1-\delta)\mathbb{E}_t \left[(P_{t+1} - c_q(q_{t+1}))\right] = 0,$$

Table 2: Stochastic Productivity: Business Cycle Moments

	FB	MPE	FC
Mean I	0.135	0.128	0.095
Mean P	1.000	1.137	2.070
Mean Markup	0	0.160	1.323
St. Dev. I/St. Dev. Y	2.438	2.252	2.864
St. Dev. P	0.008	0.008	0.004
St. Dev. Markup	0	0.001	0.009
Corr. Y and I	0.970	0.977	0.957
Corr. Y and P	0.971	0.974	0.941
Corr. Y and Markup	0	0.924	-0.973

Notes: The table reports several moments related to investment, the price of the oligopolistic investment good, and the static markup rate, from a long a simulation of the model with stochastic productivity in the domestic economy. The first column refers to the first-best allocation, the second column to the Markov Perfect Equilibrium, and the third column to the case of full commitment. Standard deviations and correlations are computed for the logarithm of the variables, except for the markup rate, and the simulated data are HP-filtered with a smoothing coefficient equal to 6.25 for annual frequency.

Table 2 reports several business-cycle moments from a long simulation of the stochastic model. The stochastic model confirms the main insights that we have highlighted in the previous section. Prices and markups are higher on average in the presence of commitment. The model predicts a moderate business-cycle volatility and high procyclicality of prices and markups in response to productivity shocks, consistent with our findings on the effect of a permanent investment-demand shock.

In Appendix C.7, we extend the stochastic model to feature both TFP shocks and cost shocks in the production of investment goods, calibrated using data on equipment prices. The cost shock counters the procyclicality of the price of equipment and adds significant volatility to investment.

7 Policy Interventions

In this section, we analyze policy interventions to expand capacity and address market power of investment-good producers. In so doing, we aim to shed light on the likely effects of policies such as the US CHIPS and Science Act. We first consider entry subsidies in our model. We then analyze production subsidies. Finally, we formulate and solve a constrained planning problem. We stress that the geographic location of the production of investment goods is immaterial in the model and that production could take place in the domestic economy; our policy experiments are particularly relevant to understand US policy interventions targeting foreign firms, such as TSMC and Samsung, that carry out some operations in the US.[12]

7.1 Subsidizing Entry

Our findings on the implications of market power for capital accumulation motivate us to analyze the effects of a change in the number of producers. To this end, we first simulate an increase in the number of competitors from $N = 3$ to $N = 4$ and compute the equilibrium transitional dynamics after this regime change in the Markov Perfect Equilibrium.

We interpret this experiment as the outcome of a policy intervention that reduces the perceived entry cost for investment-goods producers. To determine the range of the implicit subsidy, we assume that the size of entry costs—which we did not model explicitly—would support $N = 3$ as the equilibrium market structure. Given the discreteness of the number of firms, entry costs are in a range such that at least three and at most four firms have a positive present discounted value of profits net of entry costs. Given this range for entry costs, to induce entry of one additional firm, a flow subsidy paid to each investment-good producer in every period would have an aggregate cost ranging between zero and 0.26% of steady-state consumption in the domestic economy.

Figure 8 displays the transition of the capital stock (left panel) as well as price and marginal cost of investment (right panel). As the number of producers increases, total capacity expands and competition rises. Given any level of aggregate investment, a larger production capacity reduces individual quantities, thus reducing the marginal cost. This contributes to a decline in the price, inducing more capital accumulation in the domestic economy. Furthermore, over time, higher competition depresses markups, and thus the equilibrium price drops by approximately 60% more than the marginal cost. In turn, this price decline further stimulates capital accumulation. The welfare gain in the domestic economy, without accounting for subsidies, equals approximately 0.25% of permanent consumption.

Remarkably, increasing the number of competitors from $N = 3$ to $N = 4$ almost closes the difference in price and capital level between the new Markov Perfect Equilibrium steady state ($N = 4$) and the first-best steady state associated with $N = 3$. The first-best steady state associated with $N = 4$ features an even higher level of capital and a lower price, because a larger number of producers reduces the marginal cost of investment. Nonetheless, going from $N = 3$ to $N = 4$ reduces by approximately one third the steady-state gaps in

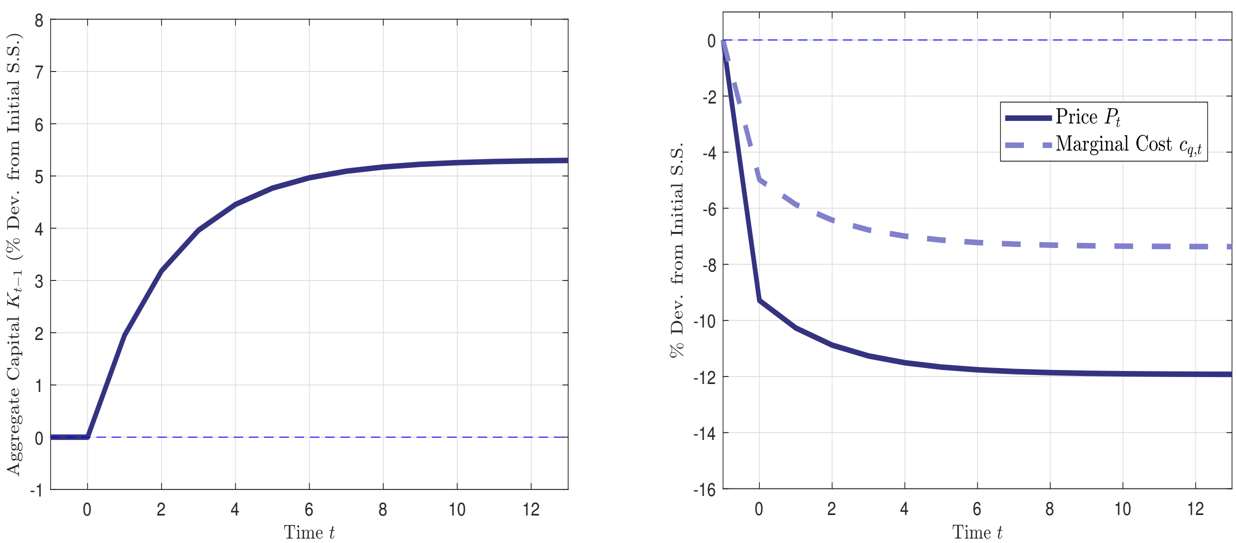
[12] See, for instance, the operations of TSMC Arizona (https://www.tsmc.com/static/abouttsmcaz/index.htm).

price and capital level between the Markov Perfect Equilibrium and the first-best allocation.

These results highlight the quantitative importance of the long-run distortion imposed by market power in investment goods. A caveat in interpreting the short-run results of this experiment, however, is that our focus on symmetric equilibrium implies that new entrants have the same level of technology as incumbents. The cost of this policy in the real world is likely larger to the extent that it should account for a transition period over which entrants learn the frontier technology. In Section 8 we introduce learning by doing in our model, although in symmetric equilibrium.

We also simulate this increase in competition in the case of full commitment and report the results in Appendix C.6. In this case, we obtain an even larger effect of entry on markups, prices, and capital accumulation.

Figure 8: Increase in the Number of Investment-Goods Producers



(a) Capital (b) Price and Marginal Cost

Notes: The figure illustrates the response of the economy in the Markov Perfect Equilibrium to an unanticipated and permanent increase in the number of investment-goods producers from $N = 3$ to $N = 4$. Panel (a) plots the transition of domestic economy's aggregate capital stock K_{t-1} to the new steady state. Panel (b) plots the transition of the investment price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

7.2 Subsidizing Capacity

Next, we investigate an alternative scenario in which we engineer a reduction in the marginal cost of the same magnitude by flattening the cost function instead of increasing the number of firms. Specifically, we approximate the effects of a relaxation of capacity constraints with a reduction in the value of c_2, thus reducing the cost convexity, and focus on the Markov Perfect Equilibrium.

We can interpret this counterfactual as the result of a cost subsidy τ, such that investment-goods producers perceive an effective cost function $c(q)(1-\tau(q))$. The function τ is designed to obtain the desired flattening of the marginal cost. Quantitatively, the subsidy rate is approximately equal to 0.085 in steady state and it implies a larger total fiscal cost than the entry subsidy of the previous subsection.[13]

Figure 9 displays the results. Although we target a decline in the marginal cost of the same magnitude as in the previous subsection, the comparison of this figure with Figure 8 reveals that only the change in market structure generates an additional price reduction due to the endogenous compression in markups.

Quantitatively, given a 7.4 percent reduction in the steady-state marginal cost, the investment subsidy determines a price decline equal to 7.9 percent. In contrast, increasing the number of competitors from $N = 3$ to $N = 4$ decreases the price by 11.9 percent. In terms of welfare, the increase in the number of producers leads to a permanent-consumption gain that is approximately 50% larger than the one implied by the counterfactual in which we flatten the cost curve. This analysis shows that the design of policy interventions aimed at expanding capacity in the semiconductor manufacturing industry should take into account the effect of these policies on the market structure.

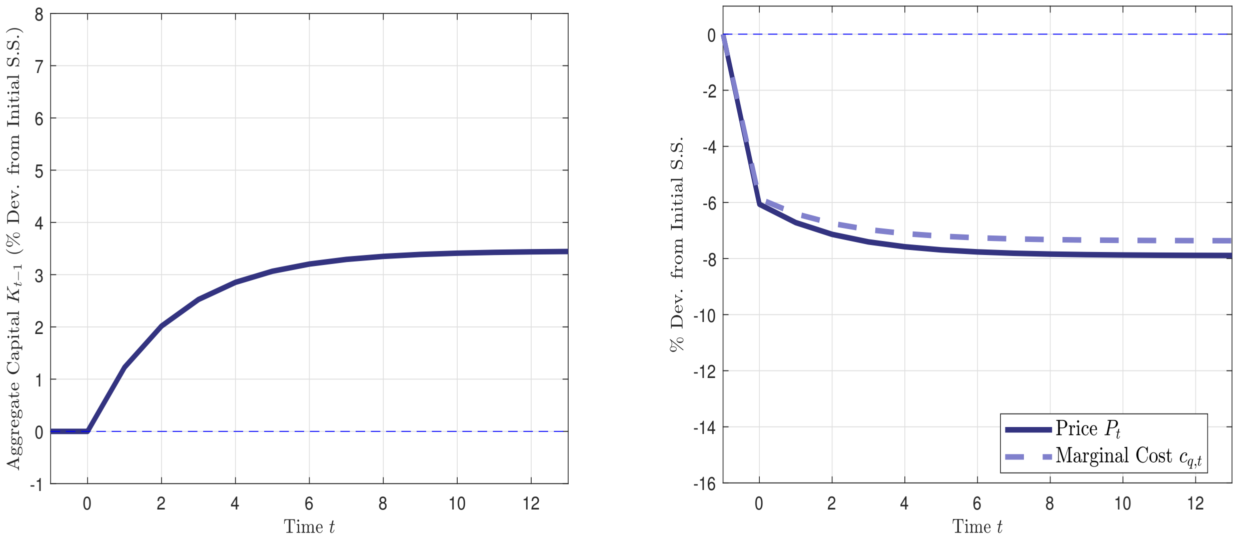
7.3 Constrained Efficiency

We conclude our policy analysis by formulating and solving a constrained planning problem. We see this analysis as a first step toward a macroeconomic theory of optimal industrial policy in durable-good industries with market power.

We consider a benevolent planner that operates N investment-goods producers to maximize welfare in the domestic economy, subject to the participation constraint that investment-goods producers must achieve a minimum level of profits and there are no lump-sum transfers between domestic economy and foreign firms. The planner is also subject to the capital accumulation equation (1) and the investment Euler equation (6), has

[13]We verify in Appendix C.8 that the function τ is approximately linear in the quantity produced around the steady state. The per-period aggregate cost of the subsidy would equal 1.3% of steady-state consumption.

Figure 9: Relaxation of Capacity Constraints



(a) Capital (b) Price and Marginal Cost

Notes: The figure illustrates the response of the economy in the Markov Perfect Equilibrium to an unanticipated and permanent decline in the slope of the marginal cost function from $c_2 = 22$ to $c_2 = 16.8$. Panel (a) plots the transition of the aggregate capital stock K_{t-1} to the new steady state. Panel (b) plots the transition of the investment price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

full commitment, and thus chooses an infinite sequence of production levels and prices.

We show in Appendix B.2 that the constrained-efficient allocation satisfies the following optimality conditions:

$$\nu_t = \eta\theta\left(P_t - c_q(q_t)\right) - u_c(C)\left(\theta P_t + 1 - \theta\right) \quad (24)$$

$$Nq_t\left(\eta - u_c(C)\right) = \Gamma_t - (1-\delta)\Gamma_{t-1} \quad (25)$$

$$\nu_t = R^{-1}\left((1-\delta)\nu_{t+1} - u_c(C)f_k(K_t) - \theta^{-1}\Gamma_t f_{kk}(K_t)\right), \quad (26)$$

where ν_t denotes the multiplier on the capital accumulation equation, η the multiplier on investment-good producers' participation constraint, and Γ_t the multiplier on the investment Euler equation.

As equation (24) reveals, the planner's shadow value of capital balances the need to deliver profits through markups with the incentive to increase welfare by increasing production and thus reducing investment prices. Furthermore, as in the case of oligopoly with commitment (Section 4.5), the path of production leads to an accumulation of multipliers on past investment Euler equations through equation (25). Similarly, equation (26) dictates the optimal evolution of markups over time and thus replaces equation (20).

We solve for the constrained-efficient allocation assuming that the initial condition is the steady state of the Markov Perfect Equilibrium under our baseline calibration. We illustrate the solution in Appendix C.9. We find that, in the short run, the planner increases the level of production of investment goods and reduces the price, which leads to a protracted period of positive capital accumulation and high output in the domestic economy, consistent with our experiments with simple policy interventions to expand capacity.

In the long run, however, the accumulation in the multipliers on past investment Euler equations advises the planner to increase prices and, in so doing, deliver profits to investment-good producers and ensure that their participation constraint is satisfied. Accordingly, the level of capital in the constrained-efficient steady state is lower than in the Markov Perfect Equilibrium. This critical role of the multiplier Γ_t as a state variable reinforces the relevance of our theoretical and quantitative analysis of the role of commitment.

8 Learning by Doing

Our analysis has assumed that the technology to produce investment-goods is exogenous. We now generalize our model to allow for endogenous technological progress in the form of learning by doing (Arrow, 1962). A large literature analyzes technological progress that reduces the cost of investment goods (e.g., Greenwood, Hercowitz, and Krusell, 1997) and a growing literature focuses on learning-by-doing spillovers specifically in the semiconductor industry (e.g., Irwin and Klenow, 1994; Goldberg, Juhász, Lane, Lo Forte, and Thurk, 2024; Miao, 2024). Our model allows us to analyze the interactions between market power and learning by doing for investment-goods producers.

To this end, we now assume that the cost function is $c(q, K)$ with $c_q > 0, c_{qq} \geq 0$, and, critically, $c_k < 0$. We assume that production costs decrease as past accumulated sales of the industry—parsimoniously approximated by the aggregate capital stock K—increase. This formulation implies both internal effects of production on future technology as well as spillovers on other producers.

We focus on the Markov Perfect Equilibrium and, thanks to our formulation of learning by doing, there is again a single state variable, the aggregate capital stock. The optimality conditions and the dynamic markup rule of Proposition 1 are as in Section 4, with the following modifications. First the marginal cost of production is now given by the partial derivative $c_q(q, K)$. Second, the Envelope condition reads as follows:

$$V_k(K) = -\theta \left(1 - \delta + \left(\frac{N-1}{N}\right) I_k(K)\right) \left(P - c_q \left(\frac{\theta I(K)}{N}\right)\right) - c_k(q, K), \qquad (27)$$

where the new term is the last partial derivative on the right-hand side, which denotes the internalized reduction in cost due to the learning by doing associated with higher production. Because $c_k(q, K)$ is negative, a higher aggregate capital stock is associated with higher productivity, and thus a higher marginal value, for investment-goods producers.

As a result, the trade-off associated with producing an additional unit of future capital is now richer. As in the case without learning by doing, higher production implies higher current profits at the expense of future profits. Furthermore, it now implies faster technological progress, which reduces future costs.

We parameterize the cost function as follows:

$$c(q, K) \equiv \left(c_1 q + c_2 q^2\right) \left(1 + \mathcal{I}\left(K \leq \tilde{K}\right) \frac{1}{\chi} \left(1 - \frac{K}{\tilde{K}}\right)^{\chi}\right), \qquad (28)$$

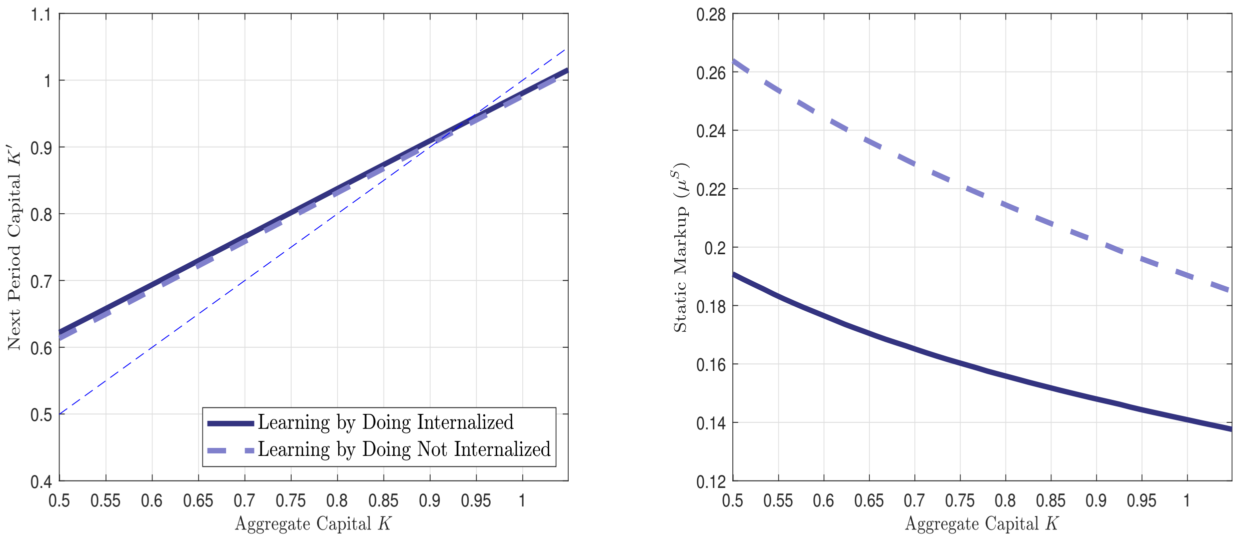
where $\tilde{K}$ denotes an upper bound for the level of aggregate capital such that learning by doing is active below this upper bound; $\mathcal{I}\left(K \leq \tilde{K}\right)$ is an indicator function, which is equal to 1 when aggregate capital is lower than the upper bound and 0 otherwise and $\chi > 0$ is a parameter the determines the speed of learning by doing.[14]

We calibrate $\chi = 1.8$ so that when the aggregate capital stock doubles in size (from 0.5 to 1 approximately), the marginal cost of production decreases by 14%, an intermediate value in the range of empirical estimates for learning by doing in semiconductor manufacturing. We set $\tilde{K} = 1.3$, which implies that the upper bound for learning by doing is sufficiently large that it is not reached in equilibrium in our simulations.

In Figure 10, we illustrate our main findings on this extended version of the model, comparing the case in which firms internalize learning by doing (solid lines) with the case in which the cost function evolves according to equation (28), but firms do not internalize the effects of their production on future cost functions—i.e., the last term in equation (27) is not present—(dashed lines). The left panel displays the law of motion for aggregate capital. Although the path of capital accumulation is similar in the two scenarios, when learning by doing is internalized, the level of investment in the domestic economy is higher and the economy reaches a steady state with a 2% higher level of capital.

[14] In the case of semiconductors, where technological improvements manifest to a large extent in the *size* of semiconductors, there is a physical lower bound for the size of components that justifies the assumption of an upper bound for learning (e.g. Miao, 2024). In other applications, it is possible to assume that $\tilde{K}$ is a large number to obtain long-lived effects of learning in the model.

Figure 10: Capital Accumulation and Markups with Learning by Doing



(a) Capital Accumulation (b) Static Markup

Notes: The figure displays capital accumulation and markups in the Markov Perfect Equilibrium (MPE) with learning by doing. Solid lines refer to the case in which firms internalize learning by doing. Dashed lines refer to the case in which the cost function evolves according to equation (28), but firms do not internalize the effects of their production on future cost functions. In panel (a), the two lines represent next-period capital (y-axis) as a function of current capital (x-axis). The intersection with the 45-degree dashed line identifies the steady-state MPE. Panel (b) displays static markups μ^S as function of the aggregate capital stock.

To explain this finding, the right panel shows that investment-good producers optimally charge a lower markup when they internalize learning by doing, because they have an incentive to increase production and reduce future costs. Higher production is associated with a lower price of investment goods. This incentive is stronger early in the transition when there is more scope for learning. Hence, the internalization of learning by doing flattens the static markup rate as a function of aggregate capital.

We highlight that the transitional dynamics in this version of the model feature an endogenous decline in the price of investment goods, consistent with empirical evidence, both due to a decline in the marginal cost and due to a decline in the endogenous markup.

Appendix C.10 illustrates the response of the economy to a positive shock to demand for investment goods in this version of the model. Learning by doing does not significantly affect our quantitative conclusion that the increase in the price of investment is predominantly driven by the response of marginal costs. Indeed, the flattening of markups with respect to the aggregate capital stock illustrated in Figure 10 contributes to dampen the increase in markups in response to the shock.

In the same appendix, we also analyze a policy intervention to increase the number of investment-goods producers in the presence of learning by doing. In this case, the policy generates a larger steady-state reduction in marginal cost (8.4%) and price (12.3%) relative to the case without learning by doing.

9 Conclusion

We have developed an open-economy model with market power in the global production of investment goods. Our analysis was originally motivated by the post-2020 global recovery, which featured a large increase in demand for inputs produced by a highly concentrated industry, such as semiconductors. This aggregate shock fueled a sharp increase in the price of durable goods and contributed to overall inflation during the recovery. Beyond this specific episode, our general model allows us to analyze the macroeconomic effects of market power in durable input markets.

In our framework, the price of investment goods equals the sum of a marginal cost—which can be affected by capacity constraints—and an endogenous markup, which depends critically on the level of demand for investment goods. When investment-goods producers behave as oligopolists without commitment, the markup rises in response to positive shocks to investment demand, thereby generating a microfounded aggregate capital adjustment cost.

When we calibrate the model to the post-2020 recovery, we find that increasing marginal costs likely played a major role in the increase in equipment prices, leaving a more moderate role for markup hikes, despite an overall increase in profits. By allowing this decomposition of the roles of technology and market power for price dynamics, our model contributes to the debate on the so-called "greedflation" in the recovery.

The model also provides a useful laboratory to analyze policy interventions that aim to increase the productive capacity in the global semiconductors industry. Our counterfactual analyses show that interventions that increase the number of producers may be particularly effective in stimulating capital accumulation because they expand aggregate capacity and reduce the long-run distortion induced by market power.

In future work, the characterization of equilibrium markups in our model will also prove useful to analyze richer economies with multiple types of capital goods and multiple sectors with heterogeneous market structures, thus closing the gap between models with durable goods and recent empirical analyses of aggregate trends in market power.

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SUPPLEMENTAL APPENDIX

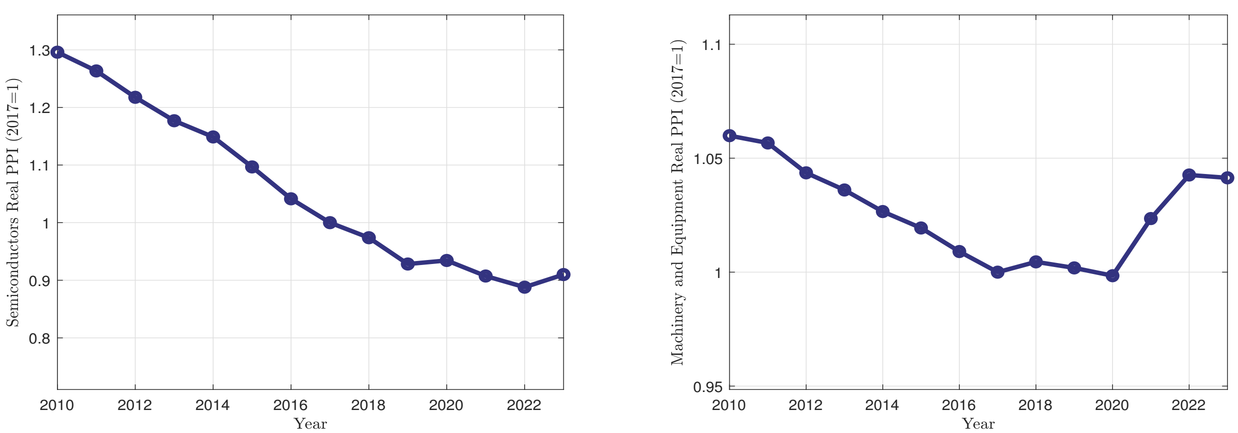
A Additional Empirical Evidence

A.1 Dynamics of Equipment and Semiconductors Investment

In this subsection we further analyze the dynamics of US investment during the post-2020 recovery and connect them with the evolution of equipment and semiconductors prices presented in Figure 1.

We first re-examine price dynamics by analyzing the evolution of the *level* of equipment and semiconductors real price-indexes (Figure A1). Both prices were on a declining long-run trend before the 2020 recession, when both series rose not only in deviation from their trend but, remarkably, in absolute terms too.

Figure A1: Semiconductor and Equipment Price Dynamics in Levels



(a) Real Semiconductors PPI (b) Real Machinery & Equipment PPI

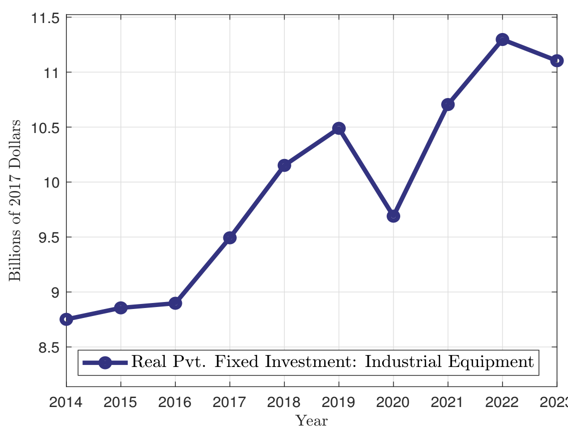
*Notes:*The figure displays the US Producer Price Index of Semiconductors (panel a, FRED series `PCU334413334413A`) and the US Producer Price Index of Machinery and Equipment (panel b, FRED series `WPU11`) during 2010-2023. Both series are normalized to equal one in 2017 and deflated using the US GDP deflator (FRED series `A191RD3A086NBEA`).

Next, we turn to investment quantities. Figure A2a illustrates real industrial equipment investment in the US. Its dynamics suggest that investment demand has been strong during the post-2020 recovery. After the sharp 7.6% decline between 2019 and 2020, the series displays a robust recovery in both 2021 (+10% relative to 2020) and 2022 (+16% relative to 2020). Consistent with such strong recovery, in 2021 real investment in industrial equipment was approximately 5% higher than its long-run trend estimated over 2000-2019. Therefore, an increase in real quantities accompanies the 7% rise in the real price of machinery and equipment documented in Figure 1.

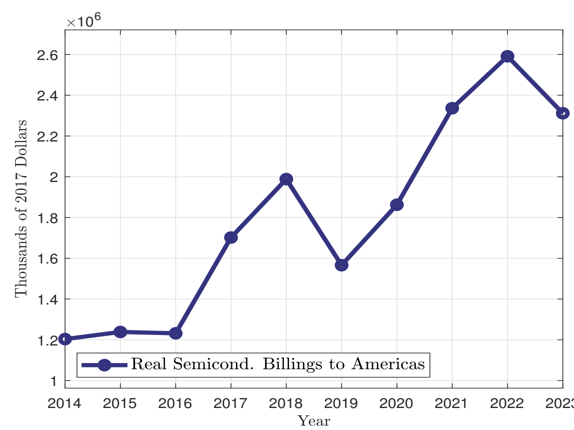
Figure A2b illustrates similar dynamics for semiconductors, a key component of industrial equipment. We proxy real investment in semiconductors by real semiconductors billings to Americas obtained from the Semiconductors Industry Association.[15] We deflate the nominal value of billings by the US Semiconductors Producer Price Index (FRED series `PCU334413334413A`). Consistent with the rise of investment in industrial equipment in the post-2020 recovery, semiconductors demand increased by approximately 40% between 2020 and 2022, being 45% above its 2000-2019 trend in 2022. Therefore, also for semiconductors both quantity and real price rose after 2020.

Finally, we observe similar dynamics for US real investment in Information Technology equipment, tightly linked to demand for semiconductors, as well as in worldwide semiconductors billings.

Figure A2: Equipment and Semiconductors Investment



(a) Real Investment in Equipment



(b) Real Semic. Billings to Americas

Notes: Panel (a) displays real US Industrial Equipment Investment, computed as nominal US Industrial Equipment Investment (FRED series `A680RC1Q027SBEA`) divided by US Equipment Price Deflator (FRED series `Y033RD3Q086SBEA`). Panel (b) displays Semiconductors Billings to Americas provided by the Semiconductors Industry Association, converted to real 2017 US dollars by dividing the series by the US Semiconductors Producers Price Index (FRED series `PCU334413334413A`).

A.2 Quantities, Prices, and Profitability in Wafer Production

In this subsection, we zoom in on quantity and price dynamics of wafer foundries. Wafers are a crucial component of chips manufacturing for which we can precisely measure physical quantities produced and unit prices. To this end, we rely on Taiwan's Ministry of Economic Affairs data on yearly production and sales of three detailed product categories

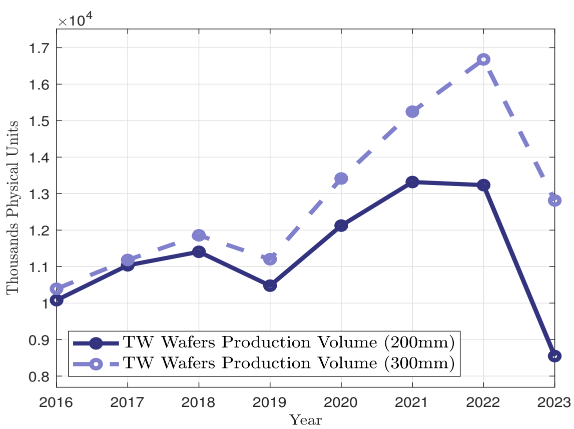
[15]The geographical granularity of the data does now allow us to focus specifically on the US, which, however, should count for the vast majority of recorded orders to Americas.

of wafer foundry: 12 inches and above (300mm); 8 inches (200mm); and 6 inches and below (150mm).[16].

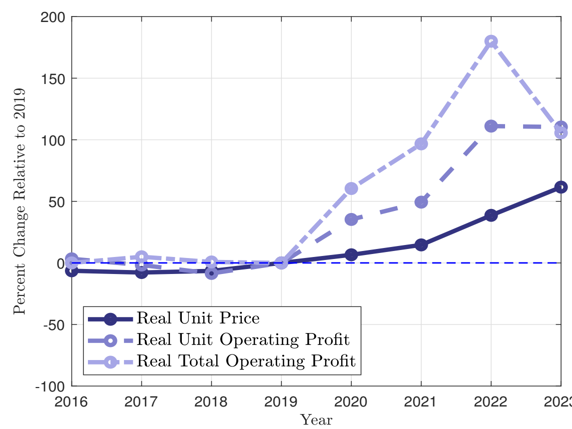
Wafer production is very concentrated globally. Taiwan Semiconductors Manufacturing Corporation (TSMC), whose plants are largely based in Taiwan, is the only player among the largest 10 producers in terms of installed capacity in all foundry categories (300mm, 200mm, 150mm).[17] Therefore, focusing on Taiwan provides an accurate account of the dynamics of global production volumes and unit prices.

We start by analyzing the dynamics of physical production volumes in Figure A3a, distinguishing by wafer size. After a decline in production in 2019, which narrative industry accounts link to a decline in global demand, production volumes display a fast rise in 2020 and during the post-2020 recovery. This is consistent with strong demand for semiconductors and overall higher final demand for manufacturing goods. Sales volumes display similar dynamics.

Figure A3: Volumes of Production by Wafer Size



(a) Wafer Production



(b) Prices and Margins

Notes: Panel (a) displays the dynamics of wafers production volumes in Taiwan, sourced from Taiwan's Ministry of Economic Affairs.The solid (dashed) line refers to wafer size smaller or equal than 200mm (300mm) and it is computed as the sum of production volumes for product codes 2611110 and 2611120 (2611130 for the dashed line). Panel (b) represents the dynamics of average real unit prices (solid line), average real unit operating profit (dashed line), and total real operating profit (dashed-dotted line) for wafer foundry in Taiwan. All series are expressed in percent deviation from their level in 2019.

Next, we analyze the dynamics of average unit prices, which we obtain by dividing production values (in New Taiwan Dollars) by physical volumes. We covert average unit

[16]We downloaded the data from https://dmz26.moea.gov.tw in April 2024. The relevant product codes are 2611110, 2611120, and 2611130.

[17]As of December 2020, TSMC had the second-largest installed capacity (15% of global capacity) after Samsung (21%) for 300mm wafers; it had the largest installed capacity (10%) for 200mm wafers; and it had 3% of installed capacity for 150mm wafers. *Source:* https://www.design-reuse.com/news/49551/tsmc-top-10-capacity-three-wafer-size-categories.html.

prices to real US Dollars using FRED's exchange rate series (`DEXTAUS`) and US GDP deflator. The solid line in Figure A3b displays average unit price dynamics around 2020, expressed in percent deviation from 2019 level. The real price of wafers increases dramatically starting from 2020, with a cumulative change of approximately +60% between 2019 and 2023. Therefore, wafers replicate the positive co-movement of prices and quantities already documented for US industrial equipment and semiconductors.

Finally, we investigate the evolution of real unit margins and profits. We combine production volume data with balance-sheet variables for TSMC and Mediatek, the other Taiwanese foundry, from Orbis. We compute real average unit margins as Operating Profits (EBIT)—i.e., the difference between total sales and cost of goods sold plus depreciation and amortization—deflated by the US GDP deflator and divided by sales volumes data from Taiwan's Ministry of Economic Affairs.

In Figure A3b the dashed line depicts real unit margins in percent deviation from their 2019 level. The cumulative increase over 2023-2019 equals approximately 110%, which is almost twice as large as the increase in unit prices. The relative magnitude of the price and unit margin effect is consistent with the model predictions in response to a demand shock, which we study in Appendix C.4 for an alternative calibration of the model where wafers represent the oligopolistic investment good.

Moreover, in Figure A3b the dashed-dotted line represents the evolution of aggregate real Operating Profits for TSMC and Mediatek, in percent deviation from 2019. Total profits result from the combination of changes in average unit margin (dashed line) and volumes sold (Figure A3a). As quantities also increase markedly during the post-2020 recovery, the increase in total operating profits exceeds the increase in average unit margins. This finding is also qualitatively consistent with the model's response to a positive demand shock analyzed in Appendix C.4.

Our analysis combines balance sheet data of individual companies with country-wide administrative data on production volumes. To address potential concerns of this approach, we first note that TSMC and Mediatek account for virtually all wafer production capacity in Taiwan. Therefore, government's statistics should provide an accurate account of TSMC and Mediatek production volumes. Second, to validate our approach we compute an alternative measure of average unit prices dividing TSMC's and Mediatek's total sales from Orbis by production volumes from Taiwan's Ministry of Economic Affairs. We then verify that the dynamics of this alternative measure are similar to those displayed in Figure A3b (solid line) for average unit prices computed using administrative data only.

B Additional Model Derivations

B.1 First-Best Planning Problem

In this subsection we present the first-best planning problem. The social planner chooses sequences $\{C_t, B_t, q_{jt}, K_t\}$ for $j = 1, .., N$ and $t = 0, .., \infty$ to maximize household utility (1) subject to the resource constraint

$$C_t + \sum_{j=1}^{N} c(q_{jt}) + X_t + B_t = f(K_{t-1}) + \beta^{-1} B_{t-1},$$

with multiplier $\beta^t \lambda_t$, where $X_t = \theta^{-1}(1-\theta)\sum_{j=1}^{N} q_{jt}$ and where we used $R = \beta^{-1}$, as well as the capital accumulation equation

$$K_t = \theta^{-1} \sum_{j=1}^{N} q_{jt} + (1-\delta) K_{t-1},$$

with multiplier $\beta^t \nu_t$.

The optimality conditions are

$$\begin{aligned} u_c(C_t) &= \lambda_t \\ \lambda_t &= \lambda_{t+1} \\ \lambda_t \left(c_q(q_{jt}) + \theta^{-1}(1-\theta) \right) &= \theta^{-1} \nu_t \\ \nu_t &= \beta \left(\lambda_{t+1} f_k(K_{t-1}) + (1-\delta) \nu_{t+1} \right), \end{aligned}$$

which imply symmetric production $q_{jt} = q_t = \frac{\theta I_t}{N}$ for all j if $c_{qq} > 0$, and can be combined to obtain equation (9):

$$\theta c_q \left(\frac{\theta I_t}{N} \right) + 1 - \theta = R^{-1} \left(f_k(K_t) + (1-\delta) \left(\theta c_q \left(\frac{\theta I_{t+1}}{N} \right) + 1 - \theta \right) \right).$$

B.2 Constrained Efficiency

In this subsection we formulate a more general version of the planning problem and characterize the efficient allocation given the friction of market power in investment goods. The planning problem nests first best as a special case, when there are lump-sum transfers between consumer and producers.

We assume that participation of investment-goods producers requires that the present discounted value of profits has to be at least equal to the present discounted value of a perpetuity that pays $\underline{\pi} > 0$, a fixed cost of operation. We can interpret this present discounted value as an entry cost, which justifies the market structure with N producers.

With lump-sum transfers across agents. The budget constraint in the domestic economy reads:

$$C_t + (\theta P_t + 1 - \theta)\,\theta^{-1} \sum_{j=1}^{N} q_{j,t} + B_t = f(K_{t-1}) + RB_{t-1} - \sum_{j=1}^{N} T_{j,t}.$$

The participation constraint is

$$\sum_{t=0}^{\infty} R^{-t}\left(P_t q_{jt} - c(q_{jt}) + T_{j,t} - \underline{\pi}\right) \geq 0.$$

We can recover the first-best plan by setting $T_{j,t} = \underline{\pi} - (P_t q_{jt} - c(q_{jt}))$. Substituting this transfer in the budget constraint, we obtain the resource constraint:

$$C_t + \sum_{j=1}^{N} c(q_{j,t}) + N\underline{\pi} + (1-\theta)\,\theta^{-1} \sum_{j=1}^{N} q_{j,t} + B_t = f(K_{t-1}) + RB_{t-1},$$

which coincides with the one in Appendix B.1, except for the fixed cost $\underline{\pi}$, which does not affect the first-order conditions of the planning problem.

Without lump-sum transfer across agents. In the absence of lump-sum transfers ($T_{j,t} = 0$), we obtain the "constrained-efficient" allocation of Section 7.3 because redistribution between the domestic economy and investment-good producers is only possible through prices. The allocation must satisfy the Euler equation, which we assume the planner cannot distort. The planner's objective is again welfare in the domestic economy:

$$\sum_{t=0}^{\infty} R^{-t} u(C_t). \tag{B1}$$

The maximization is subject to the participation constraint

$$\sum_{t=0}^{\infty} R^{-t}\left(P_t q_{jt} - c(q_{jt}) - \underline{\pi}\right), \geq 0,$$

for all j, with multiplier η_j, the resource constraint

$$C_t + (\theta P_t + 1 - \theta)\,\theta^{-1} \sum_{j=1}^{N} q_{j,t} + B_t = f(K_{t-1}) + RB_{t-1},$$

with multiplier $R^{-t}\lambda_t$, the investment Euler equation

$$P_t = R^{-1}\left(\theta^{-1} f_k(K_t) + (1-\delta)P_{t+1}\right) - \kappa,$$

with multiplier $R^{-t}\Gamma_t$, and the capital accumulation equation

$$K_t = (1-\delta)K_{t-1} + \theta^{-1}\sum_{j=1}^{N} q_{jt},$$

with multiplier $R^{-t}\nu_t$.

The planner's first-order optimality conditions are

$$\begin{aligned}
\lambda_t &= u_c(C_t) \\
\lambda_t &= \lambda_{t+1} \\
\nu_t &= \eta_j\theta\left(P_t - c_q(q_{j,t})\right) - \lambda_t\left(\theta P_t + 1 - \theta\right) \\
\sum_{j=1}^{N} q_{j,t}\left(\eta_j - \lambda_t\right) &= \Gamma_t - (1-\delta)\Gamma_{t-1} \\
\nu_t &= R^{-1}\left((1-\delta)\nu_{t+1} - \lambda_{t+1} f_k(K_t) - \theta^{-1}\Gamma_t f_{kk}(K_t)\right)
\end{aligned}$$

Using the first two optimality conditions in the other three equations, we obtain equations (24), (25), and (26).

Furthermore, we note that the planning problem with a participation constraint is equivalent to an alternative planning problem with objective:

$$\omega\sum_{t=0}^{\infty} R^{-t}u(C_t) + \frac{(1-\omega)}{N}\sum_{t=0}^{\infty} R^{-t}\left(P_t\sum_{j=1}^{N} q_{jt} - \sum_{j=1}^{N} c(q_{jt})\right),$$

and without participation constraint. To see the equivalence between the two problems, we can normalize the weight on the consumer to 1 dividing the objective function by ω and let the multiplier $\eta_j = \eta$ play the role of the effective planner weight on profits to achieve a given present discounted value of $\underline{\pi}$.

This equivalent formulation highlights that the problem also nests two other important settings. First, the collusion case, where the planner maximizes the joint profits of investment-good producers disregarding consumer welfare ($\omega = 0$). We analyze collusion in Section B.3. Second, the full-commitment problem of a single investment-goods producer, if positive weight is attributed on one firm only.

B.3 Commitment with Collusion

In this subsection we analyze the equilibrium under both commitment and collusion. A planner chooses sequences of prices and quantities for all N producers, $\{P_t, q_{jt}\}$, for $t = 0, .., \infty$ and $j = 1, .., N$ to maximize

$$\sum_{t=0}^{\infty} R^{-t} \left(P_t \sum_{j=1}^{N} q_{jt} - \sum_{j=1}^{N} c(q_{jt}) \right),$$

subject to

$$P_t = R^{-1} \left(\theta^{-1} f_k(K_t) + (1-\delta) P_{t+1} \right) - \kappa,$$

for $t = 0, 1, ..,$ with multiplier $R^{-t}\Gamma_t$, and

$$K_t = (1-\delta) K_{t-1} + \theta^{-1} \sum_{j=1}^{N} q_{jt},$$

with multiplier $R^{-t}\nu_t$.

The first-order conditions with respect to P_t, q_{jt}, and K_t are:

$$\begin{aligned}
\sum_{j=1}^{N} q_{jt} - \Gamma_t + (1-\delta)\Gamma_{t-1} &= 0 \\
P_t - c_q(q_{jt}) - \theta^{-1}\nu_t &= 0 \\
\Gamma_t R^{-1} \theta^{-1} f_{kk}(K_t) + \nu_t - R^{-1}(1-\delta)\nu_{t+1} &= 0,
\end{aligned}$$

which imply $q_{jt} = q_t$ for all j (as long as $c_{qq} > 0$) and

$$\theta P_t - \theta c_q \left(\frac{\theta I_t}{N} \right) = -\Gamma_t R^{-1} \theta^{-1} f_{kk}(K_t) + R^{-1} \theta (1-\delta) \left(P_{t+1} - c_q \left(\frac{\theta I_{t+1}}{N} \right) \right). \tag{B2}$$

We underscore the similarity between equation (B2) and equation (20). The key difference between these two optimality conditions is given by the multiplier on the investment Euler equation, which under collusion accounts for the aggregate capital accumulation path.

B.4 Stochastic Model

In this subsection, we present the stochastic version of the model that we analyze in Section 6.3. We define s_t to be the vector of shocks. Given s_0, we define the history of shocks as $s^t = \{s^{t-1}, s_t\}$.

B.4.1 Investment Demand

A stochastic open economy is populated by a representative household with utility function

$$\sum_{t=0}^{\infty}\sum_{s^t}\beta^t u(C(s^t))Pr(s^t), \tag{B3}$$

where $\beta \in (0,1)$ denotes the discount factor and $C_t = C(s^t)$ is aggregate consumption. Further, we assume that $u_c > 0$ and $u_{cc} \leq 0$, where subscripts denote first and second derivatives, respectively.

We assume the household has access to state-contingent bonds. Given s^t, the budget constraint of the household at time t reads

$$C(s^t)+P^I(s^t)I(s^t)+\sum_{s_{t+1}}B(s_{t+1}|s^t) = W(s^t)L+R^K(s^t)K(s^{t-1})+R^b(s_t|s^{t-1})B(s_t|s^{t-1})+D(s^t), \tag{B4}$$

where $P^I(s^t) = P^I_t$ is the price of investment goods $I(s^t) = I_t$, $B_t = B(s_{t+1}|s^t)$ are state-contingent bonds that pay the gross interest rate $R^b(s_t|s^{t-1})$, $W_t = W(s^t)$ is the wage, L is a constant endowment of labor, $R^K_t = R^K(s^t)$ denotes the rental rate of capital $K_{t-1} = K(s^{t-1})$, and $D_t = D(s^t)$ are profits obtained from ownership of domestic firms. For ease of notation, we will occasionally summarize the dependency of variables from the history of shocks s^t with the corresponding time subscript.

Furthermore, we assume that the household is only subject to the natural debt limit.

Investment adds to the capital stock, which depreciates at rate δ. Therefore, capital continues to evolve according to equation (1). As in the deterministic model, we assume that investment has to be non-negative and restrict attention to a region of the parameter space where this constraint is not binding.

The first-order conditions of the utility maximization problem with respect to bonds and investment are

$$\forall s^{t+1}: \quad 1 = \beta\frac{u_c(C(s^{t+1}))}{u_c(C(s^t))}R^b(s_{t+1}|s^t)Pr(s^{t+1}) \tag{B5}$$

$$P^I_t = \mathbb{E}_t\left[\beta\frac{u_c(C_{t+1})}{u_c(C_t)}\left(R^K_{t+1}+(1-\delta)P^I_{t+1}\right)\right]. \tag{B6}$$

A representative firm rents capital and hires labor from the household to produce output with a constant-returns to scale production function:

$$Y_t = F(A_t, K_{t-1}, L). \tag{B7}$$

The first-order conditions of the profit maximization problem are

$$F_K(A_t, K_{t-1}, L) = R_t^K \tag{B8}$$
$$F_L(A_t, K_{t-1}, L) = W_t.$$

For notational convenience, we define $f(A_t, K_{t-1}) \equiv F(A_t, K_{t-1}, L)$. Because of constant-returns to scale, the representative firm makes zero profits in equilibrium—i.e., $D_t = 0$.

We assume that the risk-free interest rate satisfies $R = \beta^{-1}$ and that $R^b(s_{t+1}|s^t)Pr(s^{t+1}) = R$. Given our choice of R, equation (B5) implies that $\forall s^{t+1} : \frac{u_c(C(s^{t+1}))}{u_c(C(s^t))} = 1$. Hence, by combining the household and firm optimality conditions (B5), (B6), and (B8), we obtain the following investment Euler equation that describes optimal capital accumulation in the stochastic version of the economy:

$$P_t^I = R^{-1}\mathbb{E}_t\left[f_k(A_{t+1}, K_t) + (1-\delta)P_{t+1}^I\right]. \tag{B9}$$

Equation (B9) implicitly expresses the demand for investment goods as a function of capital stock K_{t-1}, current and future investment prices P_t^I and P_{t+1}^I), and future shocks.

As in the deterministic case, as long as markets are complete, our assumptions on ownership of the capital stock are immaterial and we can equivalently derive this condition assuming that firms accumulate capital instead of households.

B.4.2 Investment-Goods Producers

We now describe the supply side of the market for investment goods. We assume that there is an integer number $N \geq 1$ of identical investment-goods producers owned by foreign investors. The objective of investment-goods producers is to maximize the present discounted value of profits:

$$\sum_{t=0}^{\infty}\sum_{s^t} R^{-t}\pi_t(s^t)Pr(s^t). \tag{B10}$$

Similarly to the deterministic case, we assume that a perfectly competitive representative firm combines an amount Q_t and an amount X_t of output good to assemble domestic investment with a Leontief production function. Hence, $P_t^I = \theta P_t + 1 - \theta$, as in equation (7), and the stochastic investment Euler equation (B9) becomes:

$$P_t = R^{-1}\mathbb{E}_t\left[\theta^{-1}f_k(A_{t+1}, K_t) + (1-\delta)P_{t+1}\right] - \underbrace{\theta^{-1}(1-\theta)(1-R^{-1}(1-\delta))}_{\equiv\kappa}. \tag{B11}$$

B.4.3 First Best

Before analyzing the effects of market power, we briefly introduce the competitive benchmark. This coincides with the solution to the problem of a planner who maximizes welfare in the open economy taking as given the cost function to produce investment goods.

In a competitive equilibrium without market power, investment-goods producers choose a plan of production levels $\{q(s^t)\}_{t=0}^{\infty}$ to maximize (B10) taking as given the sequence of prices schedules $\{P(s^t)\}_{t=0}^{\infty}$. Thus, the equilibrium price satisfies $P_t = c_q\left(\frac{I_t}{N}\right)$ and optimal capital accumulation satisfies

$$\theta c_q\left(\frac{\theta I_t}{N}\right) + 1 - \theta = R^{-1}\mathbb{E}_t\left[f_k(A_{t+1}, K_t) + (1-\delta)\theta c_q\left(\frac{\theta I_{t+1}}{N}\right) + 1 - \theta\right]. \tag{B12}$$

B.4.4 Markov Perfect Equilibrium and Generalized Euler Equation

We now proceed to derive the Markov Perfect Equilibrium. We denote by s and s' current- and next-period stochastic states. A generic investment-goods producer solves the following recursive problem:

$$\max_{P,K',q} \; Pq - c(q) + R^{-1}\mathbb{E}[V(K', s')|s], \tag{B13}$$

subject to the demand schedule

$$P = R^{-1}\mathbb{E}\left[\theta^{-1} f_k(A', K') + (1-\delta)P(K', s')|s\right] - \kappa,$$

to the market-clearing condition

$$(N-1)q_{-}(K) + q = Q = \theta I,$$

and to the law of motion for capital

$$K' = (1-\delta)K + I.$$

To obtain the stochastic Generalized Euler Equation (GEE) (B14), we first substitute investment I from the market-clearing condition in the law of motion for capital. Second, we use the derived equation to substitute q in the objective function. Third, we substitute P in the objective function using the demand schedule. Finally, we take the first-order condition with respect to K'.

$$\theta P - \theta c_q(q) + qR^{-1}\mathbb{E}\left[\theta^{-1} f_{kk}(A', K') + (1-\delta)P_k(K', s')|s\right] + R^{-1}\mathbb{E}[V_k(K', s')|s] = 0 \tag{B14}$$

The GEE includes the derivative of the future price with respect to capital in every possible future realization of shocks.

B.4.5 Commitment to Future Production

We now examine the problem of investment-good producers under commitment. Given initial capital K_{-1}, oligopolists problem involves finding sequences $\{P(s^t), K(s^t)\}_{t=0}^{\infty}$ such that

$$\sum_{t=0}^{\infty}\sum_{s^t} R^{-t}\left(P_t\left(\theta(K_t-(1-\delta)K_{t-1})-(N-1)q_{-,t}\right)-c\left(\theta(K_t-(1-\delta)K_{t-1})-(N-1)q_{-,t}\right)\right)Pr(s^t) \tag{B15}$$

is maximized subject to the demand schedule (or, using the language of Ramsey-optimal policy, "implementability constraint")

$$P_t = R^{-1}\mathbb{E}_t\left[\theta^{-1}f_k(A_{t+1},K_t)+(1-\delta)P_{t+1}\right]-\kappa$$

for $t = 0, 1, ..,$ with multiplier $R^{-t}\gamma_t$. The first-order conditions with respect to price $P_t = P(s^t)$ and capital level $K_t = K(s^t)$ are:

$$\begin{aligned} q_t-\gamma_t+\gamma_{t-1}(1-\delta) &= 0 \\ \theta P_t-\theta c_q(q_t)+\gamma_t R^{-1}\mathbb{E}_t\left[\theta^{-1}f_{kk}(A_{t+1},K_t)\right]-R^{-1}\theta(1-\delta)\mathbb{E}_t\left[(P_{t+1}-c_q(q_{t+1}))\right] &= 0, \end{aligned}$$

with initial condition on the multiplier $\gamma_{-1} = 0$.

C Additional Quantitative Analyses

C.1 Additional Details on the Solution Method

In this subsection, we provide additional details on our global solution method.

Markov Perfect Equilibrium. We approximate the Markov Perfect Equilibrium (Definition 1) using a version of the time-iteration algorithm to approximate the policy functions $I(K)$ and $P(K)$. Specifically, we implement the following steps: (1) We guess a second-order polynomial approximation for $I(K)$ on a 50-point grid for K. (2) Given this candidate policy function, we obtain an associated guess for $P(K)$ by doing time iteration on equation (6), recursively solving for the left-hand side on the same grid for K and then plugging the obtained price function in the right-hand side. (3) Once we obtain a converged price function, we use it to numerically approximate the derivative $P_k(K)$. (4) Then, to update

$I(K)$, we apply time iteration to the GEE (12) substituting in it the envelope condition (13) with a numerical approximation of the derivative $I_k(K)$. (5) We repeat these steps until all policy functions converge.

Commitment. To approximate the equilibrium with commitment (Definition 2), we solve the model recursively by adding the multiplier on the past investment Euler equation as a state variable. Specifically, we implement the following steps: (1) We guess third-order polynomial approximations for the policy functions $I(K, \gamma)$ and $\gamma'(K, \gamma)$ on a 15-point grid for K and a 10-point grid for γ. The polynomials include a constant, all individual terms $(K, K^2, K^3, \gamma, \gamma^2, \gamma^3)$ and cross-products $(\gamma K, \gamma^2 K, \gamma K^2)$. (2) We then use a time-iteration algorithm on equations (19) and (20) to update the policy functions $I(K, \gamma)$ and $\gamma'(K, \gamma)$ on the (K, γ) grid. (3) Given the new policy functions, we update the guess for the third-order polynomial coefficients. (4) We repeat these steps until all policy functions converge.

C.2 Markup Decomposition under Commitment

In this subsection, we analyze the role of demand elasticity and quantities produced for the dynamics of the static markup rate in the full commitment equilibrium. As in Section 5.6 we consider the transitional dynamics of the economy to the steady-state equilibrium starting from initial conditions $K_{-1} = 0.5$ and $\gamma_{-1} = 0$.

We can reformulate the commitment first-order condition (20) as follows:

$$\frac{P_t - c_q(q_t)}{c_{q,t}} = -\sum_{s=0}^{\infty} R^{-s}(1-\delta)^s \frac{\gamma_{t+s}}{c_{q,t}} \left(\frac{dP_{t+s}}{dQ_{t+s}}\right) \tag{C1}$$

with $\frac{dP_t}{dQ_t} = R^{-1}\theta^{-2} f_{kk}(K_t)$ and decompose the roles of quantities and slopes of the demand curve along the equilibrium path.

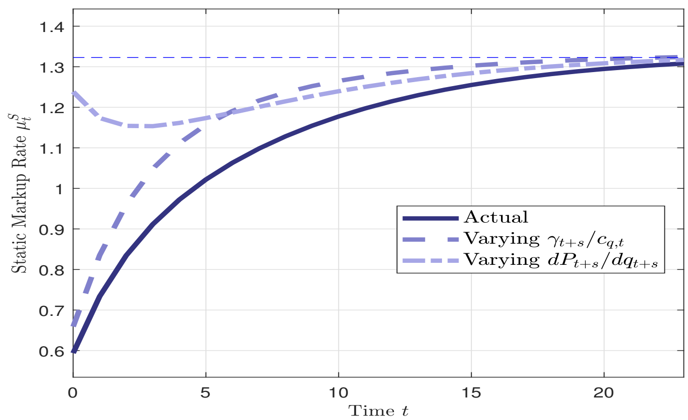
Figure C1 illustrates that quantities are the most important driver of the dynamics of the static markup rate.

C.3 Alternative Calibration to Aggregate Capital Stock

In this subsection, we revisit our main results with an alternative model calibration where we interpret K as aggregate capital, i.e., as the sum of equipment and structures.

Calibration. Column "Aggr. K" of Table C1 reports the new parameter values. We follow the same calibration strategy of Section 5. We set the capital share of income and the rate of physical depreciation to standard values in the real-business-cycles literature

Figure C1: Markup Decomposition under Commitment



Notes: The figure displays a decomposition of the evolution of the static markup rate $\mu_t^S = (P_t - c_{q,t})/c_{q,t}$ over the transition of the economy to steady state in the Full Commitment Equilibrium. The figure disentangles variation in the static markup rate (solid line) driven by: (i) quantities $q_{t+s}/c_{q,t}$ produced by each oligopolist (dashed line); (ii) the derivative of inverse demand with respect to quantities dP_{t+s}/dQ_{t+s} (dash-dotted line); and (iii) implicit discounting $B_{t,t+s}$ (dotted line).

consistent with the new interpretation of K as aggregate capital. We calibrate the productivity level such that the capital stock is equal to one in the first-best steady state. We adjust the steepness of the marginal cost function to match a ratio of operating income over sales of around 30% and the marginal cost intercept so that capital price equals one in the first-best steady state. Finally, we divide the baseline weight of the imported oligopolistic input in total investment by three because equipment represents approximately one third of the aggregate capital stock in US data.

Investment Demand Shock. Figure C2 illustrates the response of prices and marginal cost (panel a) and markups (panel b) to a positive investment demand shock. We consider a 10.7% TFP increase in the domestic economy, which we calibrate to match an approximate 20% increase in the real price of semiconductors in the US over 2019-2023.

As in the main calibration, price and marginal cost overshoot their new steady-state levels. Moreover, the marginal cost increases by 17.7% and thus determines most of the observed price dynamics following the investment demand shock. Accordingly, static and dynamic markup only increase by 2.4 and 1 percentage points on impact, respectively.

C.4 Alternative Calibration to Oligopolistic Wafer Production

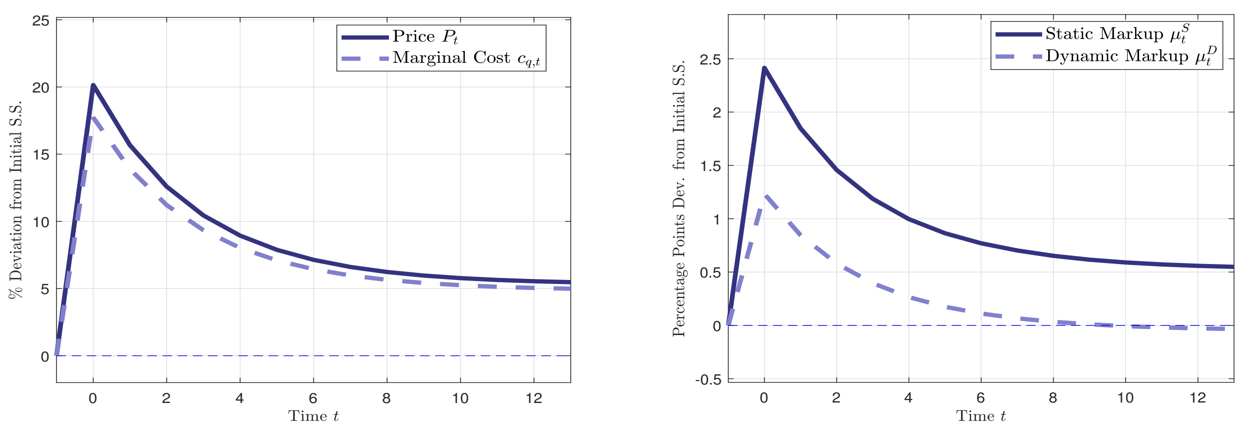
In this subsection, we re-examine our main results with an alternative model calibration where we interpret the imported oligopolistic input as wafers, i.e., the physical support of chips, a key component in semiconductors manufacturing. We relate our findings to the

Table C1: Parameters Values for Alternative Calibrations

	Parameter	Symbol	Aggr. K	Wafer	Capacity
Demand	Discount Factor	β	0.96	0.96	0.96
	Depreciation	δ	0.08	0.1354	0.1354
	Capital Share	α	0.333	0.0645	0.0645
	Oligopolistic Capital Share	θ	0.122	0.1206	0.1206
	Total Factor Productivity	A	0.365	2.743	2.743
Supply	Number of Producers	N	3	3	3
	Marginal Cost (Intercept)	c_1	0.6747	0.7073	0.6864
	Marginal Cost (Slope)	c_2	100	55	19
	Capacity Constr. Penalty	c_3			100
	Capacity Constr. Param.	κ			1.05

Notes: The table reports the parameter values of alternative calibrations of the model. The "Aggr.K" column refers to the calibration where K represents aggregate capital, i.e., the sum of equipment and structures. The "Wafer" column refers to the calibration where we interpret the oligopolistic input as wafers. The "Capacity" column refers to the calibration where we explicitly model capacity constraints in the form of a large change in the slope of the marginal cost function when the quantity produced exceeds a threshold.

Figure C2: Investment-Demand Shock with Calibration to Aggregate Capital Stock



(a) Price and Marginal Cost (b) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent 10.7% increase in TFP in the Markov Perfect Equilibrium under the alternative calibration summarized by Table C1, column "Aggr. K". Panel (a) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (b) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

empirical evidence of Appendix A.2.

Calibration. The "Wafer" column of Table C1 reports the new parameter values. We calibrate the parameters of investment demand consistent with Table 1. We change the parameter governing the share of oligopolistic input on total investment so that the observed cumulative increase in the real price of wafers over 2019-2023 (62%) induces an approximate 7% increase in the real price of equipment. Appendix A.2 describes how we compute real unit prices using Taiwan Ministry of Economic Affairs' data on wafer production values and volumes.

Moreover, we adjust the slope of the marginal cost function to match a ratio of Operating Profits over sales of around 33%, which we observe in Orbis data for the main Taiwanese chips manufacturers (TSMC and Mediatek). We focus on Taiwanese manufacturers for consistency with administrative price and quantity data used in the calibration of the oligopolistic investment share. Finally, we set the marginal cost intercept so that the price of investment equals one in the first-best steady state.

Investment Demand Shock. Figure C3 illustrates the response of price and marginal cost (panel a) and markups (panel b) to a positive investment demand shock. We calibrate an increase in TFP to match an approximate 60% increase in the real price of wafers over 2019-2023.

As in the main calibration, prices and marginal costs overshoot their new, higher steady-state levels. As in our baseline, the marginal cost determines most of the observed price dynamics increasing by 48.7 percent on impact. However, in this alternative calibration endogenous markups also rise significantly by 9.9 percentage points on impact.

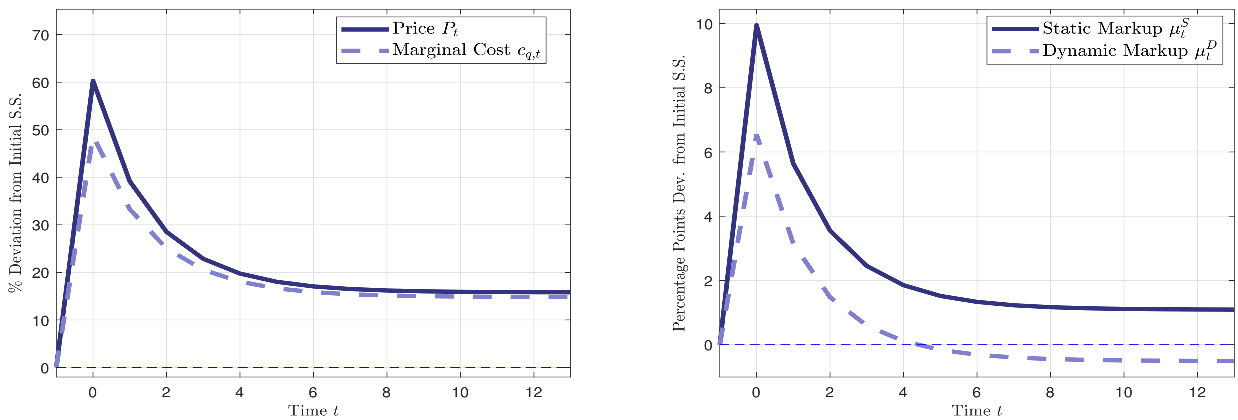
The dynamics implied by the model with this alternative calibration are broadly consistent with the empirical patterns of Appendix A.2. Indeed, because the price increase applies to all infra-marginal units, the model predicts an increase in *average* unit margins approximately twice as large as the increase in unit prices, consistent with Figure A3b.

C.5 Alternative Calibration with Capacity Constraints

In this subsection, we examine an alternative calibration of the model where we explicitly consider capacity constraints in the form of a large change in the slope of the marginal cost function.

To this end, we generalize the cost function used in the baseline model as $c(q) = c_1 q + \frac{c_2}{2} q^2 + \mathcal{I}[q \geq \bar{q}] \cdot \frac{c_3}{2}(q - \bar{q})^2$, where $\mathcal{I}[\cdot]$ is an indicator function that takes value of one when quantity q exceeds a threshold $\bar{q}$ and zero otherwise. We specify $\bar{q}$ as a multiple κ of the quantity produced by each supplier in the first-best steady state. For large values of c_3, the new functional form is a reasonable proxy of hard capacity constraints—i.e., $q \leq \bar{q}$—but

Figure C3: Investment-Demand Shock with Calibration to Oligopolistic Wafer Production



(a) Price and Marginal Cost (b) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent 50% increase in TFP in the Markov Perfect Equilibrium under the alternative calibration summarized by Table C1, column "Wafer". Panel (a) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (b) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

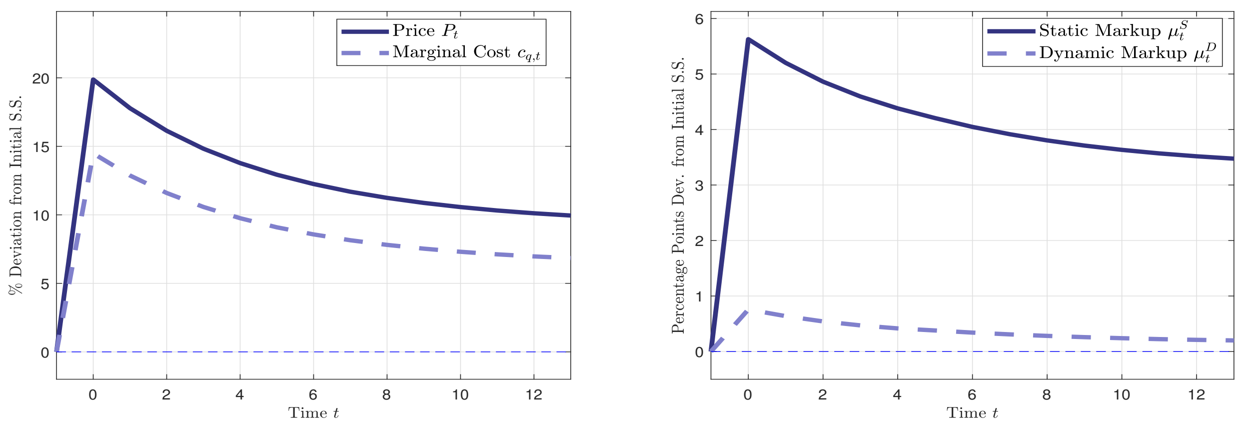
has the important advantage of preserving differentiability. This allows us to extend the Generalized Euler Equation (12) to the new setting without changing our solution method.

Calibration. Column "Capacity" of Table C1 reports the parameter values for this version of the model. We calibrate the parameters of investment demand consistent with Table 1. For the calibration of the cost function parameters, we first set c_3 to a large number to proxy a hard capacity constraint above the threshold $\bar{q}$. Second, we set κ, which governs the size of the threshold $\bar{q}$ relative to the first-best steady state quantity, so that both the first-best and the Markov Perfect Equilibrium steady states feature non-binding capacity constraints. Third, we adjust the slope c_2 of the marginal cost function to match a ratio of operating income over sales of around 30%, consistent with the main calibration. Finally, we set the marginal cost intercept c_1 so that the price of investment equals one in the first-best steady-state equilibrium.

Investment Demand Shock. Figure C4 illustrates the response of price and marginal cost (panel a) and markups (panel b) to a positive investment demand shock, which we proxy with an increase in TFP in the domestic economy. For consistency, we calibrate the size of shock (+15.5%) to induce an increase of investment-goods price equal to 20 percent, as in Section 5. The shock is large enough to activate capacity constraints in our model extension. Moreover, it is smaller than the size of the shock required in our baseline calibration exactly because binding capacity constraints drive a larger increase in marginal cost and price.

As in the main calibration, prices and marginal costs overshoot their new, higher steady-state levels. As in our baseline, the increase in the marginal cost (+14.5%) determines most of the observed price dynamics. However, with hard capacity constraints the response of markup is larger and equivalent to 5.6 percentage points on impact, which drives more than one quarter of the price increase. These dynamics provide further support to our analysis of Section 5.5 on the role of technology for market power.

Figure C4: Investment-Demand Shock with Calibration with Capacity Constraint



(a) Price and Marginal Cost (b) Static and Dynamic Markups

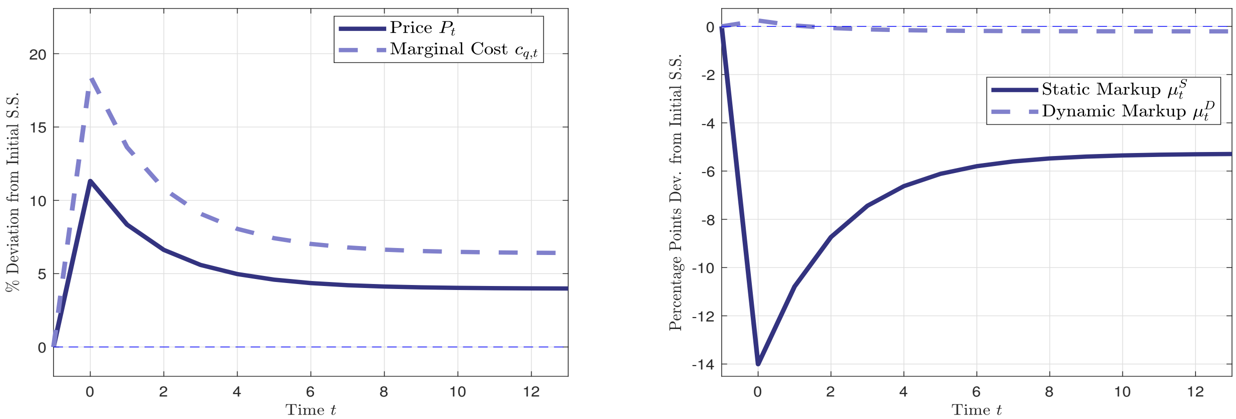
Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent 15.5% increase in TFP in the Markov Perfect Equilibrium under the alternative calibration with capacity constraints summarized by Table C1, column "Capacity". Panel (a) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (b) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

C.6 Aggregate Shocks with Full Commitment

In this subsection, we analyze the response of the economy to aggregate shocks when investment-goods producers can commit to future production. We first focus on an aggregate demand shock and compare its effects to the Markov Perfect Equilibrium dynamics presented in Section 6. Then we replicate the change in market structure of Section 7.1.

Figure C5 displays the evolution of aggregate variables in response to a positive TFP shock of the same size as in Figure 6a. As in the Markov Perfect Equilibrium, the rise in capital demand induces an increase in quantities produced and, thus, in the static marginal cost. However, under commitment the price increases by less than the marginal cost, which determines a significant compression (-14 percentage points) in the static markup. Moreover, the dynamic markup is barely affected by the investment demand shock. Therefore, increasing marginal costs are the main driver of higher equilibrium prices also under alternative assumptions about commitment by investment-goods producers.

Figure C5: Investment-Demand Shock with Full Commitment



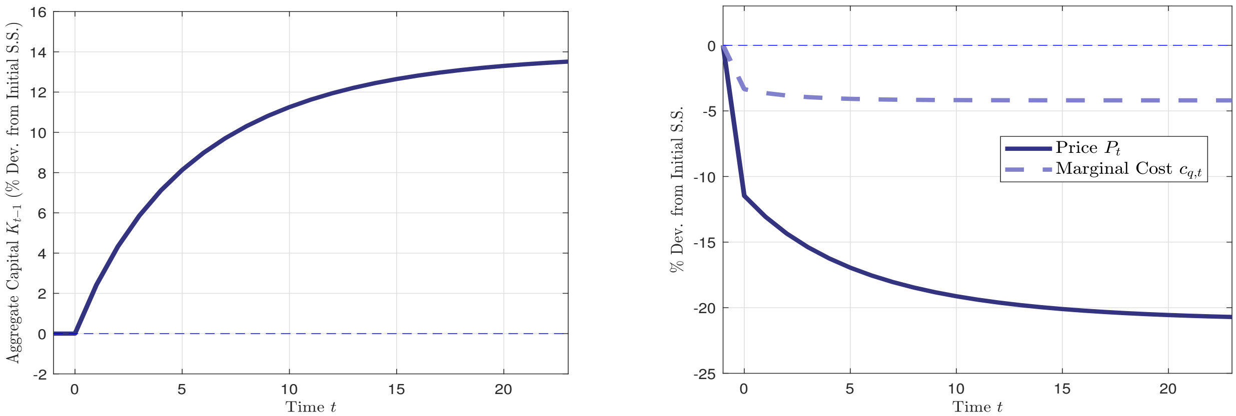
(a) Price and Marginal Cost

(b) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent increase in TFP in the full commitment equilibrium. Panel (a) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (b) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

Next, we analyze a shock to market structure, namely an increase in the number of investment-goods producers from 3 to 4, in the full commitment setting. Figure C6 displays the response of capital, price, and marginal cost to the shock. Although the expansion in production capacity induces a smaller decline in the static marginal cost with full commitment (+4%) compared to the Markov Perfect Equilibrium (around 7%), the decline in price is significantly larger in the presence of commitment (-20% vs. -12%). This finding suggests that the competition channel is even stronger under full commitment, and that the effects of changes in market structure presented in Subsection 7.1 represent a lower bound. Accordingly, we find that the larger compression in markups generates an increase in the level of capital that is more than twice as large under commitment than in the Markov Perfect Equilibrium.

Figure C6: Increase in the Number of Investment-Goods Producers with Commitment



(a) Capital (b) Price and Marginal Cost

Notes: The figure illustrates the response of the economy in the full commitment equilibrium to an unanticipated and permanent increase in the number of investment-goods producers from $N = 3$ to $N = 4$. Panel (a) plots the transition of domestic economy's aggregate capital stock K_{t-1} to the new steady state. Panel (b) plots the transition of the investment price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

C.7 Business Cycles with TFP and Cost Shocks

In this subsection, we analyze an extension of the stochastic model of Section 6.3 that includes stochastic shocks to both productivity of the domestic economy and cost function of investment-goods producers.

Calibration. As in Section 6.3, we assume that productivity follows an AR(1) process in logs: $\log(A_t) = (1-\rho)\mu_A + \rho_A \log(A_{t-1}) + \varepsilon_t^A$ and we consider the same stochastic process for the cost-function shock: $\log(Z_t) = (1-\rho)\mu_Z + \rho_Z \log(Z_{t-1}) + \varepsilon_t^Z$.

Table C2 reports the stochastic-processes parameter values used in the simulations, which we calibrate to match five data moments summarized in Table C3. For calibration, we first estimate a VAR(1) model using (i) the natural logarithm of US real GDP and (ii) Machinery and Equipment real US Producers Price Index. We HP-filter both series at yearly frequency. We restrict the lagged effects of each series on the other to be zero but allow for a non-zero covariance among residuals. The second column of Table C3 reports the empirical estimates. We then find through indirect inference the vector of parameters of $\log(A_t)$ and $\log(Z_t)$ stochastic processes that minimize the distance between the empirical moments and those implied by a long simulation of the model. The third column of Table C3 compares model performance to the data.

Table C2: Parameter Values for the Stochastic Processes

	Parameter	Symbol	Value
TFP Stochastic Process	Autocorrelation	ρ_A	0.850
	Standard Deviation	σ_A	0.018
Cost Level Stochastic Process	Autocorrelation	ρ_Z	0.575
	Standard Deviation	σ_Z	0.085
Correlation	Correlation	$\frac{\sigma_{A,Z}}{\sigma_A \sigma_Z}$	-0.290

Notes: The table reports the parameter values for the stochastic processes of TFP A_t and cost-level Z_t used in simulations.

Table C3: Stochastic Processes Calibration: Data and Model Moments

Parameter	Model	Data
log(GDP) Autocorrelation	0.09	0.136
log(GDP) Standard Deviation	0.010	0.014
Equipment Price Autocorrelation	0.028	0.024
Equipment Price Standard Deviation	0.015	0.022
log(GDP)-Equipment Price Correlation	0.008	0.002

Notes: The table illustrates the performance of the calibrated stochastic model against the targeted empirical moments. The Data column reports empirical estimates of a yearly VAR(1) model with two variables: (i) HP-filtered natural logarithm of real US GDP and (ii) HP-filtered Machinery and Equipment US Producers Price Index deflated by the US GDP deflator. We restrict the lagged effects of each series on the other to be zero. The Model column reports the model counterparts of the empirical moments, obtained by estimating the same VAR(1) model on the HP-filtered natural log of GDP (Y_t) and the HP-filtered investment price P_t^I obtained from a long simulation of the stochastic model given parameters of Tables 1 and C2.

The parameters of the TFP stochastic process are similar to the calibration of Section 6.3. Moreover, we find a small negative correlation of TFP shocks with cost-function shocks, which are less persistent but significantly more volatile than TFP shocks.

Business Cycle Moments. Table C4 reports several business-cycle moments from a long simulation of the richer stochastic model. Consistent with Section 6.3, prices and markups are higher on average in the presence of commitment. The model predicts a moderate business-cycle volatility of prices and markups in response to productivity shocks, consistent with our findings on the effect of a permanent investment-demand shock. Moreover, cost shocks dampen the comovement between prices, investment, and output generated by TFP shocks. At the same time, in this richer stochastic environment the model generates significantly higher volatility of investment relative to GDP.

Table C4: Stochastic Productivity and Cost: Business Cycle Moments

	FB	MPE	FC
Mean I	0.134	0.128	0.098
Mean P	0.990	1.136	1.702
Mean Markup	0	0.160	0.908
St. Dev. I/St. Dev. Y	18.306	6.694	21.484
St. Dev. P	0.025	0.037	0.025
St. Dev. Markup	0	0.008	0.074
Corr. Y and I	0.135	0.482	0.184
Corr. Y and P	-0.150	0.007	0.383
Corr. Y and Markup	0	0.275	0.272

Notes: The table reports several moments related to investment, the price of the oligopolistic investment good, and the static markup rate, from a long a simulation of the model with both stochastic domestic economy productivity and stochastic cost-level. The first column refers to the first-best allocation, the second column to the Markov Perfect Equilibrium, and the third column to the case of full commitment. Standard deviations and correlations are computed for the logarithm of the variables, except for the markup rate, and the simulated data are HP-filtered with a smoothing coefficient equal to 6.25 for annual frequency.

C.8 Implicit Capacity-Subsidy Rates

In this subsection we connect the experiment of Section 7.2—in which we simulate a reduction in the slope c_2 of investment-goods producers marginal cost function—to an explicit subsidy scheme. We first derive the subsidy $\tau(q_t, \tilde{\tau})$ such that

$$c(q_t)(1 - \tau(q_t, \tilde{\tau})) = c_1 q_t + (1 - \tilde{\tau}) c_2 q_t^2$$

as a function of the quantity q_t and of the desired reduction $\tilde{\tau}$ of the marginal cost slope.

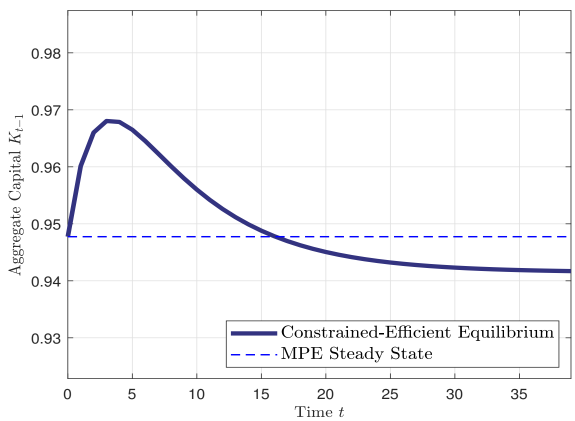
Then, we analyze its properties around the steady state of the Markov Perfect Equilibrium for an approximate $\tilde{\tau}$=0.24 reduction in c_2—i.e., the percent change implied by a reduction of c_2 from 22 to 16.8. We verify that the function is approximately linear and that the implied subsidy rate is almost 8.5% at the MPE steady-state value of q (0.0157).

C.9 Constrained-Efficient Equilibrium

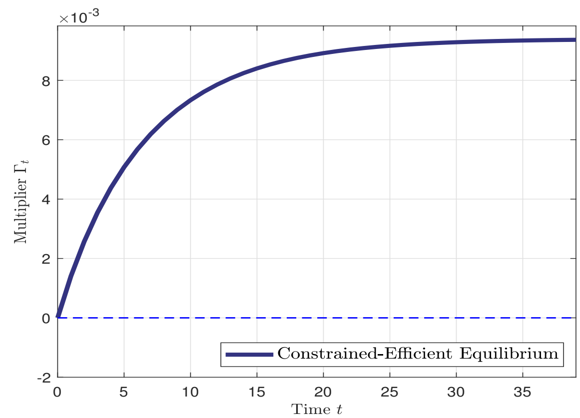
In this subsection, we analyze the constrained-efficient optimal allocation. Figure C7 illustrates the transition of the economy to constrained-efficient equilibrium steady-state (solid lines). We assume that the initial level of capital equals the Markov Perfect Equilibrium steady-state value, that the initial value of the multiplier Γ_t equals zero, and that the lower bound on profits $\underline{\pi}$ in the participation constraint equals the value of profits in the Markov Perfect Equilibrium steady state.

In the absence of previous commitment ($\Gamma_0 = 0$) the planner finds it optimal to expand production and lower both price and markup relative to the Markov Perfect Equilibrium steady state, represented by the dashed lines. The increase in the quantity of capital and the reduction in its price initially benefit consumers in the domestic economy, but depress profits below $\underline{\pi}$. Therefore, profits must subsequently increase along the transition to satisfy firms participation constraint. The planner achieves this by raising price and markup and reducing quantities.

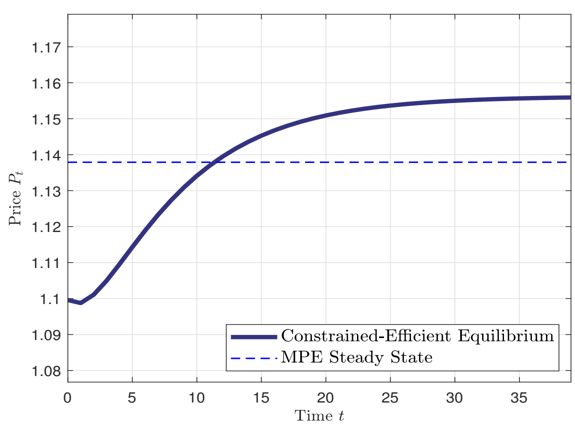
Figure C7: Transitional Dynamics to the Constrained-Efficient Equilibrium



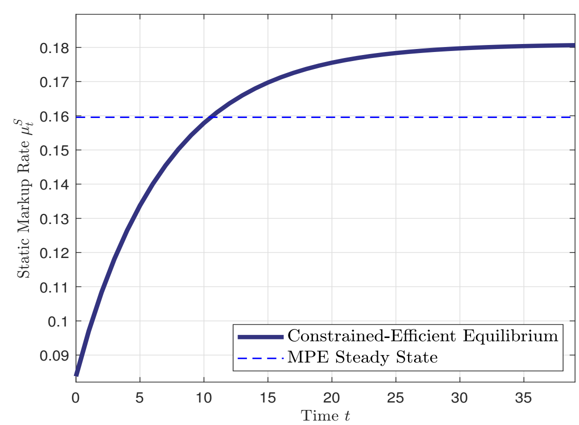
(a) Aggregate Capital



(b) Multiplier Γ_t



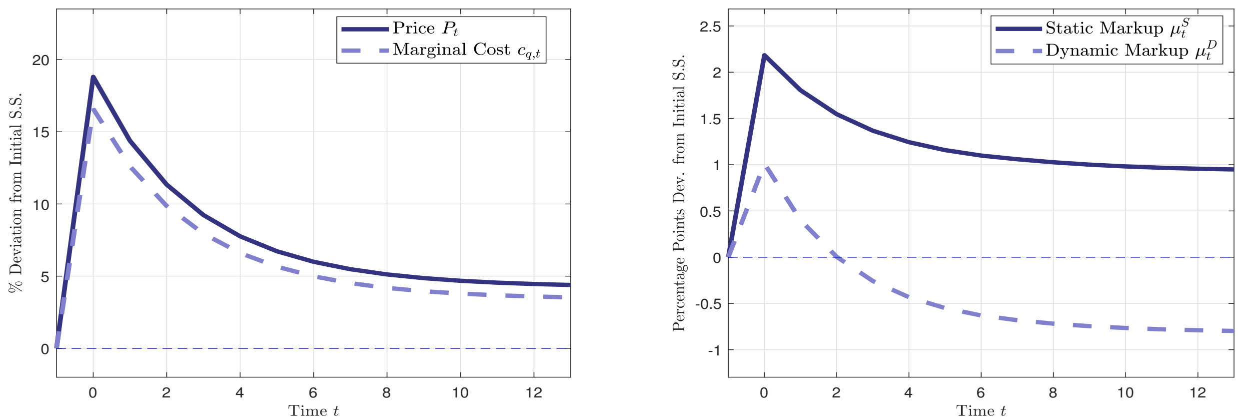
(c) Price



(d) Static Markup

Notes: The figure illustrates the transition of the economy to the constrained-efficient steady-state equilibrium. We assume that the initial level of capital equals the Markov Perfect Equilibrium steady-state value, that the initial value of the multiplier Γ_t equals 0, and that the lower bound on profits $\underline{\pi}$ in the participation constraint equals the value of profits in the Markov Perfect Equilibrium steady state. The solid lines in panels (a), (b), (c), and (d) plot the transitions of aggregate capital K_{t-1}, multiplier Γ_t, price P_t, and static markup rate μ_t^S respectively. The dashed lines in panels (a), (c), and (d) represent the Markov Perfect Equilibrium steady-state values of aggregate capital, price, and static markup, respectively.

Figure C8: Investment-Demand Shock with Learning by Doing



(a) Price and Marginal Cost (b) Static and Dynamic Markups

Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent increase in TFP in the Markov Perfect Equilibrium of the model with learning by doing (Section 8). Panel (a) plots the transition of the price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. Panel (b) plots the transition of the static markup rate μ_t^S (solid line) and of the dynamic markup rate μ_t^D (dashed line) to the new steady-state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.

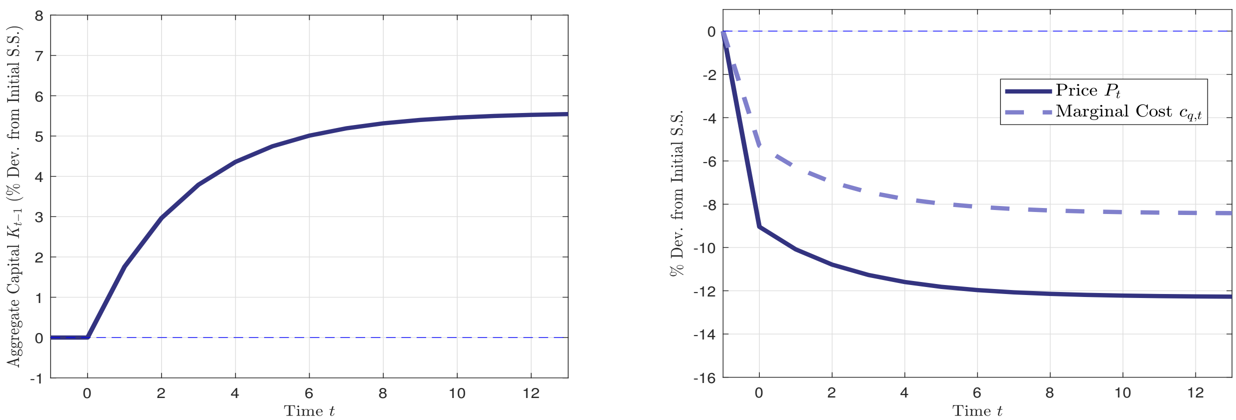
C.10 Aggregate Shocks with Learning by Doing

In this subsection, we analyze the effect of aggregate shocks in the Markov Perfect Equilibrium of the model with learning by doing. For the simulations, we assume that firms internalize learning by doing effects on marginal cost.

Figure C8 displays the dynamics of key aggregates in response to a positive TFP shock in the domestic economy. For the sake of comparability, the size of the shock is the same as in Figure 6. Most of the price increase is driven by changes in the marginal cost (panel a). However, the size of the response is smaller for two reasons. First, capital accumulation dampens the response of the marginal cost through learning by doing. Second, the increase in markups is smaller as oligopolistic producers partly internalize the benefit of larger production in terms of lower future marginal cost.

Figure C9 illustrates the effect of increasing the number of investment-goods producers from $N = 3$ to $N = 4$ on aggregate capital (left panel) and on the price and marginal cost (right panel). Total capacity expands and competition rises. Therefore, the marginal cost declines—more than in the baseline economy due to learning by doing—and contributes to a larger decline in the price, together with a larger compression of markups.

Figure C9: Increase in the Number of Investment-Goods Producers with Learning by Doing



(a) Capital (b) Price and Marginal Cost

Notes: The figure illustrates the response of the economy in the Markov Perfect Equilibrium of the model with learning by doing (Section 8) to an unanticipated and permanent increase in the number of investment-goods producers from $N = 3$ to $N = 4$. Panel (a) plots the transition of domestic economy's aggregate capital stock K_{t-1} to the new steady state. Panel (b) plots the transition of the investment price P_t (solid line) and producers' marginal cost $c_{q,t}$ (dashed line) to the new steady state. We assume that the shock occurs at $t = 0$, that the economy is in the initial steady state at $t = -1$, and that agents have perfect foresight of the evolution of all variables after the unexpected shock occurs.