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Investment-Goods Market Power and Capital Accumulation*

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May 2024

Abstract

We develop a model of capital accumulation in an open economy that imports investment goods from large foreign firms with market power. We model investment-goods producers as a dynamic oligopoly and characterize a Markov Perfect Equilibrium with a Generalized Euler Equation. We use this optimality condition to analyze the joint evolution of investment, prices, and markups. The markup on investment goods decreases as the economy accumulates capital toward its steady state, generating a state-dependent capital adjustment cost. We analyze the role of commitment to future production of investment goods for the dynamics of markups and investment. We use a calibrated version of the model to simulate the effects of shocks to the demand for durable goods and semiconductors during the post-2020 world recovery. Finally, we perform counterfactual analyses on the effects of expanding the production capacity. The model highlights the separate roles of increasing marginal costs—akin to capacity constraints—and market power.

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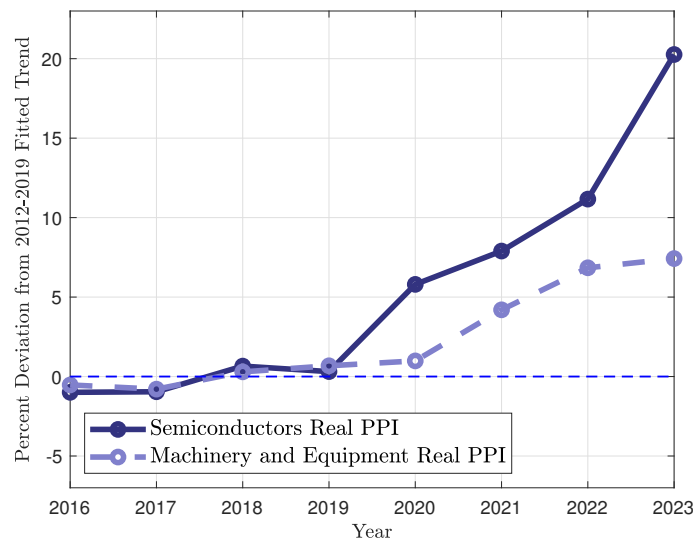
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1 Introduction

The post-2020 global recovery has been a stark reminder of the dependence of the macroeconomy on the supply of critical inputs that most countries import from highly concentrated industries, such as semiconductors. When demand for durable goods increased during the recovery, prices soared, thereby dampening capital accumulation, contributing to the increase in inflation, and leading to the design of ambitious policy plans to modify the global production structure.¹

Figure 1: Semiconductor and Equipment Price Dynamics



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

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 also increased significantly and was 7% higher than its trend in 2023.

Semiconductors are necessary components of equipment goods and it is likely that future economic growth will increasingly rely on them. More in general, many important

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

types of durable inputs are produced by highly concentrated industries. As examples, consider commercial aircraft, commercial ships, electric vehicles, or construction and mining machinery. For all of these investment goods, a relatively small number of large global producers supply the world economy.

What is the role of market power in investment-goods markets for the dynamics of prices, capital accumulation, and output? The goal of this paper is to develop a framework to address this question. To this end, we combine a neoclassical growth model of capital accumulation with a dynamic oligopoly model of investment-goods producers and use it to analyze the aggregate dynamics of investment, prices, and markups.

In the model, an open 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. We then leverage this characterization to understand the evolution of markups along the equilibrium path of capital accumulation.

We calibrate the model interpreting the foreign oligopoly as the semiconductor industry and perform a quantitative exploration of the role of market power for the dynamics of investment. When the level of capital in the domestic economy is low, the price of investment and the markup are high because there is high demand for investment goods. 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. Forward-looking investment-goods producers anticipate future demand conditions along the transition path and internalize the competition with the future capital stock. This feature of our model reinforces the

endogenous capital-accumulation friction.

We contrast these findings with 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.

Our analysis of the transitional dynamics is useful to understand the response of the economy to aggregate shocks that shift the optimal level of capital. 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 first simulate an increase in Total Factor Productivity (TFP) in the domestic economy, which drives a rise in demand for investment goods. 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. However, the calibrated model suggests that the equilibrium price increase is predominantly driven by increasing marginal costs.

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 thus 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, so do markups 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. These counterfactual analyses confirm the importance of analyzing market power and capital accumulation in a dynamic equilibrium framework.

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 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 \(2020\)](#) studies 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 dynamic 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. To gain tractability of the Markov Perfect Equilibrium, we abstract from firm heterogeneity, but our analysis can be extended to the case of heterogeneous firms in future work. [Fiori \(2012\)](#) analyzes the role of fixed adjustment costs on the supply side of investment goods in a model with heterogeneous firms. Our focus on competition on the production side of investment-goods markets builds on the work [Bertolotti and Lanteri \(2024\)](#), which models endogenous product innovation, but abstracts from strategic interactions.

This paper also contributes to the large literature on international trade and macroeconomic dynamics (e.g. [Ghironi and Melitz, 2005](#); [Atkeson and Burstein, 2008](#)). Several papers analyze the role of investment-goods trade and prices in open economies. Since the work of [Eaton and Kortum \(2001\)](#), the literature has emphasized the high degree of geo-

graphic concentration in the global production of investment goods. [Restuccia and Urrutia \(2001\)](#) and [Hsieh and Klenow \(2007\)](#) study the effects of investment prices on investment rates and growth across countries. [Engel and Wang \(2011\)](#) emphasizes the critical role of trade in durable goods for the comovement between aggregate activity and trade flows. [Burststein, 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. 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 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](#); [Kahn, 1986](#); [Suslow, 1986](#)) and 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](#)). We build on this literature to analyze the aggregate capital-accumulation effects of market power, in particular in response to shocks to the demand for investment goods. Consistent with the 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. In similar spirit to the dynamic financial oligopoly characterized by [Villa \(2023\)](#), investment-goods producers internalize the effect of their decisions on future prices through a dynamic demand equation. Following the approach of [Villa \(2023\)](#), we characterize the equilibrium dynamics with an interpretable 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 open 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 make the analysis clearer and then extend the model to stochastic shocks in our quantitative analysis.

3.1 Investment Demand in an Open Economy

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 only 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

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

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

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

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

The first-order conditions of the profit maximization problem are

$$F_K(K_{t-1}, L) = R_t^K \quad (5)$$

$$F_L(K_{t-1}, L) = W_t.$$

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., $D_t = 0$.

We assume that the interest rate satisfies $R = \beta^{-1}$. 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:

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

Equation (6) implicitly expresses the demand for investment goods 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 ownership of the capital stock are immaterial and we can equivalently derive this condition assuming that firms accumulate capital instead of households.

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 on the determination of the price of investment goods, which is instead endogenous and is affected by the path of capital accumulation in the open economy. The exogeneity of the interest rate allows us abstract from the possible internalization of interest-rate changes in the decisions of large investment-

goods producers, which would add technical complexity, but appears less relevant for our question of interest.

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

$$P_t^I = \theta P_t + 1 - \theta, \quad (7)$$

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-goods 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 we assume $c_q > 0$ and $c_{qq} \geq 0$. Hence, 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-goods producers is to maximize the present discounted value of profits:

$$\sum_{t=0}^{\infty} R^{-t} \pi_t. \quad (8)$$

Our analysis can be extended to domestic investment-goods producers owned by the representative household. However, in this case the objective function (8) would not coincide with the objective of the firm owner when firms do not take prices as given.²

3.3 First Best

Before analyzing the effects of market power, we briefly introduce the competitive benchmark, which coincides with the solution to the problem of a planner who maximizes household welfare in the domestic economy taking as given the cost function to produce investment goods. We formulate this problem explicitly in Appendix A.1.

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

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

Notice that if the cost function c is convex, it acts as a capital adjustment cost. 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.

4 Investment-Goods Oligopoly

We now analyze the case of investment-goods producers that act as oligopolists and internalize the residual demand for investment. We describe the Markov Perfect Equilibrium and derive the optimality conditions of the investment-goods producers. We then use these optimality conditions to relate markups and capital accumulation. Finally, we contrast this problem with the case of commitment to future production.

²For an analysis of common ownership in oligopoly in general equilibrium models, see [Azar and Vives \(2021\)](#).

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:

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

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

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:

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

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

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

where we used the market-clearing condition $(N - 1)q_-(K) + q = Q = \theta I$ to express aggregate production of the investment good. This formulation of the capital accumulation equation clarifies that each firm effectively competes with the other $N - 1$ as well as the existing stock of undepreciated capital.

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

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

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:

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

where $I(K)$ denotes aggregate investment and we have used the fact that in a symmetric equilibrium each firm produces a fraction 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 the quantity produced q (and an associated increase in future capital K'). This increase in production has three effects on the present discounted value of profits. First, it yields additional profits equal to the current markup $P - c_q(q)$.

Second, it moves the equilibrium of the market for investment goods along the demand curve, reducing the market-clearing price. The effect of this price change on profits is encoded in the term $qR^{-1}(\theta^{-1}f_{kk}(K') + (1 - \delta)P_k(K'))$.

Third, it leads to a higher future level of capital, which in turn 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 of the current production, as well as with their competitors.

We define a Markov Perfect Equilibrium as follows.

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 oligopoly Generalized Euler Equation (12), and envelope condition (13).*

4.2 Dynamic Markup Rule and Static Markup

We now use the GEE to express the price in terms of the marginal cost and a markup rate. To this end, we first rewrite equation (12) as follows:

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

We then observe that $\frac{dP}{\partial Q} = \frac{dP}{dK'} \frac{dK'}{dQ} = \theta^{-1} \frac{dP}{dK'}$, as one additional unit of output of the oligopolistic industry translates into θ^{-1} additional unit of future capital. Thus, defining the inverse price elasticity of demand

$$\eta \equiv -\frac{Q}{P} \frac{dP}{dQ} = -\frac{Q}{P} \theta^{-1} R^{-1} (\theta^{-1} f_{kk}(K') + (1-\delta) P_k(K')), \quad (14)$$

and using $q = \frac{Q}{N}$ we get

$$P = \underbrace{\frac{N}{N-\eta}}_{\text{Dynamic Markup}} \cdot \underbrace{(c_q(q) - R^{-1}\theta^{-1}V_k(K'))}_{\text{Dynamic Marginal Cost}}. \quad (15)$$

Equation (15) expresses the price as a *dynamic markup* rule. Notice that the appropriate notion of marginal cost is composed of two terms. First, we have the “static” marginal cost $c_q(q)$, which is the cost of producing one additional unit at the current date. Second, because of the dynamic nature of the oligopolist’s problem, we have the discounted 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 marginal cost as $\mu^D \equiv \frac{\eta}{N-\eta}$, where the superscript D stands for “dynamic.” In equilibrium, the inverse elasticity η 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 , over the static marginal cost $c_q(q)$, as follows:

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

The term in parenthesis on the right-hand side of equation (16) adjusts the dynamic markup

to account for the effect of future competition on the overall marginal cost.

4.3 Prices and Markups Around Steady State

To gain further insight into the effect of the level of capital on the equilibrium price, 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). We will verify this condition numerically. In a neighborhood of the steady state, we then have $0 \leq g_k(K) < 1$. 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

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

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

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

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.

Furthermore, in steady state we can use the envelope condition (13) together with equation (16) to express the static markup rate as follows:

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

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

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

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.

4.5 Commitment to Future Production

We now analyze the role of commitment to a future production plan. We consider the following game. 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.

In this formulation, we assume that investment-goods producers cannot collude because of coordination costs that we do not explicitly model. In Appendix A.2 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 $N = 1$.

The oligopolist's maximization problem is

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

subject to the demand schedule (or, using the language of Ramsey-optimal policy, “implementability constraint”)

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

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

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

The first-order conditions of this problem are:

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

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

with initial condition on the multiplier $\gamma_{-1} = 0$. These optimality conditions trade off 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 no-commitment case, 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:

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

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

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

we get

$$P_t = \underbrace{\frac{N}{N - \left(1 + \frac{N(1-\delta)\gamma_{t-1}}{Q_t}\right) \eta^{FC}}}_{\text{Dynamic Markup}} \cdot \underbrace{\left(c_q(q_t) + R^{-1}(1 - \delta)(P_{t+1} - c_q(q_{t+1}))\right)}_{\text{Dynamic Marginal Cost}}. \quad (21)$$

Equation (21) 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’s problem, we have the discounted future markup. Similarly to the no-commitment case, we can also define the dynamic markup rate under commitment as a fraction of the marginal cost.

5 Quantitative Analysis

In this section, we calibrate the model and solve it numerically to 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.

5.1 Solution Method

We begin this section by briefly discussing our global solution method.

Markov Perfect Equilibrium. We solve the Markov Perfect Equilibrium 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. In this case, we solve the model recursively by adding the multiplier on the past investment Euler equation as a state variable. We then solve the equilibrium under commitment using 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 A.4 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. In Appendix A.5 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 set the number of foreign investment-goods producers to closely resemble the highly concentrated market structure in semiconductor manufacturing. We then experiment with a change in market structure in Section 6.4. We assume that the cost function to produce investment goods is quadratic: $c(q) = c_1 q + \frac{c_2}{2} q^2$. Given a calibrated value for the slope of the marginal cost c_2 , we set the intercept c_1 to normalize the marginal cost of investment to one in the first-best steady state. We calibrate c_2 so that the ratio of profits to sales in steady state closely matches the ratio of operating income to sales in balance-sheet data

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.

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

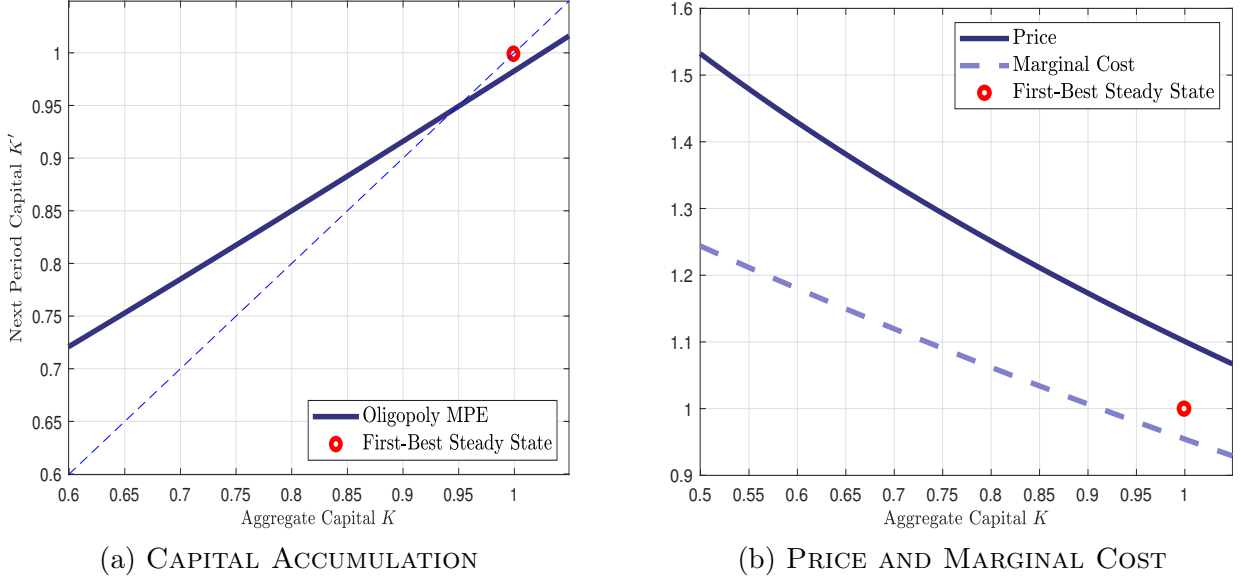
Figure 2 illustrates some key properties of the Markov Perfect Equilibrium. The left panel portrays the law of motion of aggregate capital, comparing the oligopoly outcome (solid line) with the first-best allocation (red circle). The right panel portrays the equilibrium price (solid line) and the marginal cost (dashed line) as functions of the capital level.

In the Markov Perfect Equilibrium, the steady-state level of capital is lower than in first best because of the presence of a markup. Moreover, as the economy grows toward its steady state, the price of investment declines faster 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. Hence, less competition among investment-goods suppliers dampens capital accumulation and growth. This mechanism is related to the one that arises in the presence of dynamic oligopoly in the credit market, which [Villa \(2023\)](#) analyzes.

Overall, the model predicts a 0.3% permanent-consumption loss in the Markov Perfect Equilibrium relative to first best.

Next we investigate the dynamics of markups, which Figure 3 displays. We distinguish

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



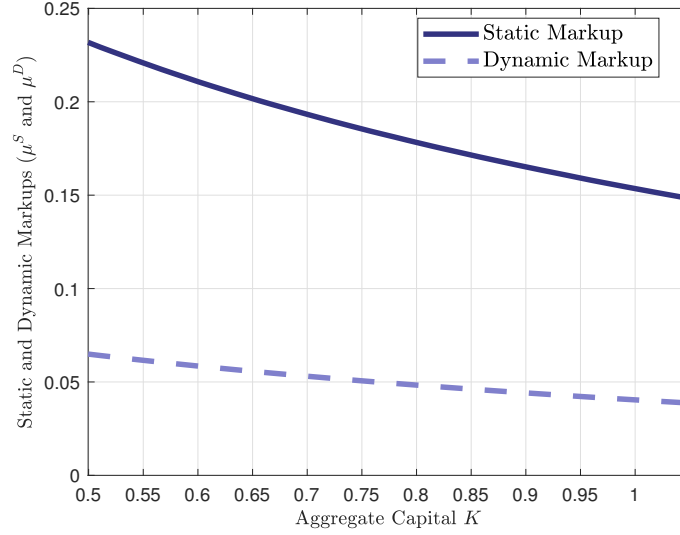
Notes: The figure displays capital accumulation and prices in the Markov Perfect Equilibrium (MPE). Panel (a) illustrates the law of motion of capital in the domestic economy. The solid line represents next-period capital (y-axis) as a function of current capital (x-axis). Its intersection with the 45-degree 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.

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 marginal cost due to competition with the future undepreciated capital stock. Both markup rates decline as aggregate capital increases. When the level of capital is low, the price elasticity of investment is low, consistent with the analytical insights of Section 4.4 in a simplified setting. This feature accounts for the negative slope of μ_t^D .

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. This anticipation of future markups accounts for the decreasing gap between μ_t^S and μ_t^D in the figure. Overall, both the price elasticity and the anticipation of future markups contribute to generate a larger distortion for lower levels of capital.

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.

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 Commitment

We now investigate the difference between the Markov Perfect Equilibrium and the case of full commitment to future production (Section 4.5). Figure 4 displays the dynamics of aggregate capital, multiplier on the investment Euler equation (γ_t), price of investment, and static markup. The figure compares the Markov Perfect Equilibrium (solid lines) with the case of commitment (dashed lines).

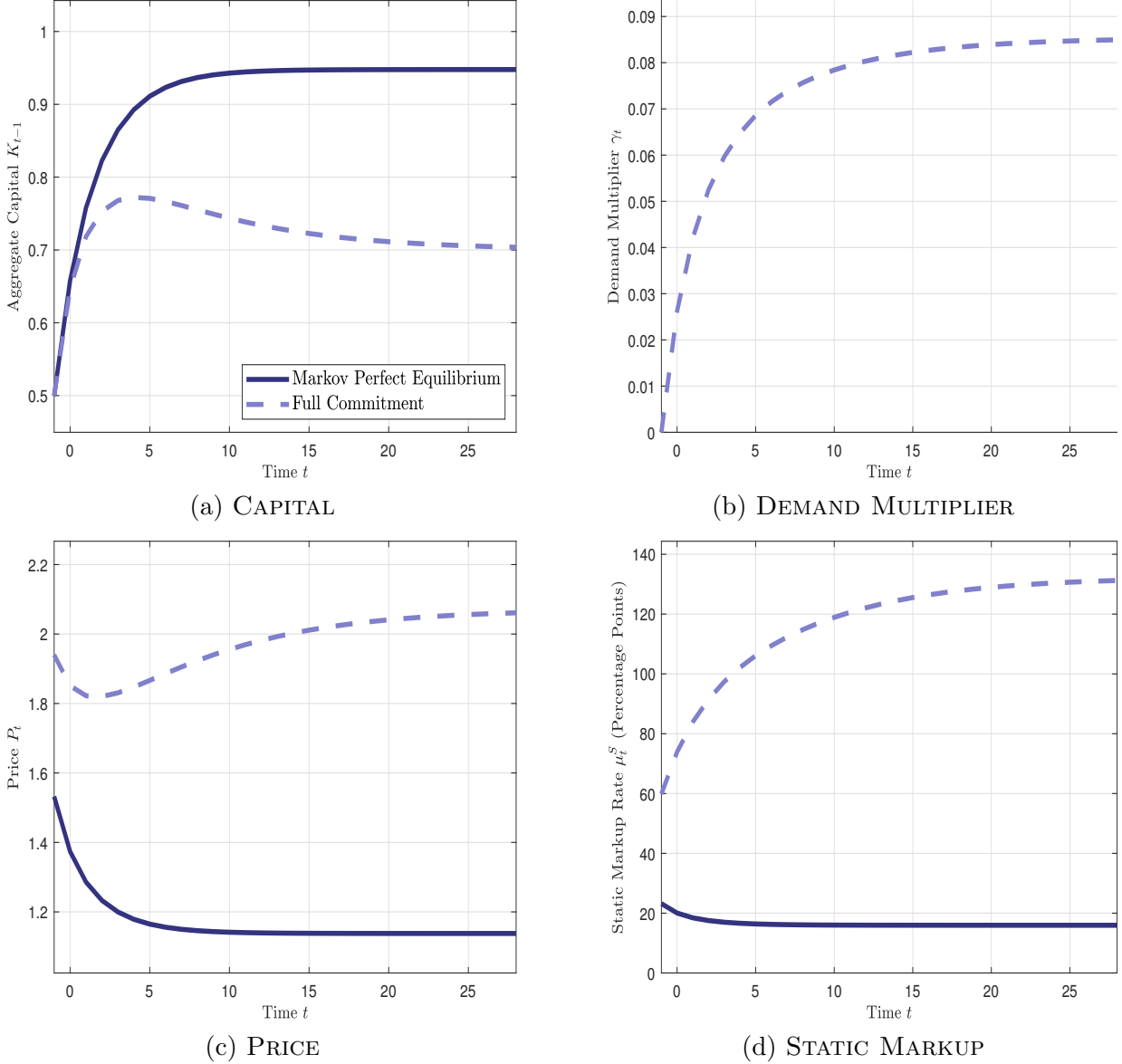
First, we notice that in the presence of commitment the price of investment and the markup are substantially higher than in the Markov Perfect Equilibrium. As a result, capital converges to a lower steady-state level. In steady state, the static markup rate is approximately 130% with commitment and 16% in the Markov Perfect Equilibrium. Accordingly, in the presence of commitment the welfare cost of the oligopoly is significantly higher and equal to 2.3% 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, prices

and markups grow and the economy reverts to its steady-state level of capital.

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 4: Role of Commitment



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.

5.5 Inspecting the Mechanism: Markup Decomposition

We now provide a decomposition of markups along the equilibrium capital-accumulation path. This decomposition highlights the main forces at play in the evolution of markups, namely shifts in the demand for investment goods and changes in the slope of the demand curve.

In the Markov Perfect Equilibrium, we can reformulate the GEE (12) along the transition path in terms of future sequences of three objects: quantities produced, derivatives of the demand function $\frac{dP_t}{dQ_t} \equiv \theta^{-1}R^{-1}(\theta^{-1}f_{kk}(K_t) + (1 - \delta)P_k(K_t))$, and 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 express the difference between price and marginal cost as follows:

$$P_t - c_q(q_t) = - \sum_{s=0}^{\infty} B_{t,t+s} q_{t+s} \frac{dP_{t+s}}{dQ_{t+s}}. \quad (22)$$

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

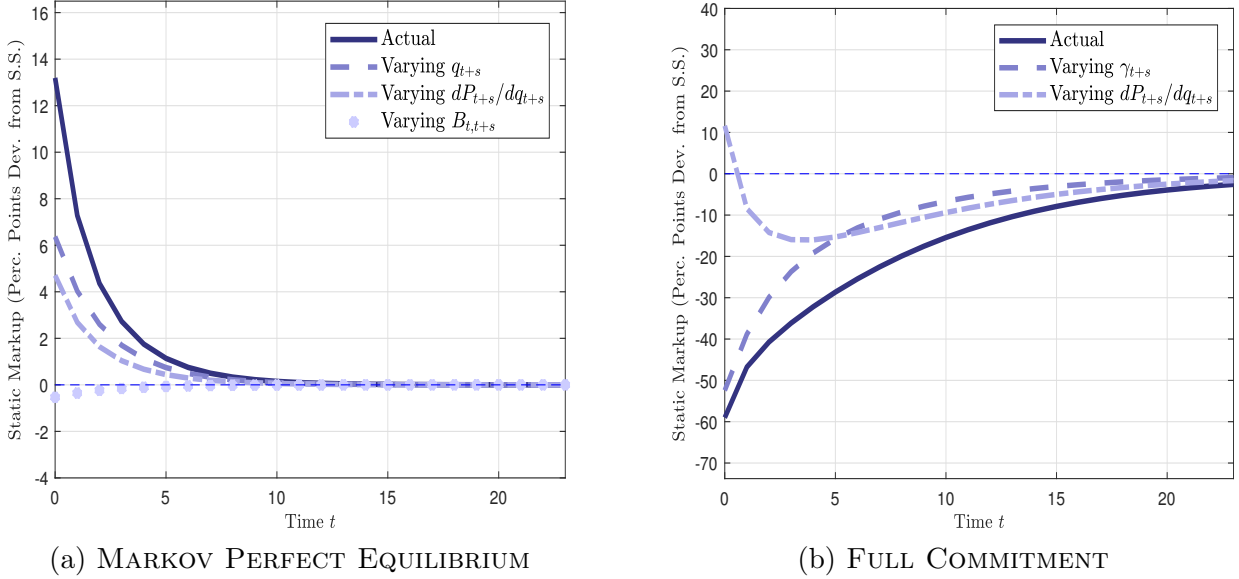
Similarly, we can reformulate the commitment first-order condition (20) as follows:

$$P_t - c_q(q_t) = - \sum_{s=0}^{\infty} R^{-s} (1 - \delta)^s \gamma_{t+s} \left(\frac{dP_{t+s}}{dQ_{t+s}} \right) \quad (23)$$

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 5 illustrates this decomposition for the Markov Perfect Equilibrium (left panel) and the case of commitment (right panel). In the absence of commitment, quantities decline over time because investment is initially high and then decreases as the economy approaches steady state. This path contributes to declining markups over time. Furthermore, rotations in the demand curve amplify the effect of the decline in investment, leading to a steeper decline in markups. In contrast, in the presence of commitment, the multiplier γ_t grows as capital is accumulated, leading to an increasing gap between price and marginal cost.

Figure 5: Markup Decomposition in the Markov Perfect Equilibrium vs. Commitment



Notes: The figure displays a decomposition of the evolution of the static unit markup $P_t - c_{q,t}$ over the transition of the economy to steady state. Panel (a) refers to the Markov Perfect Equilibrium. Leveraging equation (22), the figure disentangles variation in the static unit markup (solid line) driven by: (i) quantities q_{t+s} 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). Panel (b) refers to the full commitment equilibrium. Leveraging equation (23), the figure disentangles variation in the static unit markup (solid line) driven by: (i) the demand multiplier γ_{t+s} (dashed line); and (ii) the derivative of inverse demand with respect to the quantity produced dP_{t+s}/dQ_{t+s} (dash-dotted line).

6 Shocks, Marginal Costs, and Market Power

In this section, we analyze the effects of aggregate shocks. We simulate an increase in the demand for investment goods, similar to the one experienced in the post-2020 recovery. We highlight the roles of increasing marginal costs—akin to capacity constraints—and market power for the dynamics of investment and prices. We also consider an investment-cost shocks and a stochastic version of our model with persistent business-cycle shocks. Finally, we simulate the effects of a change in the number of investment-goods producers and a relaxation of capacity constraints.

6.1 Investment-Demand Shock

We now leverage 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 tight capacity constraints, which we interpret as steeply increasing marginal costs in our parsimonious model. 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. Specifically, we calibrate a permanent increase in the level of TFP in the domestic economy 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. On impact, the price of investment goods jumps and overshoots its long-run value. We find that the price dynamics are predominantly accounted for by changes in the marginal cost.

At the same time, markups also increase, although moderately, by approximately 2.5 percentage points on impact. The observed overshooting of markups is consistent with our analysis of the transition to steady state in the previous section. The demand shock effectively initiates a new transition to a higher steady-state level of capital. Thus, markups are initially high and then decline as the domestic economy converges to the new steady state.

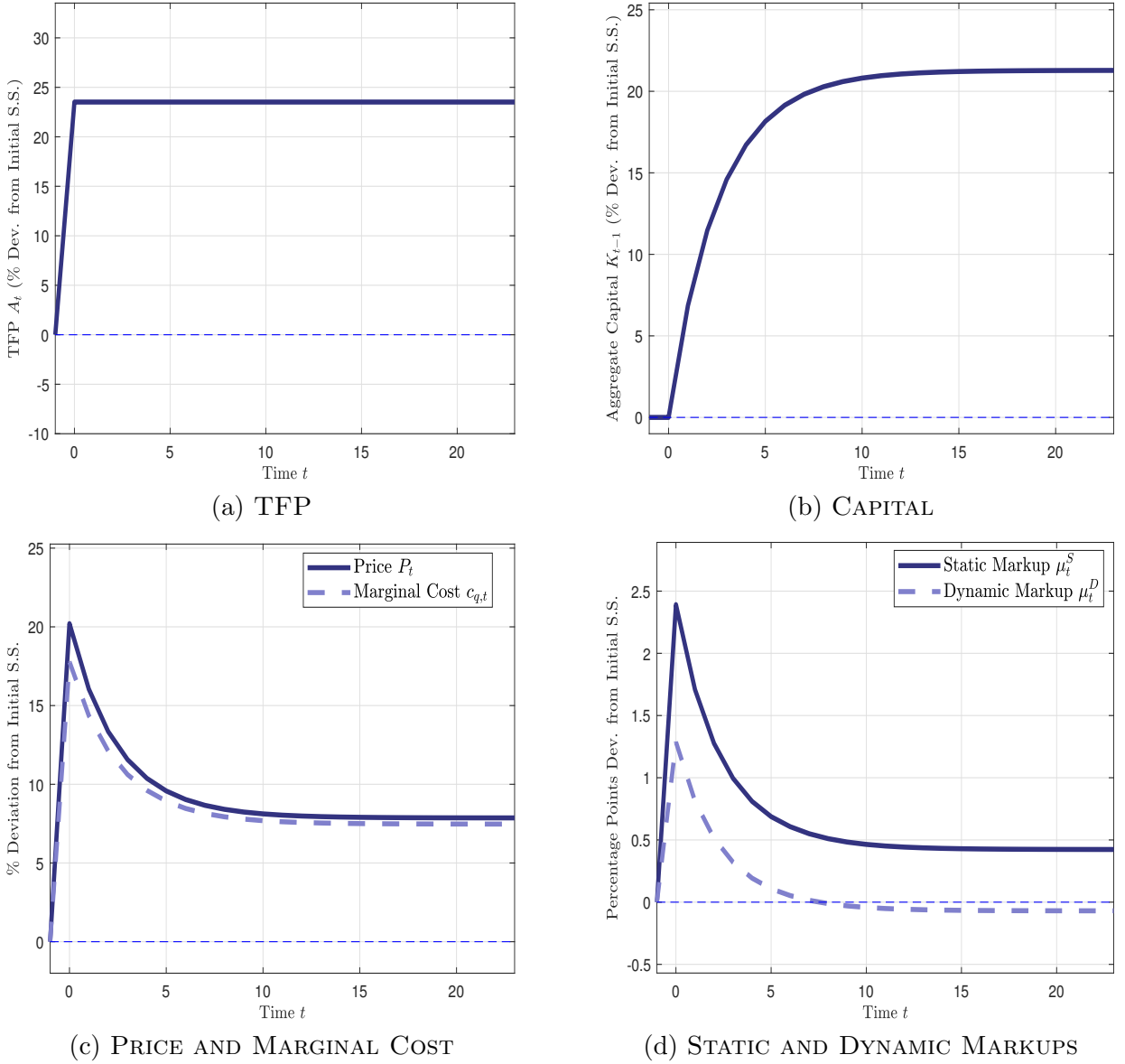
Overall, this analysis shows that in spite of the presence of market power and endogenous markups, the increase in the relative price of investment is largely driven by technological features, such as capacity constraints. Because of the convexity of the cost function, the model predicts that average (i.e., per unit sold) profits of investment-goods producers also increase in response to the shock.

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 B. 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 also perform a separate model calibration in Appendix A.5). This positive comovement of prices and production volumes confirms the important role of demand conditions in the recovery.

We also analyze the effects of the investment-demand shock when investment-goods producers have full commitment. We report the results in Appendix A.7. 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



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.

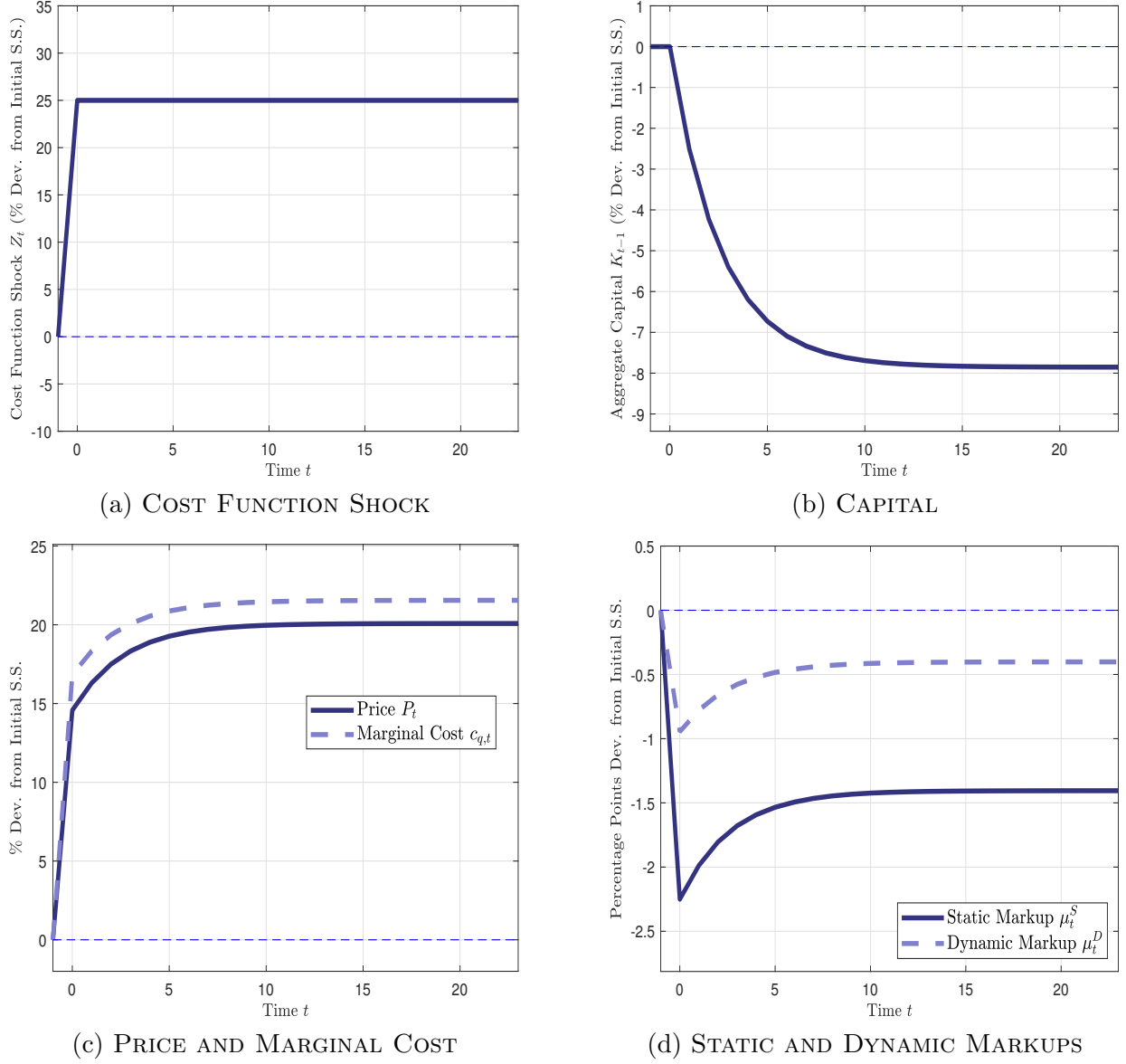
We also consider the contemporaneous occurrence of an investment-demand shock and an investment-cost shock and report the results in Appendix A.6. Because both shocks have a positive effect on prices, shocks of a smaller magnitude are needed to account for the large increase in the price of semiconductors we observe in the data. Furthermore, in the presence of both shocks the model can quantitatively account for both the price increase and the increase in the production of semiconductors during the recovery.

6.3 Business Cycles

We now extend our model to include stochastic productivity shocks in the domestic economy. To this end, 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 A.3. In the presence of stochastic shocks, the GEE of a generic investment-goods producer becomes:

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

Figure 7: Investment-Cost Shock



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:

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

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

Table 2: Stochastic Productivity: Business Cycle Moments

	FB	MPE	FC
Mean I	0.046	0.044	0.031
Mean P	1.000	1.095	2.172
Mean Markup	0	0.100	1.261
St. Dev. I/St. Dev. Y	4.063	3.494	4.705
St. Dev. P	0.004	0.005	0.002
St. Dev. Markup	0	0.001	0.004
Corr. Y and I	0.916	0.940	0.887
Corr. Y and P	0.921	0.934	0.887
Corr. Y and Markup	0	0.901	-0.904

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 A.8, 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.

6.4 Counterfactual Analyses: Market Power vs. Capacity Constraints

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. We now use our model to shed light on the likely effects of policies, such as the CHIPS and Science Act, that affect the market structure and productive capacity for dynamic inputs.

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-good producers. To quantify the implicit subsidy, we assume that the present discounted value of steady-state profits with $N = 3$ firms exactly offsets the entry cost. To induce entry of one additional firm, a flow subsidy paid to each investment-good producer in every period must equal 0.2% 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 0.3% of permanent consumption.

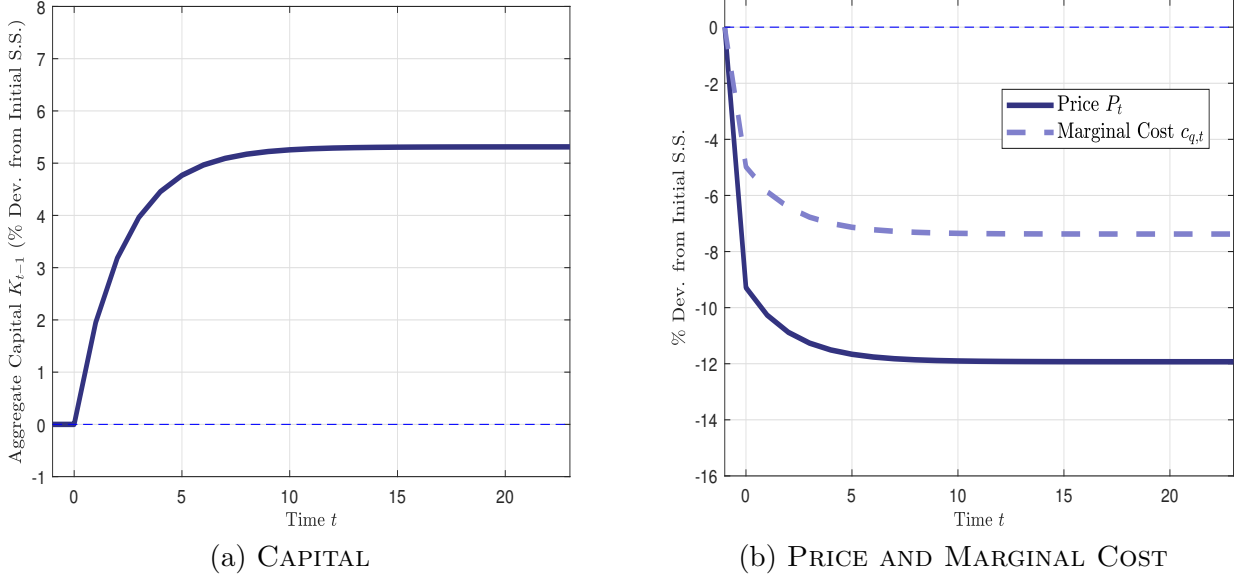
We also simulate this increase in competition in the case of full commitment and report the results in Appendix A.7. In this case, we obtain an even larger effect of entry on markups, prices, and capital accumulation.

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.

Figure 9 displays the results. Although we match the induced decline in the marginal cost, 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.

In terms of welfare, the increase in the number of producers leads to a permanent-consumption gain that is approximately one third larger than the one implied by the counterfactual in which we flatten the cost curve. Strikingly, the increase in N approximately closes the gap between the Markov Perfect Equilibrium and the first-best allocation

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



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.

associated with $N = 3$.³ This analysis shows that market power plays a critical role in the transmission of policy interventions aimed at expanding capacity in the semiconductor manufacturing industry

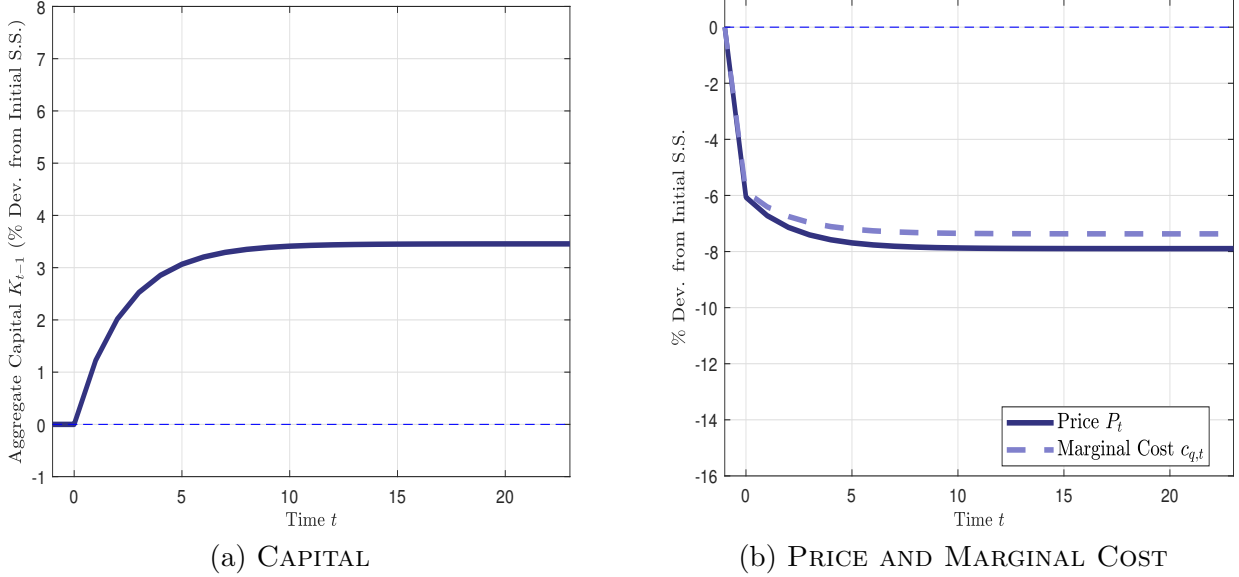
7 Conclusion

We have developed an open-economy model with market power in the global production of investment goods. In so doing, we were motivated by the post-2020 global recovery, which featured a large increase in demand for inputs produced by a highly concentrated industries, such as semiconductors.

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

³The first-best allocation associated with $N = 4$ implies an even higher level of welfare.

Figure 9: Relaxation of Capacity Constraints



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.

behave as oligopolists without commitment, the markup rises in response to positive shocks to investment demand, thereby generating a microfounded aggregate capital adjustment cost.

However, 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 limited role for markup hikes, despite an overall increase in profits. By allowing this decomposition, 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 market power.

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APPENDIX

A Additional Model Analyses

A.1 First-Best Planning Problem

The social planner chooses sequences $\{C_t, B_t, q_{jt}, K_t\}$ for $j = 1, \dots, N$ and $t = 0, \dots, \infty$ 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

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

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):

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

A.2 Commitment with Collusion

A planner chooses sequences of prices and quantities for all N producers, $\{P_t, q_{jt}\}$, for $t = 0, \dots, \infty$ and $j = 1, \dots, N$ to maximize

$$\sum_{t=0}^{\infty} R^{-t} \left(P_t \sum_{j=1}^N q_{jt} - \sum_{j=1}^N c(q_{jt}) \right), \quad (\text{A1})$$

subject to

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

for $t = 0, 1, \dots$, 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

$$\theta P_t - \theta c_q \left(\frac{\theta I_t}{N} \right) = -\Gamma_t R^{-1} \theta^{-1} f_{kk}(K_t) + R^{-1} \theta (1 - \delta) \left(P_{t+1} - c_q \left(\frac{\theta I_{t+1}}{N} \right) \right). \quad (\text{A2})$$

Notice the similarity between equation (A2) 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.

A.3 Stochastic Model

Let s_t be a vector of shocks. Given s_0 , and history of shocks $s^t = \{s^{t-1}, s_t\}$, a stochastic open economy is populated by a representative household with utility function

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t u(C(s^t)) Pr(s^t), \quad (\text{A3})$$

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

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

$$C(s^t) + P^I(s^t)I(s^t) + \sum_{s_{t+1}} B(s_{t+1}|s^t) = W(s^t)L + R^K(s^t)K(s^{t-1}) + R^b(s_t|s^{t-1})B(s_t|s^{t-1}) + D(s^t), \quad (\text{A4})$$

where $P^I(s^t) = P_t^I$ is the price of investment goods $I(s^t) = I_t$, $B_t = B(s_{t+1}|s^t)$ are state-contingent bonds that pays $R^b(s_t|s^{t-1})$, $W_t = W(s^t)$ is the wage, L is a constant endowment of labor, $R_t^K = R^K(s^t)$ 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. We assume that the household is only subject to the natural debt limit. For ease of notation, we drop the dependency from the history of shocks and simply indicates all variables with their corresponding time subscript.

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

$$K_t = (1 - \delta)K_{t-1} + I_t. \quad (\text{A5})$$

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

$$\forall s^{t+1}: \quad 1 = \beta \frac{u_c(C(s^{t+1}))}{u_c(C(s^t))} R^b(s_{t+1}|s^t) Pr(s^{t+1}) \quad (\text{A6})$$

$$P_t^I = \mathbb{E}_t \left[\beta \frac{u_c(C_{t+1})}{u_c(C_t)} (R_{t+1}^K + (1 - \delta)P_{t+1}^I) \right]. \quad (\text{A7})$$

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

$$Y_t = F(A_t, K_{t-1}, L). \quad (\text{A8})$$

The first-order conditions of the profit maximization problem are

$$F_K(A_t, K_{t-1}, L) = R_t^K \quad (\text{A9})$$

$$F_L(A_t, K_{t-1}, L) = W_t.$$

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 (A6) 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 (A6), (A7), and (A9), we obtain the following investment Euler equation that describes optimal capital accumulation in the stochastic version of the economy:

$$P_t^I = R^{-1} \mathbb{E}_t [f_k(A_{t+1}, K_t) + (1 - \delta)P_{t+1}^I]. \quad (\text{A10})$$

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

A.3.1 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:

$$\sum_{t=0}^{\infty} \sum_{s^t} R^{-t} \pi_t(s^t) Pr(s^t). \quad (\text{A11})$$

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). Equation (A10) becomes:

$$\theta P_t + 1 - \theta = R^{-1} \mathbb{E}_t [f_k(A_{t+1}, K_t) + (1 - \delta)(\theta P_{t+1} + 1 - \theta)]. \quad (\text{A12})$$

Divide everything by θ and factor out the constant to get:

$$P_t = R^{-1} \mathbb{E}_t [\theta^{-1} f_k(A_{t+1}, K_t) + (1 - \delta)P_{t+1}] - \underbrace{\theta^{-1}(1 - \theta)(1 - R^{-1}(1 - \delta))}_{\equiv \kappa}. \quad (\text{A13})$$

A.3.2 First Best

Before analyzing the effects of market power, we briefly introduce the competitive benchmark, which 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 (A11) 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

$$\theta c_q\left(\frac{\theta I_t}{N}\right) + 1 - \theta = R^{-1} \mathbb{E}_t \left[f_k(A_{t+1}, K_t) + (1 - \delta) \theta c_q\left(\frac{\theta I_{t+1}}{N}\right) + 1 - \theta \right]. \quad (\text{A14})$$

A.3.3 Markov Perfect Equilibrium and Generalized Euler Equation

A generic investment-goods producer solves the following problem:

$$\max_{P, K', q} Pq - c(q) + R^{-1} \mathbb{E}[V(K', s')|s] \quad (\text{A15})$$

subject to the demand schedule

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

the market-clearing condition

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

and the law of motion for capital

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

First, substitute investment I from the market-clearing condition in the law of motion for capital. Second, use the derived equation to substitute q in the objective function. Third, substitute P in the objective function using the demand schedule. Hence, take the first-order condition with respect to K' to get the following Generalized Euler Equation (GEE):

$$\theta P - \theta c_q(q) + q R^{-1} \mathbb{E} [\theta^{-1} f_{kk}(A', K') + (1 - \delta) P_k(K', s') | s] + R^{-1} \mathbb{E} [V_k(K', s') | s] = 0, \quad (\text{A16})$$

which involves the derivative of the future price with respect to capital in every possible future realization of shocks.

A.3.4 Commitment to Future Production

Given K_{-1} , the oligopolist's problem involves finding sequences $\{P(s^t), K(s^t)\}_{t=0}^{\infty}$ such that

$$\sum_{t=0}^{\infty} \sum_{s^t} R^{-t} (P_t (\theta(K_t - (1 - \delta)K_{t-1}) - (N - 1)q_{-,t}) - c(\theta(K_t - (1 - \delta)K_{t-1}) - (N - 1)q_{-,t})) Pr(s^t) \quad (\text{A17})$$

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

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

for $t = 0, 1, \dots$, 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:

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

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

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

Table A1: Parameters Values

	Parameter	Symbol	Value
Investment Demand	Discount Factor	β	0.96
	Depreciation	δ	0.08
	Capital Share	α	0.333
	Oligopolistic Capital Share	θ	0.122
	Total Factor Productivity	A	0.365
Investment Supply	Number of Producers	N	3
	Marginal Cost (Intercept)	c_1	0.6747
	Marginal Cost (Slope)	c_2	100

Notes: The table reports the parameter values of an alternative calibration of the model where K represents aggregate capital, i.e., the sum of equipment and structures.

A.4 Alternative Calibration to Aggregate Capital Stock

In this subsection, we analyze the transition of the economy to the steady state and its response to an investment demand shock, assuming the alternative calibration summarized in Table A1. We now interpret K as aggregate capital, i.e., as the sum of equipment and structures.

Calibration. We follow the calibration strategy used in the main text. We set the capital share of income and the rate of physical depreciation to standard values in the real-business-cycles literature. We then 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 equilibrium. Finally, we divide the baseline weight of the imported oligopolistic input in total investment by three because equipment represents approximately one third of the capital stock in US data.

Transition to Steady State. Figure A1 depicts the transition of the economy to the steady state. Solid lines refer to the Markov Perfect Equilibrium and dashed line to the full commitment case. We assume that at $t = 0$ capital is half of its first-best steady-state level and that the demand multiplier is zero in the full commitment model.

The behavior of the economy is consistent with the results of our main calibration. In

the Markov Perfect Equilibrium, capital increases monotonically to the steady state. In contrast, prices and markups start high and monotonically decline because demand for the oligopolistic investment good is at first strong and less elastic than in the new steady state. As in the main calibration, price and markup are significantly higher in the full commitment equilibrium. Moreover, they increase to the new steady state because the cost of charging lower price increases over time, as represented by the evolution of the demand multiplier.

Investment Demand Shock. Figure A2 illustrates the response of the economy 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, the percent increase in capital between the old and new steady state exceeds the increase in TFP. Prices and marginal costs overshoot their new steady-state levels and increase by a similar factor. Therefore, marginal costs determine most of the observed price dynamics following an investment demand shock. Accordingly, static and dynamic markup only increase by 2.5 and 1 percentage points on impact, respectively.

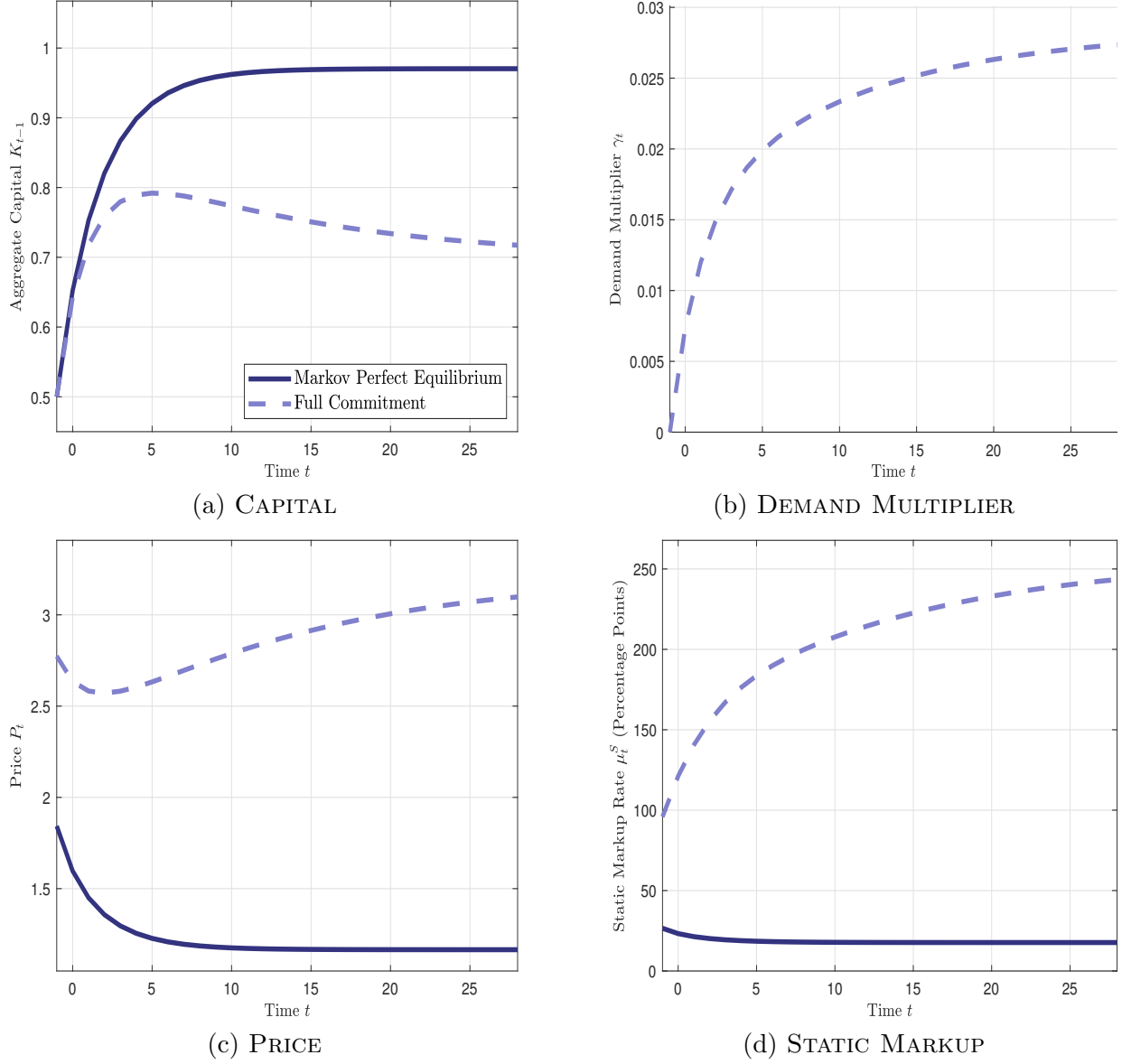
A.5 Alternative Calibration with Oligopolistic Wafer Production

In this subsection, we analyze the transition of the economy to the steady state and in response to an investment demand shock considering an alternative calibration of the model where the imported oligopolistic input represents wafers. These constitute the physical support of chips, thus being a key component in semiconductors manufacturing. We leverage the data described in Appendix B.2 Table A2 summarizes the parameter values.

Calibration. We calibrate the parameters of investment demand consistently with the main calibration of Table 1. We change the parameter governing the share of the oligopolistic input in 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.

We obtain data on unit prices for wafers from Taiwan’s Ministry of Economic Affairs,

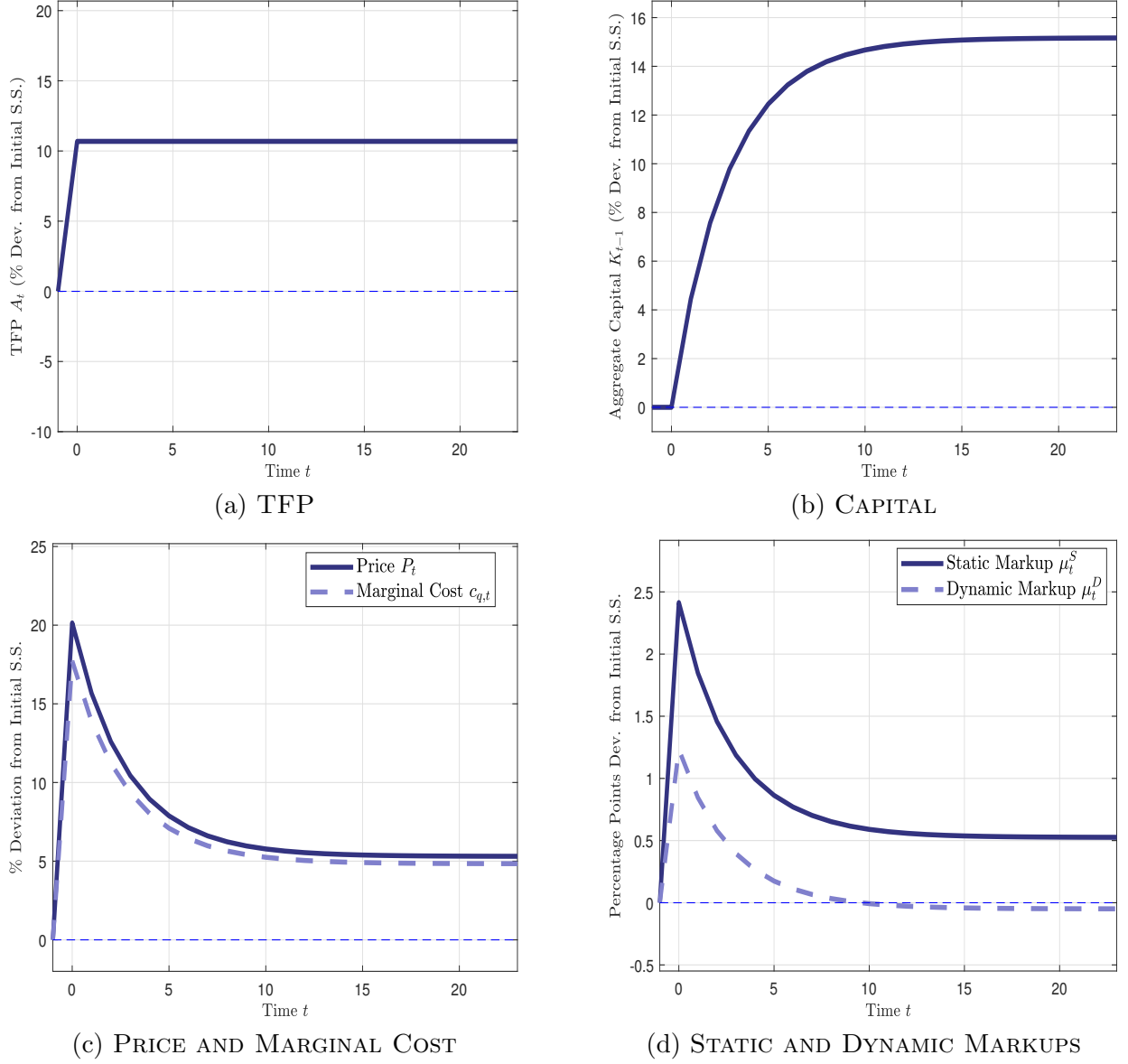
Figure A1: Transition to Steady-State with Calibration to Aggregate Capital



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) under the alternative calibration of Table A1. 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.

which publishes detailed statistics on both physical volumes and value of production at the product level. Specifically, we focus on three detailed product categories, namely wafers with size smaller than 6nm, equal to 8nm, or larger than 12nm, and aggregate them. Figures B2 and B3 represent the evolution of volumes and unit price around the 2020

Figure A2: Investment-Demand Shock with Calibration to Aggregate Capital Stock



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 A1. 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.

Table A2: 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	0.1206
	Total Factor Productivity	A	2.743
Investment Supply	Number of Producers	N	3
	Marginal Cost (Intercept)	c_1	0.7073
	Marginal Cost (Slope)	c_2	55

Notes: The table reports the parameter values of an alternative calibration of the model where wafers represent the oligopolistic input.

Covid recession.⁴

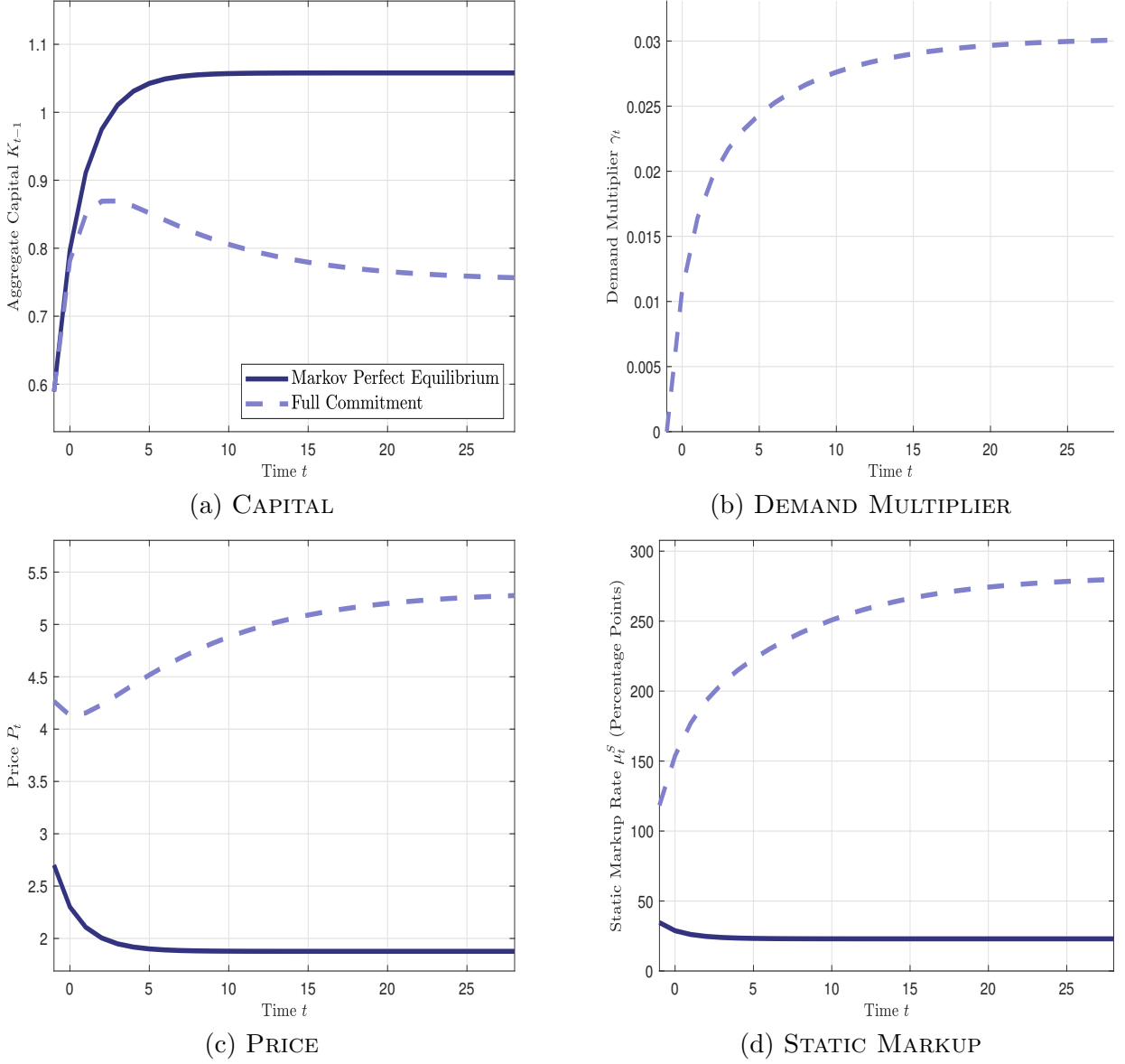
Moreover, we adjust the slope of the marginal cost function to match a ratio of operating income over sales of around 33% observed in Orbis data for Taiwanese chips manufacturers (TSMC and Mediatek). We restrict our attention to Taiwanese manufacturers to be consistent with detailed price and quantity 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 equilibrium.

Transition to Steady State. Figure A3 depicts the transition of the economy to the steady state. Solid lines refer to the Markov Perfect Equilibrium and dashed line to the full commitment case. We assume that at $t = 0$ capital is half of its first-best steady-state level and that the demand multiplier is zero in the full commitment model.

The behavior of the economy is consistent with the results of the main calibration. In the Markov Perfect Equilibrium, price and markup are initially high and monotonically decline to the new steady state because demand elasticity is initially low but increases as capital approaches its steady state level. In contrast, in the full commitment setting price and markups converge to the new steady state from below because the return from a high price increases over time, as represented by the evolution of the demand multiplier.

⁴To obtain real unit prices, we first convert Taiwanese dollars to US dollars using yearly averages of FRED's series DEXTAUS and then divide by US GDP deflator.

Figure A3: Transition to Steady-State with Calibration to Oligopolistic Wafer Production



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) under the alternative calibration of Table A2. 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.

Investment Demand Shock. Figure A4 illustrates the response of the economy 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, capital slowly adjusts to the new, higher steady-state level,

while prices and marginal costs overshoot their new steady-state levels. While the marginal cost determines most of the observed price dynamics, in this alternative calibration endogenous markups also rise significantly. On impact, they overshoot the new steady state and increase by around 10 percentage points.

The dynamics implied by the model with this alternative calibration are broadly consistent with the empirical patterns that we report in Appendix B.2.

A.6 Contemporaneous Demand and Supply Shocks

In this subsection, we analyze the response of the economy to the contemporaneous occurrence of an investment-demand shock and an investment-cost shock. Specifically, we consider an unanticipated and permanent increase in TFP A_t and an unanticipated and permanent increase in the cost-function shifter Z_t . We calibrate the size of the shocks (+14.1% in TFP and +12.5% in cost) to match the cumulative increase in the real price of semiconductors (+20%) depicted in Figure 1 and the rise in semiconductors real quantities (+18% in deviation from trend in 2022) depicted in Figure B1b.⁵

Consistent with the results of Section 6, both shocks increase investment price, reducing the size of each individual shock required to match the observed increase in semiconductors price. Furthermore, the two shocks have opposite effects on quantities. As the investment demand shock dominates quantitatively, investment and capital increase. However, relative to Figure 6b, the size of the response is dampened by the action of the investment-cost shock. Finally, both the static and the dynamic markups decline, even though their contribution to price dynamics is limited.

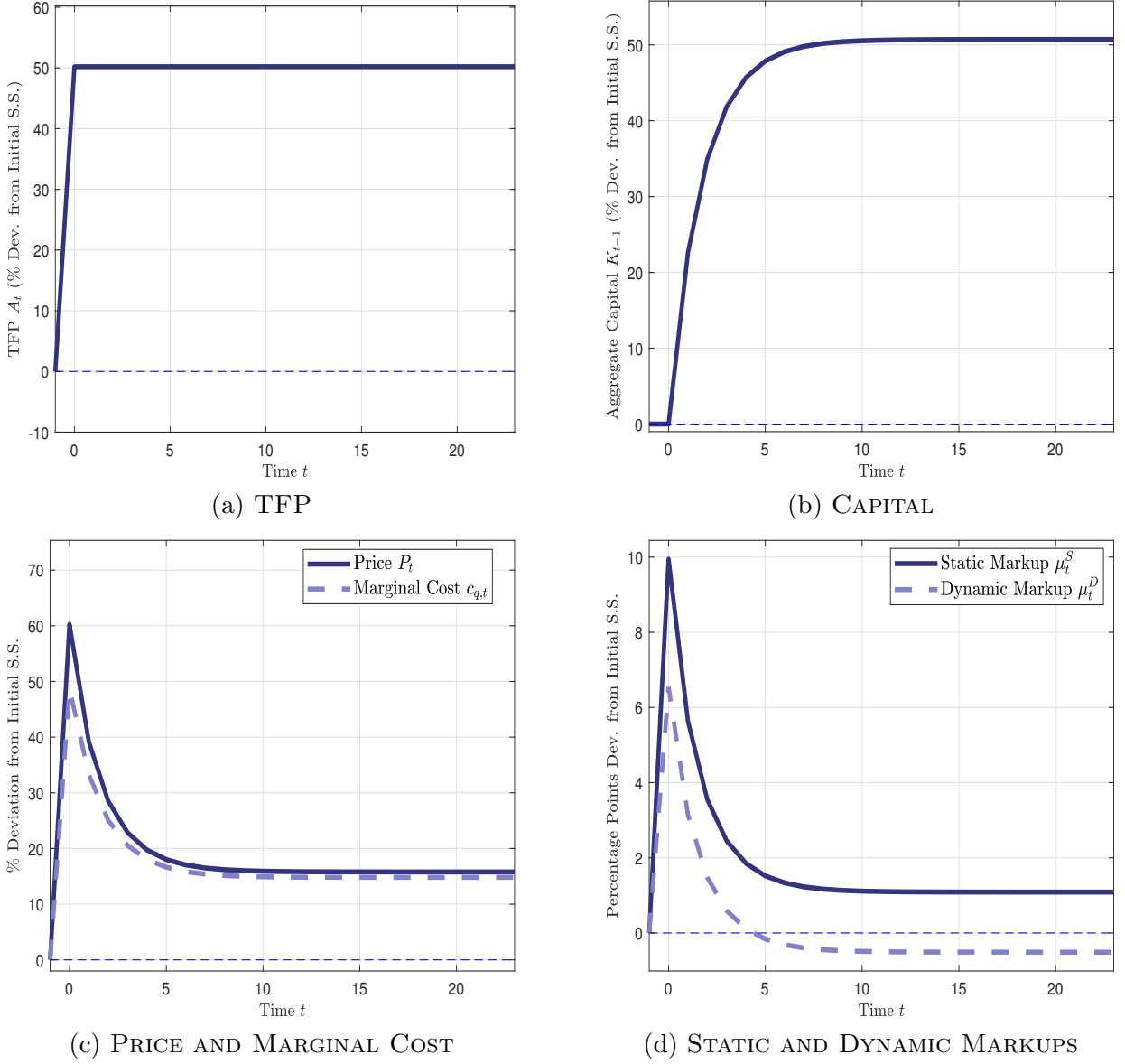
A.7 Aggregate Shocks with Full Commitment

In this subsection, we analyze the response of the economy to aggregate shocks when investment-goods producers can commit to future production. We compare the effects of an aggregate demand shock and a change in market structure to the Markov Perfect Equilibrium case examined in Section 6.

Figure A6 displays the evolution of the aggregate variables in response to a positive productivity shock of the same size as in Figure 6. The increase in capital demand in the

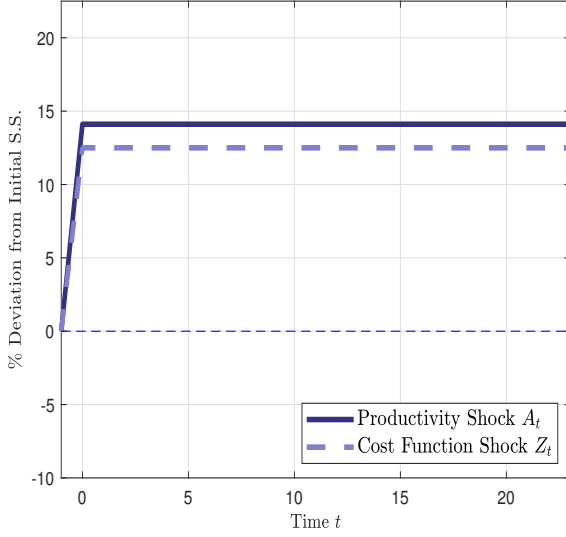
⁵We fit a linear trend over 2012-2019 on nominal billings of semiconductors to Americas (source: Semiconductors Industry Association) divided by the US Semiconductors PPI (source: FRED series PCU334413334413A).

Figure A4: Investment-Demand Shock with Calibration to Oligopolistic Wafer Production

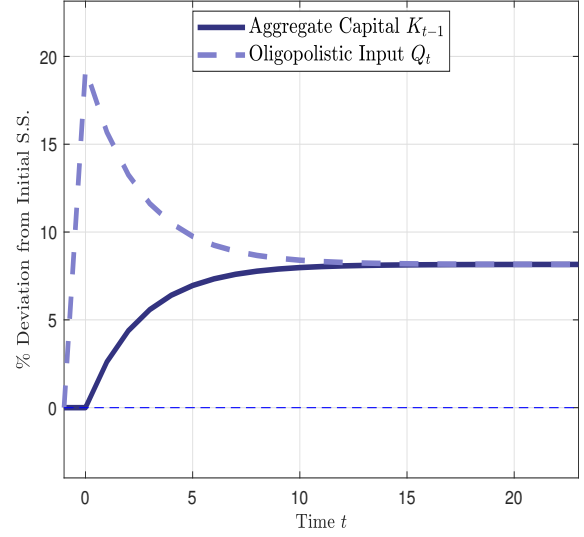


Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent 50% increase in TFP in the Markov Perfect Equilibrium under the alternative calibration summarized by Table A2. Panel (a) plots the exogenous change in TFP A_t . Panel (b) plots the transition of aggregate 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.

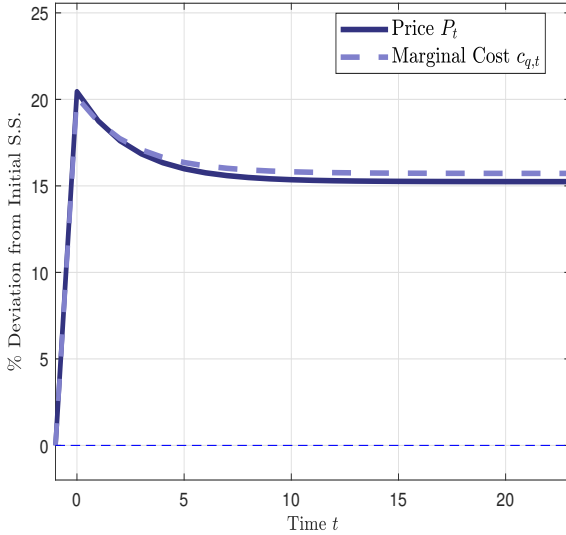
Figure A5: Contemporaneous Investment-Demand and Cost-Function Shocks



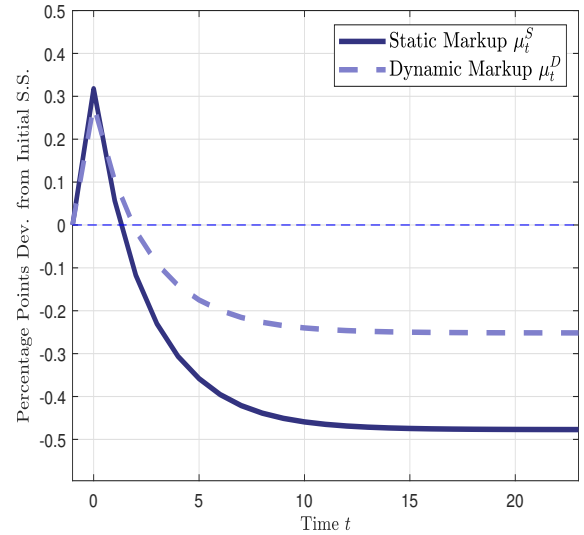
(a) TFP AND COST SHOCK



(b) CAPITAL AND OLIGOPOLISTIC INPUT



(c) PRICE AND MARGINAL COST



(d) STATIC AND DYNAMIC MARKUPS

Notes: The figure illustrates the aggregate response of the economy to two contemporaneous shocks in the Markov Perfect Equilibrium. First, an unanticipated and permanent 14.1% increase in TFP A_t . Second, an unanticipated and permanent 12.5% increase in the cost shock Z_t . Panel (a) plots the exogenous change in A_t and Z_t . Panel (b) plots the transition of aggregate capital K_{t-1} (solid line) and oligopolistic input Q_t (dashed line) 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 shocks occur 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 shocks occur.

domestic economy induces an increase in quantities produced and static marginal cost, as in the Markov Perfect Equilibrium. However, the price increases by less than the marginal cost, which determines a significant compression (-14 percentage points) in static markups. At the same time, the dynamic markup is barely affected by the investment demand shock. Overall, this analysis confirms that increasing marginal costs are largely responsible for the equilibrium price increase, irrespective of the different assumptions on commitment.

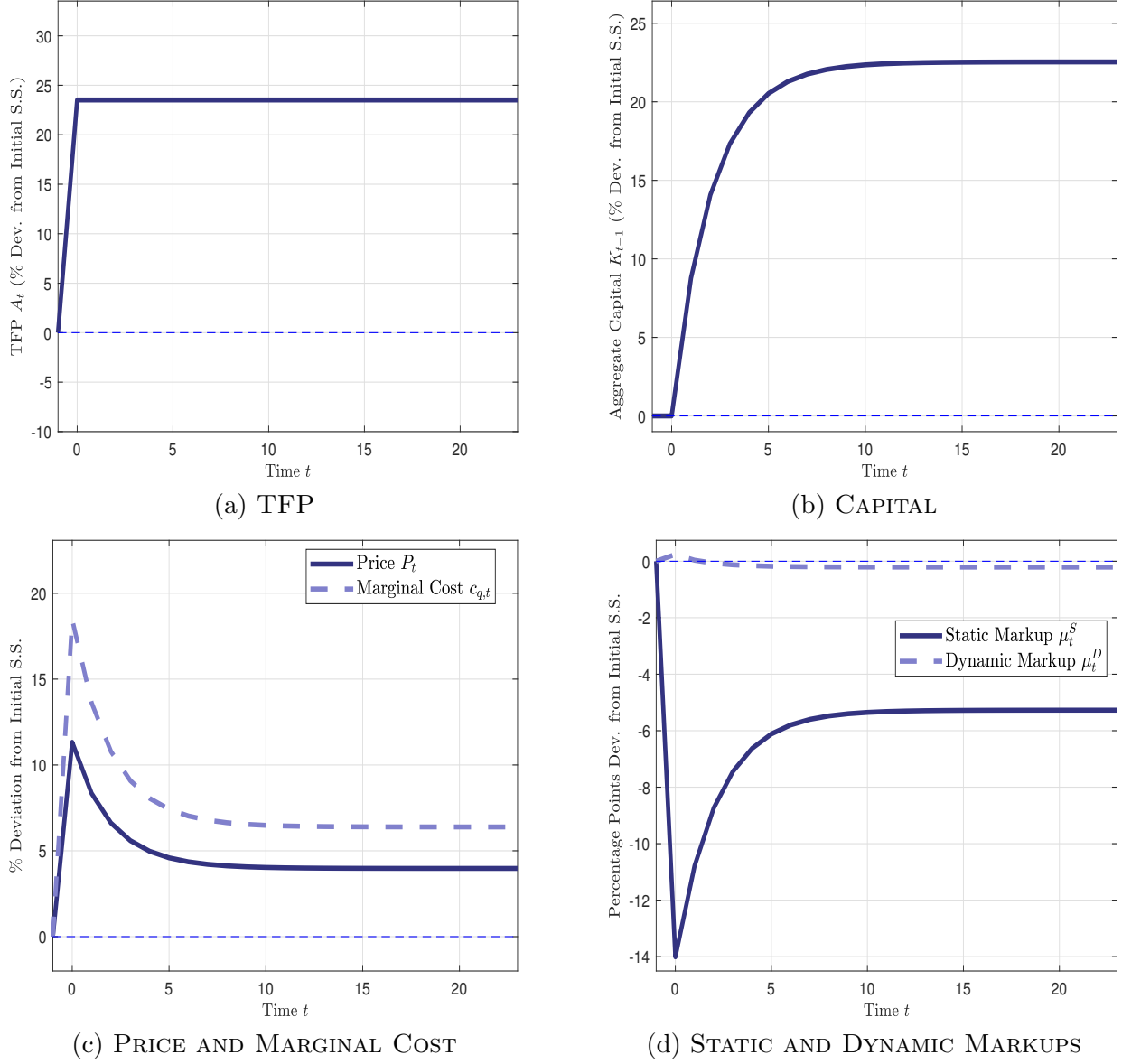
Next, we analyze a shock to the market structure, namely a change in the number of investment-goods producers from 3 to 4, in the full commitment setting. Figure A7 displays the response of capital, price, and marginal cost to the shock. Although the expansion in production capacity induces a smaller decline in the static marginal cost in the full commitment equilibrium (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 6.4 represent a lower bound. Accordingly, we also 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.

A.8 Business Cycles with TFP and Cost Shocks

We now extend the stochastic model of section 6.3 to include both stochastic productivity shocks in the domestic economy and cost function shocks in the production of investment goods. As in the main text, 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 to the cost-function shock: $\log(Z_t) = (1 - \rho)\mu_Z + \rho_Z \log(Z_{t-1}) + \varepsilon_t^Z$. Table A3 reports the values of the stochastic processes parameters used in the simulations. We parameterize them to match five data moments, summarized by Table A4.

We estimate a VAR(1) model using (i) the natural logarithm of US real GDP and (ii) Machinery and Equipment real US Producers Price Index and 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 A4 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

Figure A6: Investment-Demand Shock with Full Commitment

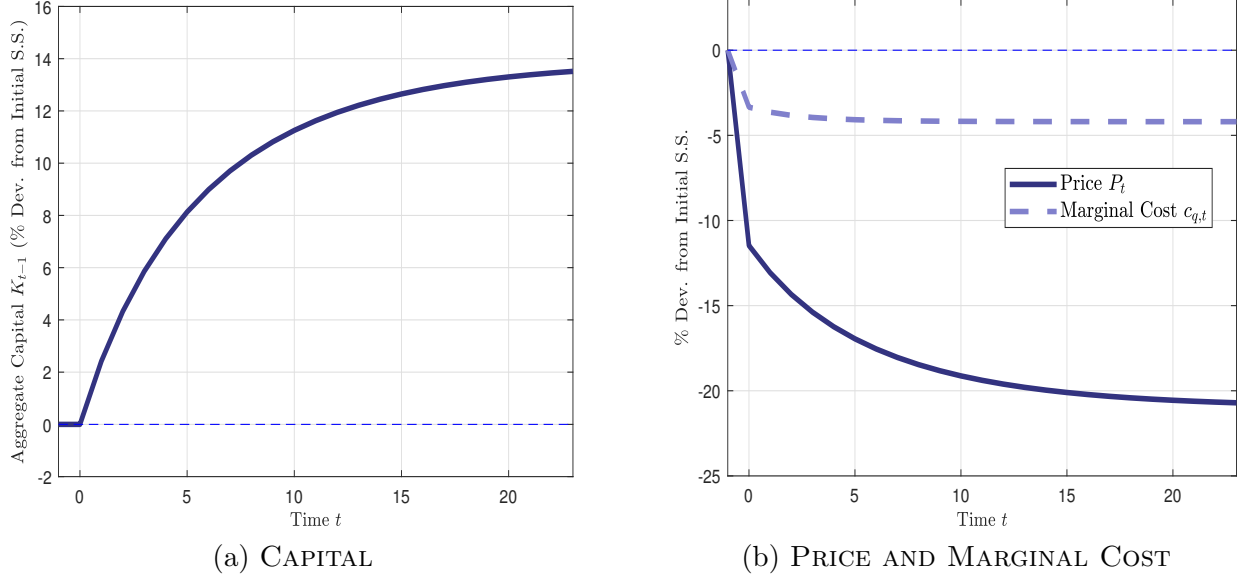


Notes: The figure illustrates the aggregate response of the economy to an unanticipated and permanent increase in TFP in the full commitment equilibrium. Panel (a) plots the exogenous change in TFP A_t . Panel (b) plots the transition of aggregate capital K_{t-1} to the new steady state in the domestic 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.

A4 compares model performance to the data.

The parameters of TFP stochastic process are similar to the calibration of section 6.3.

Figure A7: Increase in the Number of Investment-Goods Producers with Commitment



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.

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.

Table A5 reports several business-cycle moments from a long simulation of the richer stochastic model. Consistent with Subsection 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 A3: Parameter Values for the Stochastic Processes

	Parameter	Symbol	Value
TFP Stochastic Process	Autocorrelation	ρ_A	0.830
	Standard Deviation	σ_A	0.017
Cost Level Stochastic Process	Autocorrelation	ρ_Z	0.575
	Standard Deviation	σ_Z	0.085
Correlation	Correlation	$\frac{\sigma_{A,Z}}{\sigma_A \sigma_Z}$	-0.130

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

Table A4: Stochastic Processes Calibration: Data and Model Moments

Parameter	Data	Model
log(GDP) Autocorrelation	0.086	0.136
log(GDP) Standard Deviation	0.010	0.014
Equipment Price Autocorrelation	0.024	0.024
Equipment Price Standard Deviation	0.020	0.022
log(GDP)-Equipment Price Correlation	0.002	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 A3.

Table A5: Stochastic Productivity and Cost: Business Cycle Moments

	FB	MPE	FC
Mean I	0.045	0.044	0.032
Mean P	0.998	1.098	2.130
Mean Markup	0	0.100	1.214
St. Dev. I/St. Dev. Y	33.826	10.447	73.203
St. Dev. P	0.037	0.048	0.032
St. Dev. Markup	0	0.007	0.016
Corr. Y and I	0.018	0.362	-0.029
Corr. Y and P	-0.133	0.001	-0.044
Corr. Y and Markup	0	0.239	0.240

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.

B Additional Empirical Evidence

B.1 Dynamics of Equipment and Semiconductors Investment

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

Figure B1a plots 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.⁶ Therefore, the 7% rise in the real price of machinery and equipment shown by Figure 1 accompanies an increase in real quantities.

Figure B1b illustrates similar dynamics for semiconductors, a key component of industrial equipment. Specifically, the figure plots real semiconductors billings to Americas as a proxy for real investment in semiconductors.⁷ We obtain data on the nominal value of billings from the Semiconductors Industry Association and deflate them using 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 trend in the latter year.⁸ Therefore, both the quantity and the price of semiconductors 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.

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

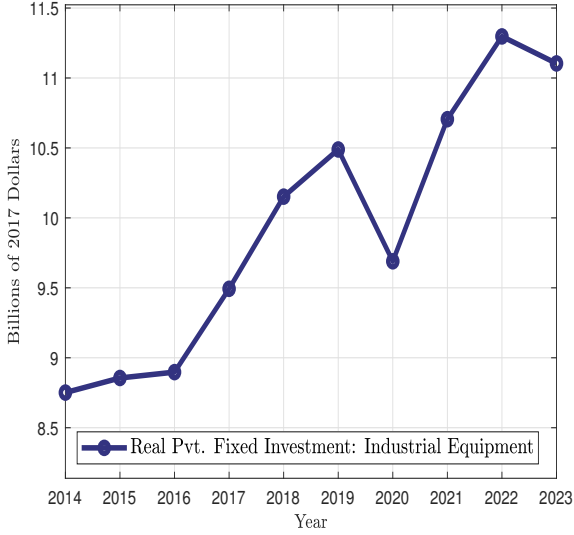
In this subsection, we zoom in on wafer foundries. Wafers are a crucial component of chips manufacturing for which we can measure physical quantities produced and unit prices more precisely. Specifically, we leverage Taiwan’s Ministry of Economic Affairs data on yearly

⁶We estimate a linear trend over the period 2000-2019.

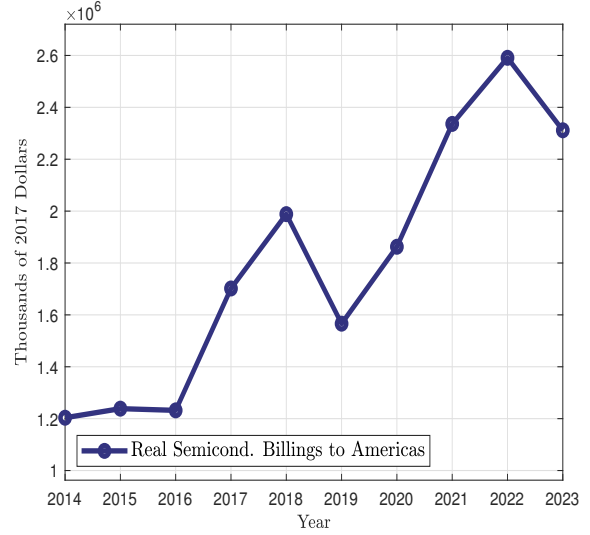
⁷The geographical granularity of the data does now allow us to focus specifically on the US, which, however, should count for the vast majority of recorded orders to Americas.

⁸We estimate a linear trend over the period 2000-2019.

Figure B1: 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).

production and sales of three detailed product categories: wafer foundry of 12 inches and above (300mm); wafer foundry of 8 inches (200mm); and wafer foundry of 6 inches and below (150mm).⁹

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).¹⁰ Therefore, focusing on Taiwan provides an accurate account of the dynamics of global production volumes and unit prices.

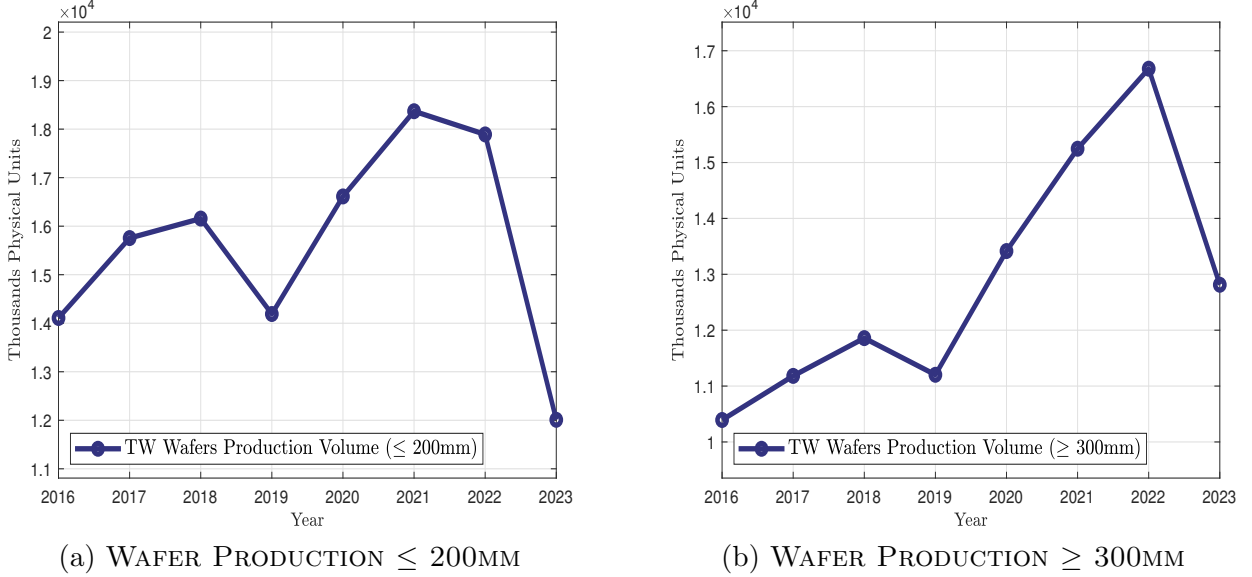
First, in Figure B2 we analyze the dynamics of physical production distinguishing by wafer size. After a decline in production in 2019, which narrative industry accounts link to a decline in global demand, production volumes display a fast rise in 2020 and during the

⁹We downloaded the data from <https://dmz26.moea.gov.tw> in April 2024. The relevant product codes are 2611110, 2611120, and 2611130.

¹⁰As 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>.

post-2020 recovery. This is consistent with strong demand for semiconductors and overall higher final demand for manufacturing goods.¹¹

Figure B2: Volumes of Production by Wafer Size



Notes: The figure displays the dynamics of wafers production volumes in Taiwan, sourced from Taiwan’s Ministry of Economic Affairs. Panel (a) refers to wafer size smaller or equal than 200mm (8 inches) and it is computed as the sum of production volumes for product codes 2611110 and 2611120. Panel (b) refers to wafer size larger or equal than 300mm (12 inches) and it corresponds to product code 2611130 in the data.

Next, we leverage information on production values to infer unit prices. Specifically, we divide production values by physical volumes to obtain average nominal prices (in New Taiwan Dollars) and we convert them to real US Dollars using FRED’s exchange rate series (DEXTAUS) and US GDP deflator. The solid line in Figure B3 displays average 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, we observe the same positive comovement between prices and quantities already documented for industrial equipment and semiconductors in the US.

Finally, we investigate the evolution of real unit margins and profits by combining production volume data with balance-sheet variables for TSMC and Mediatek, the other Taiwanese foundry. Specifically, we retrieve from Orbis the time series of Operating Profits (EBIT)—i.e., the difference between total sales and cost of goods sold plus depreciation

¹¹Sales volumes display similar dynamics with the ones reported for production.

and amortization—for these two companies, and deflate their nominal US Dollar values by US GDP deflator. We then compute average unit margins by dividing total operating profits by sales volumes from Ministry of Economic Affairs data.

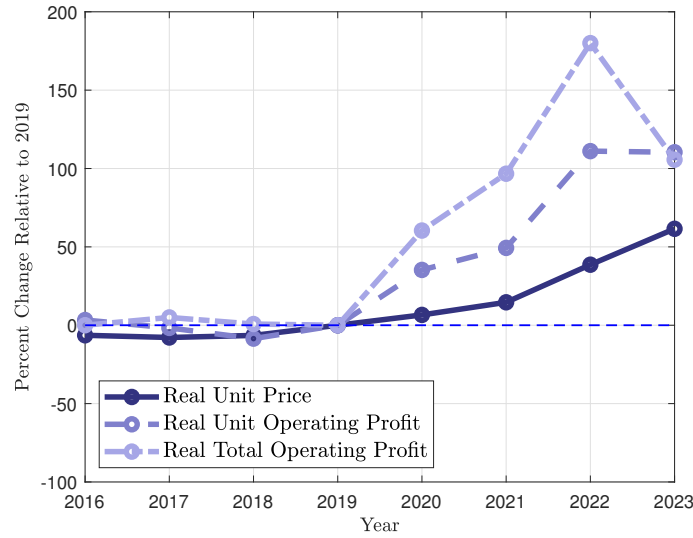
This strategy requires combining balance sheet data on individual companies with country-wide administrative data on production volumes. To address potential concerns, we first note that TSMC and Mediatek account for virtually all wafer production capacity in Taiwan. Therefore, government’s statistics should provide an accurate account for TSMC and Mediatek production volumes. Moreover, to validate our approach we compute an alternative measure of average unit prices combining balance sheet data for TSMC and Mediatek total sales divided by production volumes from Ministry of Economic Affairs’ data. We then compare this alternative measure to average unit prices computed using administrative data only. Although the levels of the two series may differ for various reasons, their dynamics are consistent with the findings displayed in Figure B3 (solid line).

Therefore, the dashed line of Figure B3 depicts real unit margins in percent deviation from their level in 2019. 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 A.5 for an alternative calibration of the model where wafers represent the oligopolistic investment good.

In response to a positive demand shock calibrated to match an approximate 60% rise in wafer price on impact, the expansion in quantities increases the marginal cost, which in turn drives the similarly-sized increase in price. However, while the latter applies to all inframarginal units, the former implies a limited increase in the average cost, thus widening the average unit margin, which increases in the model by around 120%.

Finally, Figure B3’s 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 B2). 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 studied in Appendix A.5.

Figure B3: Price, Profits, and Quantities



Notes: The figure 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. Average unit price in New Taiwan Dollars is computed as the value of sales divided by the physical volume sold of 6, 8, and 12 inches wafers produced in Taiwan (source: Ministry of Economic Affairs). We convert nominal prices in Taiwan's currency to real US Dollars by using FRED's exchange rate series **DEXTAUS** and US GDP deflator. Average unit margin is computed as Operating Profits (EBIT) by TSMC and Mediatek (source: Orbis) divided by the physical volume sold of 6, 8, and 12 inches wafers produced in Taiwan (source: Ministry of Economic Affairs). To convert nominal to real US Dollars we divide by US GDP deflator. Total real operating profits are computed as the sum of Operating Profits (EBIT) by TSMC and Mediatek (source: Orbis) divided by by US GDP deflator. All series are expressed in percent deviation from their level in 2019.