Modeling Semiconductor Export Restrictions and the US-China Trade Conflict

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Revised, February 2024

Abstract

The semiconductor industry is at the very center of the intensified Sino-American trade conflict. We employ a multi-country, multi-sector general equilibrium modelling framework with imperfect competition and heterogeneous firms as a tool for a qualitative and quantitative analysis of protectionist semiconductor measures. The main methodological contribution of the paper is twofold. First, our model includes a semiconductor industry, with semiconductor varieties at different technological levels and therefore with different substitutability. Second, we model trade restrictions using a novel approach as export bans on semiconductor varieties, consistent with actual US policy. In this way, our model allows us to analyze the macroeconomic impact of current trade restrictions in the semiconductor industry. According to our simulation results, trade restrictions, such as those imposed by the US and its allies, consistently lead to a decline in Chinese GDP and welfare. The US loses to a much lesser extent, and the effect of trade diversion leads to a positive impact on the rest of the world.

Keywords: International trade, firm heterogeneity, semiconductors, United States, China
JEL Codes: F12, F13, F41

1. Introduction

Over recent years, technology and complex policy questions at the nexus of technology and security have gained increasing importance in US-China trade. The US introduced a raft of policies to slow the pace at which China acquires new technology. Policies to promote technological disengagement or "decoupling" focus on three areas: *investment restrictions* that make it harder for Chinese firms to acquire US assets and repatriate associated technology, *export controls* that limit China's access to sensitive US technology, and *tariffs on intermediate goods* that impede efficient production.

The quest for global economic leadership has resulted in geopolitical factors gaining traction in shaping cross-border trade with many countries adopting initiatives geared to influencing the relocation of their international firms' activity and the reorganization of global value chains. Embodiments of the legal push to technological autonomy include the US Innovation and Competition Act of 2021 and the European Chips Act aimed at enhancing US and European semiconductor production capacity and research.[1] Russia's invasion of Ukraine has catapulted the issue of risk in global supply chains to the top of the current policy agenda.[2]

Since his inauguration, president Joe Biden has largely maintained the tough line of his predecessor by refusing to reverse the tariff hikes on Chinese exports imposed during the Trump administration. Biden has also put semiconductor fabrication, quantum computing, high-end artificial intelligence, satellite communication and fifth-generation networks at the heart of US strategy towards China. The technology separation and disruption manifests itself above all in the semiconductor industry. Since mighty semiconductors are the brains of high-tech products, Peter Dicken (2015) has described the microelectronics industry as today's "industry of industries".

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[1] The CHIPS and Science Act of 2022 provides USD 54 billion in grants for semiconductor manufacturing and research and a tax credit covering 25% of investments in semiconductor manufacturing through 2026. The European Chips Act aims to mobilize EUR 43 billion in policy-driven investment for the EU's semiconductor industry by 2030. The policies represent a notable shift from a long-held opposition to industrial subsidies seen as detrimental to international competition. Grossman et al. (2021) have recently presented a theoretical model that analyzes various onshore and offshore modes of business organization in an environment with supply chain disruptions. In the case of CES preferences, government subsidies promoting backup sources of input supply is socially optimal.

[2] The recent increase in US-China trade protectionism is unprecedented in terms of the scope and the type of trade frictions. Irwin (2017) presents a comprehensive review of the history of US trade policy. A growing body of research has studied the effects of the Sino-American trade dispute. For an analysis of the Sino-American "Phase One" deal enacted in early 2020, see Funke and Wende (2023). Fajgelbaum and Khandelwal (2022) have reviewed the research examining the economic impacts of the trade conflict.

As the US-China rivalry broadens from trade to technology, the stakes for China rise. China can no longer count on a growing pool of labor or debt-fueled investment to provide future growth – it needs efficient deployment of leading-edge technology across its economy. Thus, China must efficiently allocate capital in projects with high marginal returns. As these projects are likely technology rich, the special role of semiconductors will become increasingly part of an ever-broadening swath of end applications.

US policy towards China's semiconductor industry aims at crippling China's access to critical technologies needed for products at the technological frontier.[3] In response, China has announced ambitious plans for the development of its semiconductor industry to create a closed-loop semiconductor manufacturing industry with self-sufficiency at every stage of the manufacturing process (Kim and VerWey, 2019; VerWey, 2019a and 2019b).

Off-the-shelf open economy macro models inadequately represent the evolution of the semiconductor trade dispute. With global production processes fragmented across countries, the effects of tariffs, export embargos, or both, propagate through supply chains. Firms in downstream industries suffer from protectionist measures upstream. Surprisingly, little seems to be known about what the semiconductor trade conflict might entail for the US, China, or the rest of the world. We aim to fill this gap in the literature by assessing the impact of semiconductor-related trade policy restrictions. The open economy macro model employed is reminiscent of the approaches by Melitz (2003), Chaney (2008) and Ghironi and Melitz (2005). Rather than merely conducting a comparative-static analysis, this dynamic approach allows us to look at the medium-term adjustment path. Given the imminent technology rivalry, such a medium-term macro-economic impact assessment of tariff and non-tariff supply chain disruptions, considering the different effects on the intensive and extensive margin of trade, is highly relevant to the shaping of appropriate policies at national and supranational levels.

The road map to the rest of the article is as follows. Section 2 reviews China's imports of semiconductors as well as the corresponding US export control measures in recent years. Section 3 lays out the multi-country and multi-sector modelling framework. Section 4 moves on to the model calibration, and Section 5 illustrates, through the lens of our model, the impact of various protectionist trade policy measures. Section 6 presents the welfare effects. Finally, Section 7 concludes. To the best of our knowledge, the paper is the first to quantify the global trade and welfare effects of the Sino-American semiconductor trade dispute. The data and codes for the paper are available in an online replication package.

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[3] For an analysis of the semiconductor industry in the geopolitical spotlight, see Bown (2020).

2. How semiconductors became a geopolitical flashpoint

As the building blocks of the information economy and emerging fields such as artificial intelligence, autonomous vehicles, 5G networks, and quantum computing, semiconductors play a special role in decoupling. Semiconductor fabrication is highly fragmented and characterized by four stages in the global supply chain: semiconductor design, manufacturing, software, and semiconductor manufacturing equipment.[4]

While US companies lead in the design of semiconductors, the manufacturing of cutting-edge semiconductors rests to a large degree on two companies: Samsung Electronics (SE) in South Korea and the Semiconductor Manufacturing Company (TMSC) in Taiwan. Both rely on US technology. The highest-performance chips currently available are produced using the 5-nanometer (nm) manufacturing process (one nanometer equals a billionth of a meter). Smaller nanometer process nodes are important because they boost circuit performance and reduce power consumption. Compared to 7-nm technology, 5-nm technology offers a roughly 15 % speed improvement or about 30 % reduction in power consumption. TSMC seeks to implement 3-nm manufacturing in 2022. In October 2021, SE confirmed it will manufacture advanced 3-nm semiconductors in 2022. It also announced plans to mass-produce 2-nm chips starting in 2025. China's most advanced chipmaker is the Shanghai-based Semiconductor Manufacturing International Corporation (SMIC). It is heavily dependent on foreign technology for chip manufacturing. Currently, SMIC's most advanced process node is 7 nm - two generations behind the most advanced smartphone chipmaking production lines (https://www.ft.com/content/11f1c1a3-4ac4-4b2a-99cd-e347928dc51f).

Against the background of the current trade disputes, China is pursuing its own dual strategy to protect itself from the impacts of the ever-widening US technology ban. China's short-term response has been to import more semiconductors. Over the long term, China aspires to master choke-point semiconductor technology and become a self-reliant technological and manufacturing powerhouse (Mallapaty, 2021).[5] Another tit-for-tat maneuver is China's blocking legislation, approved in June 2021, which aims at prohibiting foreign companies in

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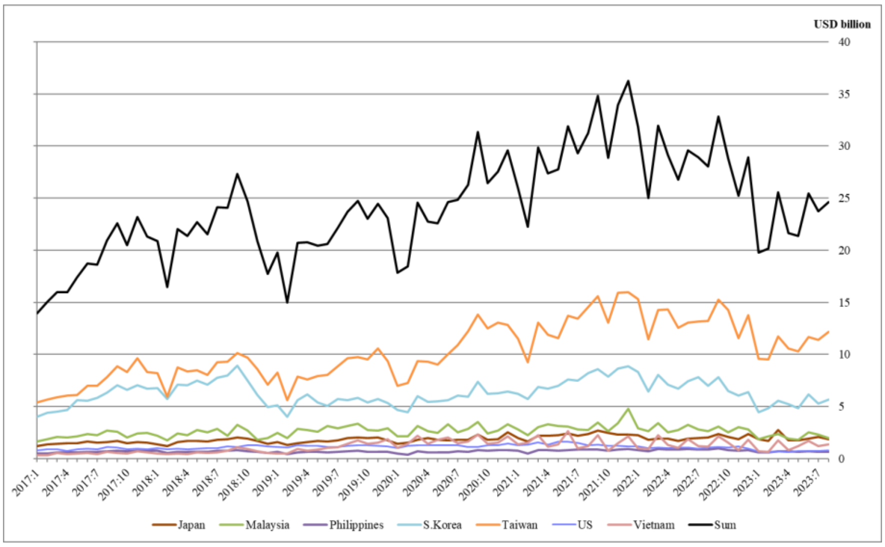
[4] For the sake of tractability, *intermediate semiconductor production* in the model is assumed here to be a monolithic industry. The industry obviously consists of numerous intertwined production stages, but here we do not attempt a deep dive into the myriad of technical details about advancing semiconductor manufacturing (Waldrop, 2016). For an illustrative diagram of the multi-stage semiconductor supply chain, see https://www.piie.com/research/piie-charts/us-trying-use-export-controls-restrict-huaweis-access-semiconductors.

[5] The Chinese government considers the semiconductor industry a top priority in its quest to achieve broad-based technological leadership. See https://www.bloomberg.com/news/articles/2021-06-17/xi-taps-top-lieutenant-to-lead-china-s-chip-battle-against-u-s.

China from complying with extraterritorial US controls. For an analysis of the potential fallout from this retaliatory measure, see Lovely and Schott (2021).

Figures 1 and 2 provide an overview of semiconductor imports of all types and the machinery and equipment used in their fabrication. Figure 1 shows China's imports of computer chips of any kind from the top seven origin countries from January 2017 to July 2023. Taiwan had the largest import market share, followed by Korea. On the timeline, the structural break in semiconductor imports at the end of 2021 is clearly visible. Figure 2 displays China's imports of equipment of manufacture semiconductors from the top six origin countries from January 2017 to July 2023. It is apparent that Chinese firms have ramped up their purchases of the machines to develop a self-sufficient Chinese semiconductor industry with reduced reliance on foreign know-how until autumn 2021. Subsequently, chipmaking equipment imports, in particular cutting-edge machinery, declined significantly. The subsequent resurgence of imports in 2023 did not occur in the most advanced extreme ultraviolet lithography technology, but nevertheless illustrates the difficulty of the US in achieving the export restriction objectives.[6]

Figure 1: China's Imports of Semiconductors, 2017:1–2023:8
(Taiwan, South Korea, Japan, US, Malaysia, Philippines, and Vietnam)



Notes: The chart shows direct Chinese imports of semiconductors as defined in Harmonized System Codes 8541 and 8542 from the top seven origin countries. HS code 8541: Diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices, including photovoltaic cells whether assembled in modules or made up into panels, light emitting diodes, mounted piezoelectric crystal. HS code 8542: Electronic integrated circuits and micro assemblies and parts thereof. Source: China's General Administration of Customs (http://stats.customs.gov.cn/indexEn).

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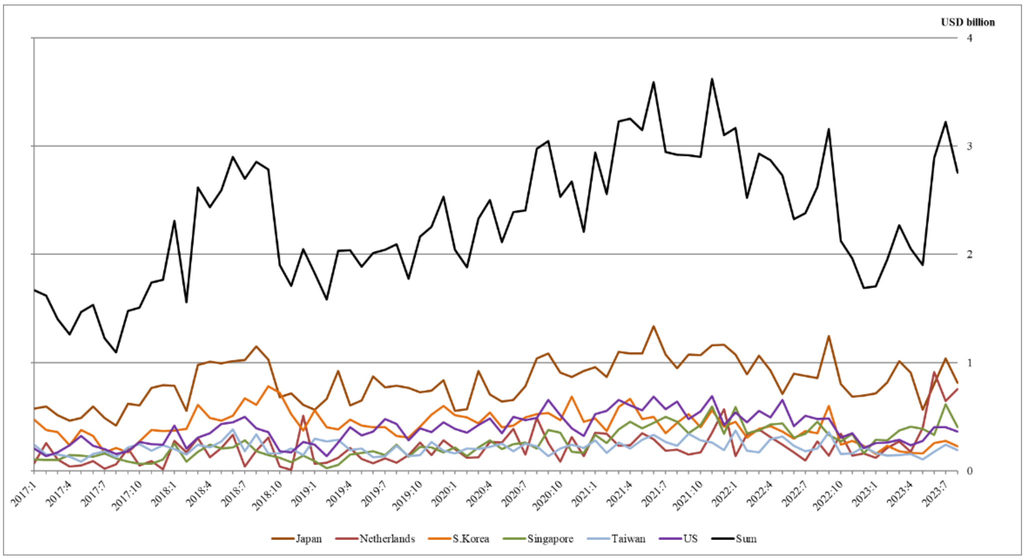
[6] As a result of the trade restrictions, Chinese support for the semiconductor industry is currently focused primarily on the semiconductor equipment industry (https://www.ft.com/content/521c8ac3-1933-4077-88b9-e9086a0196ca).

Figure 2: China's imports of semiconductor manufacturing equipment, 2017:1-2023:8 (Japan, South Korea, Taiwan, Netherlands, US, and Singapore)



<u>Notes:</u> The chart shows China's imports of semiconductor manufacturing equipment as defined in Harmonized System Code 8446 from the top six origin countries. HS code 8486: Machines and apparatus of a kind used solely or principally for the manufacture of semiconductor boules or wafers, semiconductor devices, electronic integrated circuits or flat panel displays. <u>Source:</u> China's General Administration of Customs (http://stats.customs.gov.cn/indexEn).

Developments in recent years have taken place against the backdrop of numerous trade policy escalations involving semiconductors. In 2018, the US imposed a 25 % tariff on semiconductor imports under Section 301 of the US Trade Act of 1974. China responded with retaliatory tariffs, with a carve-out for integrated circuits and manufacturing equipment. To implement semiconductor policy, the US Export Control Reform Act (ECRA) gives the president authority to control dual-use exports for national security. The US Department of Commerce Bureau of Industry and Security (BIS) administers export controls on dual-use items through the Export Administration Regulations (EAR), a set of regulations that include the Commerce Control List (CCL) of dual-use technologies subject to controls. The EAR establishes licensing policies for specific destinations, end uses, and end-user controls (Sutter and Casey, 2022). Huawei and its affiliates, which were among the many targets of these export control measures, ended up on the BIS Entity List (EL) in May 2019. The EL identifies entities that are or may be engaged in activities contrary to US national security or foreign policy interests. The BIS generally requires approval for any US export of EAR goods to entities on the list.

It soon became apparent that the initial US export control measures were off target. They were overbroad in some respects and too narrow in others. The general semiconductor export embargo in many cases applied to semiconductors that had no significance for US national security. Indeed, the broad export embargo policy design led to significant competitive disadvantages for the US semiconductor industry. Chinese firms could also circumvent the measures simply by substituting US semiconductors with similar products made in Europe, Japan, South Korea or Taiwan. As shown in Figure 1, the 2019 controls failed to stop Huawei from buying the semiconductors from either the Taiwanese TSMC or the South Korean SE. To correct this upside-down export control policy, the US expanded the jurisdictional reach of its export controls through the foreign direct product rule (FDPR) in August 2020. The extraterritorial provision has significantly broadened the scope of the export ban with wide-ranging export license requirements for products made using US-origin software, technology or equipment, irrespective of where the goods have been produced.

In October 2022, the BIS announced the most far-reaching export restrictions so far. Businesses will no longer be allowed to supply China with advanced computing chips, chipmaking equipment or related products. The new rules appear to outright ban the sale of the most powerful semiconductors, and the software and manufacturing equipment needed to produce them, to Chinese firms. Furthermore, the restrictions apply the foreign direct product rule which restricts sales of items based on American technology even if they are designed and manufactured abroad, on an unprecedented scale. However, the US government may grant temporary waivers. The Taiwanese manufacturer TSMC and the South Korean manufacturer SK Hynix have recently been granted such exemptions for a period of one year upon request.

In 2019, BIS reviewed licenses of software and technology exports to China worth USD 6.8 billion. This number increased to USD 106.1 billion in 2020 and to USD 544.9 billion in 2021, but then decreased to $204.8 billion in 2022. In the years 2019, 2020, 2021 and 2022, 64.7 % (1.5 %), 27.4 % (0.5 %), 42.1 % (53.4 %) and 55.5 % (32.1 %) were approved (denied), respectively. The remaining license applications were returned due to incomplete application documents. The trend reversal in the first half of 2022, seen clearly in Figures 1 and 2, reflects the rise of these trade restrictions.

These measures were taken against the background of an accelerated digitization as a result of the COVID-19 pandemic, the 5G upgrade cycle in the wireless market, and the need for more advanced chips for applications such as artificial intelligence, machine learning, and cloud computing – all big levers of semiconductor demand growth.

Table 1: US export control actions with regard to semiconductors, 2021–2022

Date	Export control action
April 8, 2021	BIS adds 7 Chinese supercomputing entities to Entity List.
July 9, 2021	BIS adds 34 entities to the Entity List: 19 related to China, 14 for enabling human rights abuses in Xinjiang, and 5 for using US technology to fuel China's military modernization efforts.
November 24, 2021	BIS adds 8 technology entities based in China to the Entity List to prevent US emerging technologies from being used for China's quantum computing efforts that support military applications.
December 16, 2021	BIS adds 34 Chinese entities including China's Academy of Military Medical Sciences and 11 of its research institutes, as well as 22 corporate entities including several semiconductor companies.
February 7, 2022	BIS adds 33 parties based in China to its Unverified List. Most firms listed are high-tech manufacturers.
August 12, 2022	The US implements new multilateral controls on advanced semiconductor and gas turbine engine technologies.
August 31, 2022	US officials instruct Nvidia to stop selling its A100 and H100 graphics processing units to customers in China. AMD receives new license requirements that prevent its MI250 artificial intelligence chips from being exported to China. The BIS issues no official announcement.
October 7, 2022	Firms are no longer allowed to supply advanced computing chips, chipmaking equipment and other products to China unless they receive a special license. In particular, exports are banned for cutting-edge graphic processing units used to power AI applications. 28 more businesses are added to the EL.
December 16, 2022	BIS adds 36 entities to the Entity List, 21 of them are major artificial intelligence chip R&D, manufacturing, and sales entities that are or have close ties to government organizations that support the PRC military and defense industry.

Source: US Department of Commerce press releases. See https://www.commerce.gov/news/press-releases, https://www.bis.doc.gov/index.php/about-bis/newsroom/press-releases and https://www.reuters.com/technology/nvidia-says-us-has-imposed-new-license-requirement-future-exports-china-2022-08-31/.

3. Analytical framework

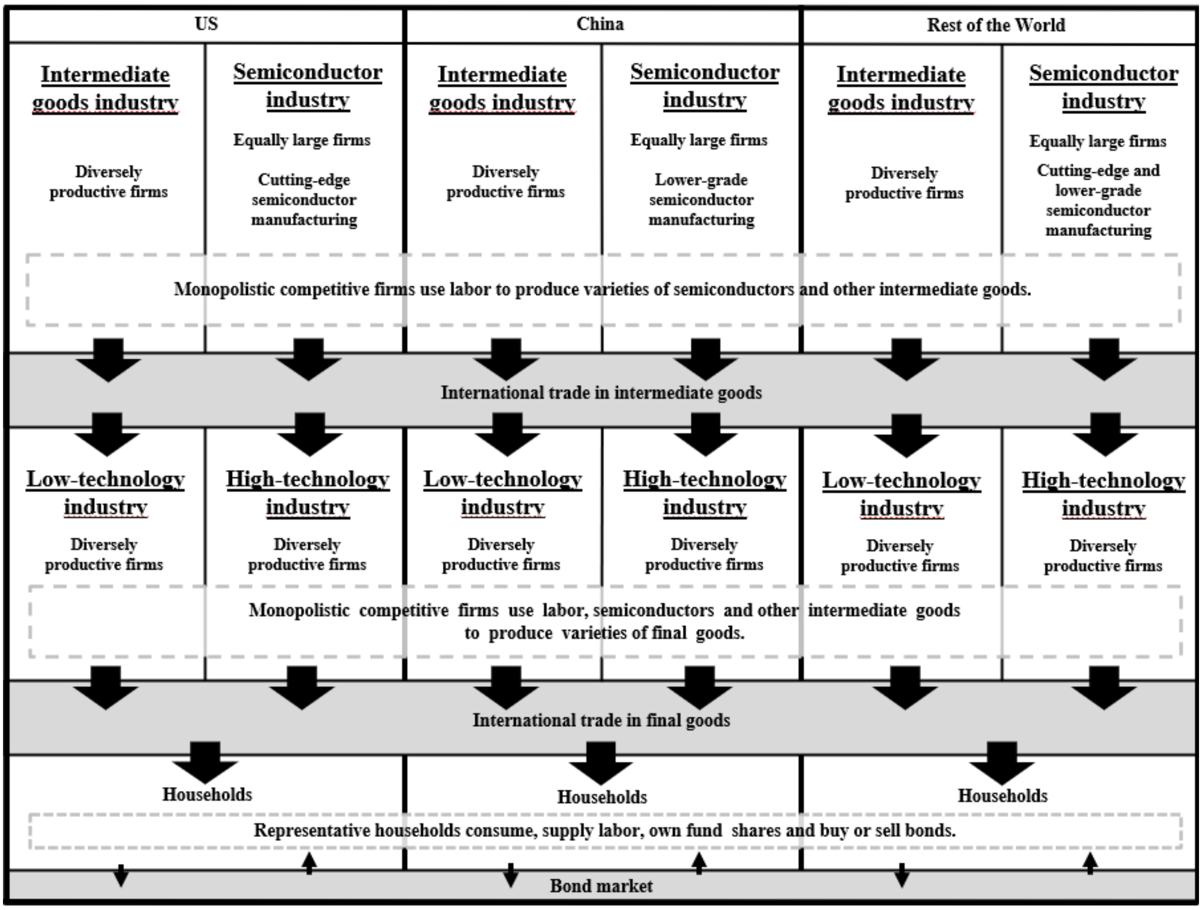
This section presents the modeling framework guiding our quantitative analysis. Time is infinite and discrete. The theoretical underpinning for the modeling endeavor dates back to Melitz (2003), Ghironi and Melitz (2005), and Melitz and Redding (2014). This study also relates to the theoretical and empirical literature on the role of input-output linkages in quantitative trade models in the tradition of Caliendo and Parro (2015) and Caliendo et al. (2019).

3.1 General setup

We begin by outlining the general structure of the multi-country general equilibrium model graphically displayed in Figure 3. To simplify the graph, the government sector is not shown.

Final and intermediate goods firms are monopolistically competitive and Pareto-distributed in terms of productivity. This introduces asymmetries between firms and leads to trade-driven reallocations and selection: it shifts employment towards firms with the best attributes and forces marginal firms to exit. Only the most productive firms find it profitable to export. Conversely, all monopolistically competitive semiconductor firms are equally productive, but heterogeneous with respect to the substitutability of their products. We thus distinguish between lower-grade semiconductors which are readily easy to substitute and cutting-edge semiconductors that are difficult to substitute. In the absence of protectionist measures, all semiconductor varieties are traded internationally.

Figure 3. Schematic drawing of the model structure.



There are three countries or regions and five industrial sectors. The US, China, and the Rest of the World are denoted by $i \in \{US, CN, RW\}$.[7] The five industrial sectors $s \in$

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[7] We consider all RW countries as a single country. The homogeneity assumption provides a good starting point for a trade conflict analysis such as ours.

$\{AS, BS, OI, LT, HT\}$ represent cutting-edge semiconductor manufacturing (AS), lower-grade semiconductor manufacturing (BS), other intermediate manufacturing goods (OI), low-tech final good manufacturing (LT), and high-tech final good manufacturing (HT), respectively. Given the varying degrees of technological intensity across industries, digital trade policy is intrinsically a sectoral shock. To understand its effects, it is therefore meaningful to distinguish between industries of different technology intensity. For later use, we also define an index for each production stage, namely $s_1 \in \{LT, HT\}$ for the final good stage, and $s_2 \in \{AS, BS, OI\}$ for the intermediate good stage. We define a semiconductor industry index given by $s_3 \in \{AS, BS\}$.

The extension capturing the semiconductor value chain provides a means for analyzing the semiconductor trade restrictions at the heart of the current Sino-American trade conflict. In principle, all sectors s are present in all countries and regions i. The only technological constraint within the model is that the US (China) has only cutting-edge (lower grade) semiconductor manufacturing.

We divide production into two stages. In the first stage, both types of semiconductors and other intermediate goods are produced. In the second stage, final goods are produced, with the intermediate products serving as inputs. Semiconductors and other intermediate goods s_2 are purchased by the final-goods-producing industry s_1, and ultimately by private households. The only production factor is labor. It is assumed to be mobile across sectors within a country, but immobile across countries.[8] The following sections, starting with trade policy, provide a description of the individual model components in detail.

3.2 Trade policy

The US consider digital technologies as key for both security and economic objectives. Given the Chinese dependence on imports of cutting-edge semiconductors embedded in digital devices, this dependency has made semiconductors a target for American sanctions. Consequently, the US has imposed protectionist export restrictions on semiconductors to prevent China from catching up in key high-tech sectors.[9] To mirror such protectionist

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[8] For simplicity, capital is not modeled. The formulation is akin to the standard production function with capital as an input.

[9] A vast empirical literature has documented the significant impact of trade on innovation. See, for example, Melitz and Redding (2021). In a Melitz-type model, Perla et al. (2021) find that lowering trade barriers induces faster technology adoption and growth because of increased gains in the relative profit of average and marginal adopting firms.

measures, the model includes the possibility of export restrictions contributing to the fragmentation of the digital sphere. Specifically, we assume that only a fraction $\left(1-\aleph_{s_3,t}^{ij}\right)$ of varieties produced in the semiconductor industry $s_3 \in \{AS, BS\}$ of country i is allowed to be exported to country j:

$$\frac{N_{xs_3,t}^{ij}}{N_{s_3,t}^{i}} = \left(1-\aleph_{s_3,t}^{ij}\right), \tag{1}$$

$N_{s,t}^{i}$ denotes the overall number of firms (varieties) in the industry s of country i and $N_{xs,t}^{ij}$ is the number of firms in this industry exporting to country j.[10] Equation (1) describes the trade-policy-induced undoing of cross-border trade in semiconductors. The share of exporting firms for all other goods is determined endogenously in the model as described below.[11]

Through the protectionist policy variable $\aleph_{s_3,t}^{ij}$, governments can directly influence the domestic exports in the semiconductor industry at the extensive margin. In contrast, the second margin at play – the intensive margin – can be influenced via an export tariff. To compare these two policy alternatives and to highlight the transmission channels in the model, we introduce such an export tariff for comparison as well.[12] In the subsequent model evaluation, however, it must be kept in mind that the US Constitution prohibits the adoption of export tariffs. The Export Clause, found in Article I, Section 9, Clause 5 of the US Constitution, states "No Tax or Duty shall be laid on Articles exported from any State."

The imposition of import tariffs remains standard. In recent years, these have been increased to levels not seen for a long time, especially between the US and China.[13] Both import and export tariffs are collected by the government and refunded to households as lump sum

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[10] We employ the following notational convention: whenever there are two superscripts, the leftmost (rightmost) superscript corresponds to the source (destination) country.

[11] In contrast to modeling two differentiated semiconductor sectors subject to different trade restrictions, Ghironi et al. (2022) have modeled sanctions against Russia in response to the war in Ukraine in a framework with heterogeneous firm productivities in one industry. When analyzing the sanctions impacts, the assumption is then made that the most productive firms are targeted by the sanctions.

[12] Recent theoretical findings speak in favor of considering export tariffs. In the context of monopolistic competitive environments with heterogeneous firms, Costinot et al. (2020) have shown that unilaterally optimal policies are as follows: (*i*) domestic taxes that are uniform across all domestic producers; (*ii*) export taxes that are uniform across all exporters; and (*iii*) import taxes that are uniform across the most profitable foreign exporters and strictly increasing with profitability across the least profitable ones (import subsidies).

[13] This follows the assessment that president Biden and his team are recalibrating de-Sinicization tactics to more dedicated measures, while keeping president Trump's strategic goals intact. As a result, there is little indication that import tariffs will return to pre-2016 situation.

transfers to balance the budget in each period. The respective transfer of the government in country i is given by

$$\Gamma_t^i = \sum_s \sum_{j \neq i} \tau_{s,t}^{ij} \varepsilon_t^{ij} N_{Xs,t}^{ji} \tilde{r}_{Xs,t}^{ji} + \sum_{s_3} \sum_{j \neq i} \tau_{s_3,t}^{ijex} N_{xs_3,t}^{ij} \tilde{r}_{Xs_3,t}^{ij}, \tag{2}$$

where $\tau_{s_3,t}^{ijex}$ is the export tariff on semiconductors from industry s_3 in country i exported to j, $\tau_{s,t}^{ij}$ is the import tariff levied by i on products from industry s in country j, ε_t^{ij} is the real exchange rate in direct notation, $N_{Xs,t}^{ji}$ are the number of firms in industry s of country j exporting to i and $\tilde{r}_{Xs,t}^{ji}$ are real average revenues from exporting to country i of firms in industry s from country j.

In summary, governments have three trade policy instruments at their disposal. *Export restrictions* and *export tariffs* with respect to the semiconductor industry and *import tariffs* with respect to all industries. Trade policy is the only task of the government in our model. Thus, the model's government sector is completely described.

3.3 Firms

So far, we have described the trade policy block of the general equilibrium model. This section outlines the behavior of firms in the multiple-good environment. To organize the exposition, the demand side is considered first, followed by the supply side. Throughout the presentation, special attention is paid to the modeling of semiconductors and their operation in the model.

3.3.1 CES indices and trade elasticities

The Armington elasticity of substitution between goods produced in different countries is a crucial parameter in evaluating the output and welfare impacts of trade protectionism. Feenstra et al. (2018) have underlined the conceptual distinction between the top-level macro elasticity of substitution between domestic and a composite foreign good and the lower-level micro elasticity of substitution between alternate foreign supply sources. Both are clearly important in determining effects of tariff and non-tariff measures. Following this tradition, we implement a nested CES demand system in our model and assume micro and macro trade elasticities in all sectors except the semiconductor industry. Given the special focus on this industry, a case distinction is made between *cutting-edge* and *lower-grade* semiconductor elasticities.[14]

The composite output produced by firm φ in industry s_2 of country i and purchased by a buyer from the industry s_1 of country j, or produced in industry s_1 of country i and purchased by households of country j, is defined over a continuum of goods Φ determined according to CES functions as

$$Q_{s_2,t}^{s_1 ij} = \left(\int_{\varphi \in \Phi} \left(Q_{s_2,t}^{s_1 ij}(\varphi) \right)^{\frac{\theta_{s_2}-1}{\theta_{s_2}}} d\varphi \right)^{\frac{\theta_{s_2}}{\theta_{s_2}-1}} \; ; \; Q_{s_1,t}^{ij} = \left(\int_{\varphi \in \Phi} \left(Q_{s_1,t}^{ij}(\varphi) \right)^{\frac{\theta_{s_1}-1}{\theta_{s_1}}} d\varphi \right)^{\frac{\theta_{s_1}}{\theta_{s_1}-1}} \tag{3}$$

where θ_s is the micro substitution elasticity. The agreement and the departure from the literature lies in the following two assumptions. We assume equal micro elasticities $\theta_{s_1} = \theta_{OI} = \theta$ for all industries except the semiconductor industry, and we allow for different lower-level micro substitution elasticities of semiconductors of different types.

More specifically, we assume that cutting-edge semiconductors are more difficult to substitute than lower-grade semiconductors. The output from the semiconductor industry bought by firms of industry $s_1 \in \{LT, HT\}$ in country i are given by the CES index

$$Q_{SC,t}^{s_1 i} = \left(\sum_j \left(\upsilon_{AS}^{ij} \right)^{\frac{1}{\eta_{AS}}} \left(Q_{AS,t}^{s_1 ij} \right)^{\frac{\eta_{AS}-1}{\eta_{AS}}} + \left(\upsilon_{BS}^{i} \right)^{\frac{1}{\eta_{AS}}} \left(Q_{BS,t}^{s_1 i} \right)^{\frac{\eta_{AS}-1}{\eta_{AS}}} \right)^{\frac{\eta_{AS}}{\eta_{AS}-1}}, \tag{4}$$

where η_{AS} is the elasticity of substitution between bundles of cutting-edge semiconductors, $\sum_j \upsilon_{AS}^{ij} + \upsilon_{BS}^{i} = 1$ are the respective weights, and $Q_{AS,t}^{s_1 ij}$ is a bundle of cutting-edge semiconductors as defined in equation (3). The bundle of lower grade semiconductors $Q_{BS,t}^{s_1 i}$ can be substituted by cutting-edge semiconductors with elasticity η_{AS}. Furthermore, within the bundle of lower grade semiconductors $Q_{BS,t}^{s_1 i}$, substitution is comparatively easier and given by

$$Q_{BS,t}^{s_1 i} = \left(\sum_j \left(\upsilon_{BS}^{ij} \right)^{\frac{1}{\eta_{BS}}} \left(Q_{BS,t}^{s_1 ij} \right)^{\frac{\eta_{BS}-1}{\eta_{BS}}} \right)^{\frac{\eta_{BS}}{\eta_{BS}-1}}, \tag{5}$$

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[14] Under this modeling assumption, barriers to semiconductor trade across countries can have profound effects on production and consumption patterns as they influence fast-growing sectors and high-tech production is particularly dependent on cross-border semiconductor trade.

where η_{BS} is the elasticity of substitution of lower grade semiconductors, $\sum_j \upsilon_{BS}^{ij} = 1$ are the weights of semiconductors produced in i and bought in j and $Q_{BS,t}^{s_1 ij}$ is again a bundle of varieties as defined in equation (3).

The quantitative semiconductor substitution capabilities are regulated by the micro elasticity θ_{s_3} and the country elasticity η_{s_3}, where $s_3 \in \{AS, BS\}$. The former is the elasticity between the varieties of different firms in a country and thus determines the level of markup. The latter is the elasticity between the bundles of goods of different countries. For lower-grade semiconductors, we assume that both elasticities are equal, $\eta_{BS} = \theta_{BS}$, and larger than η_{AS} and θ_{AS}. It is just as easy to substitute between two semiconductors from the same country as between two semiconductors from different countries. Our analysis focuses on cutting-edge semiconductors, which are assumed to have smaller trade elasticities. The following three combinations of cutting-edge semiconductor trade elasticities are considered:

$\eta_{AS} = \theta_{AS}$: Cutting-edge semiconductors rely on firm specific technology and are difficult to substitute regardless of origin.

$\eta_{AS} < \theta_{AS}$: Cutting-edge semiconductors rely to some extent on country-specific technology, human capital, or both, and thus substitution across countries is particularly difficult.

$\eta_{AS} > \theta_{AS}$: The country has superstar firms with strategic competitive advantages over national competitors. Substitution among international superstar firms is thus easier than substitution within a single country.

In the non-semiconductor industries, demand is the function of the top-level macro elasticity ω according to

$$Q_{OI,t}^{s_1 i} = \left(\left(1 - \alpha_{OI}^{i}\right)^{\frac{1}{\omega}} \left(Q_{DOI,t}^{s_1 i}\right)^{\frac{\omega-1}{\omega}} + \left(\alpha_{OI}^{i}\right)^{\frac{1}{\omega}} \left(Q_{XOI,t}^{s_1 i}\right)^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}}$$

$$Q_{s_1,t}^{i} = \left(\left(1 - \alpha_{s_1}^{i}\right)^{\frac{1}{\omega}} \left(Q_{Ds_1,t}^{i}\right)^{\frac{\omega-1}{\omega}} + \left(\alpha_{s_1}^{i}\right)^{\frac{1}{\omega}} \left(Q_{Xs_1,t}^{i}\right)^{\frac{\omega-1}{\omega}} \right)^{\frac{\omega}{\omega-1}} \tag{6}$$

and there is a similarly defined bundle for final goods bought by households. The basic idea behind the distinction between micro and macro elasticities is simply that it is more difficult to substitute between a domestic and a foreign product than to substitute between two domestic or two foreign products (Feenstra et al., 2018). α_s^i is the degree of openness of industry $s \ \forall \ s \notin \{AS, BS\}$ in country i and the bundle of foreign goods is defined as

$$Q_{XOI,t}^{is_1} = \left(\sum_{j \neq i} \left(\kappa_{OI}^{ij}\right)^{\frac{1}{\theta}} \left(Q_{OI,t}^{ijs_1}\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}; \ Q_{Xs_1,t}^{i} = \left(\sum_{j \neq i} \left(\kappa_{s_1}^{ij}\right)^{\frac{1}{\theta}} \left(Q_{s_1,t}^{ij}\right)^{\frac{\theta-1}{\theta}} \right)^{\frac{\theta}{\theta-1}}, \quad (7)$$

where $\sum_j \kappa_s^{ij} = 1$ are the country weights, θ is the non-semiconductor micro elasticity and the bundles of products of the individual firms $Q_{OI,t}^{iis_2}$ and $Q_{OI,t}^{ijs_2}$ are again defined in equation (3). Note that the micro elasticity in the semiconductor industry is defined slightly differently from micro elasticity in the other industries. In the former, it is only the industry-specific elasticity of substitution of goods. The latter includes the elasticity of substitution of goods from one foreign country with goods from another foreign country.

Final goods are bought by the representative household using a CES aggregator to substitute between high-tech and low-tech final goods:

$$C_t^i = \left(\frac{Q_{LT,t}^i}{1-\upsilon_{HT}^i}\right)^{\left(1-\upsilon_{HT}^i\right)} \left(\frac{Q_{HT,t}^i}{\upsilon_{HT}^i}\right)^{\upsilon_{HT}^i}, \quad (8)$$

where υ_{HT}^i is the weight of high-tech goods in the household's utility function and $Q_{HT,t}^i$ and $Q_{LT,t}^i$ are the bundles of high-tech and low-tech goods, respectively. The latter are defined in equation (6).

3.3.2 Price indices and trade tariffs

The preceding CES production and preference structures imply a structure of price indices and sub-indices starting with the consumer price index $P_t^i = {P_{LT,t}^{i,n}}^{\left(1-\upsilon_{HT}^i\right)} {P_{HT,t}^{i,n}}^{\upsilon_{HT}^i}$, where $P_{LT,t}^{i,n}$ and $P_{HT,t}^{i,n}$ are the nominal price indices of low-tech and high-tech goods in country i, respectively. The superscript n denotes a nominal variable. Trade models typically solve only for relative prices. In other words, the solution values for all real variables are independent of any measure of the aggregate price level. These models assume some price or price index to be fixed in order to provide an anchor for a price system that defines the benchmark (numeraire) against which relative prices are measured. Following standard practice, we choose the price index P_t^i

of the final consumer goods bundle C_t^i as the anchor price. The model then solves for changes in prices vis-à-vis this anchor.[15] Dividing the consumer price index equation by P_t^i yields

$$1 = {P_{LT,t}^{i}}^{(1-\upsilon_{HT}^{i})} {P_{HT,t}^{i}}^{\upsilon_{HT}^{i}} \,. \tag{9}$$

P_{LT}^i and P_{HT}^i are the real price indices of low-tech and high-tech goods in country i, respectively. They are given by

$$P_{s_1,t}^{i} = \left[\left(1-\alpha_{s_1}^{i}\right) {P_{Ds_1,t}^{i}}^{1-\omega} + \alpha_{s_1}^{i} \, {P_{Xs_1,t}^{i}}^{1-\omega}\right]^{\frac{1}{1-\omega}}, \tag{10}$$

where

$$P_{Xs_1,t}^{i} = \left(\sum\nolimits_{j\neq i} \kappa^{ij} \left(P_{Xs_1,t}^{ij}\right)^{1-\theta}\right)^{1/(1-\theta)}, \tag{11}$$

is the price index of imported products of industry s_1 by households of country i, $P_{Ds_1,t}^{i} = \left(\int_{\varphi\in\Phi} \left(P_{Ds_1,t}^{i}(\varphi)\right)^{1-\theta} d\varphi\right)^{1/(1-\theta)}$ is the price index of domestically produced varieties of industry s_1 and $P_{Xs_1,t}^{ij} = \left(\int_{\varphi\in\Phi} \left((1+\tau_{s_1,t}^{ij})P_{Xs_1,t}^{ij}(\varphi)\right)^{1-\theta} d\varphi\right)^{1/(1-\theta)}$ is the price of imported varieties of the same industry. $\tau_{s,t}^{ij}$ denotes an import trade tariff imposed by country i on products of industry s imported from country j. Equivalent price indices exist for other intermediate goods. The overall price index of differentiated non-semiconductor intermediate goods bought by industry s_1 is

$$P_{OI,t}^{s_1 i} = \left[\left(1-\alpha_{s_1}^{i}\right) {P_{DOI,t}^{s_1 i}}^{1-\omega} + \alpha_{s_1}^{i} \, {P_{XOI,t}^{s_1 i}}^{1-\omega}\right]^{\frac{1}{1-\omega}}, \tag{12}$$

where $P_{DOI,t}^{s_1 i} = \left(\int_{\varphi\in\Phi} \left(P_{DOI,t}^{s_1 i}(\varphi)\right)^{1-\theta} d\varphi\right)^{1/(1-\theta)}$ is the price index of domestic varieties of other intermediates, and $P_{XOI,t}^{s_1 i}$ is the price index of imported varieties of other intermediate goods defined analogous to equation (11). Thus, unlike for final goods, two price indices exist

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[15] The choice of numeraire does not matter as the model satisfies the nominal homogeneity test. An increase in the numeraire increases all the prices proportionally and relative prices remain unchanged, i.e. no actual effect.

for other intermediate goods, since they are purchased by two buyers who can weight the intermediate goods differently. In the semiconductor industry, the price index is given by

$$P^{s_1 i}_{SC,t} = \left[\sum\nolimits_j \upsilon^{ij}_{AS}\, P^{s_1 ij}_{AS,t}{}^{1-\eta_{AS}} + \upsilon^{i}_{BS}\, P^{s_1 i}_{BS,t}{}^{1-\eta_{AS}}\right]^{\frac{1}{1-\eta_{AS}}}, \tag{13}$$

where $P^{s_1 ij}_{AS,t} = \left(\int_{\varphi\in\Phi}\left((1+\tau^{ij}_{AS,t}+\tau^{exji}_{AS,t})P^{s_1 ij}_{AS,t}(\varphi)\right)^{1-\theta_{AS}} d\varphi\right)^{1/(1-\theta_{AS})}$ is the price index of cutting-edge semiconductors imported from country j by industry s_1 of country i, $\tau^{ij}_{AS,t}$ is the import trade tariff imposed by country i on advanced semiconductors imported from country j and $\tau^{exji}_{s_3,t}$ is an export trade tariff imposed by country j on semiconductor exports to country i. If $i = j$, $\tau^{ii}_{AS,t} = \tau^{exii}_{AS,t} = 0$ always holds. The price index of lower-grade semiconductors can be written as

$$P^{s_1 i}_{BS,t} = \left[\sum\nolimits_j \upsilon^{i}_{BS}\, P^{s_1 ij}_{BS,t}{}^{1-\eta_{BS}}\right]^{\frac{1}{1-\eta_{BS}}}, \tag{14}$$

where $P^{s_1 ij}_{BS,t} = \left(\int_{\varphi\in\Phi}\left((1+\tau^{ij}_{BS,t}+\tau^{exji}_{BS,t})P^{s_1 ij}_{BS,t}(\varphi)\right)^{1-\theta_{BS}} d\varphi\right)^{1/(1-\theta_{BS})}$ is the price index of the bundle of semiconductor varieties imported from country j by industry s_1 of country i.

Note that the demand system presented here implies the usual CES demand functions. As an example, and for later use, only the respective demand function of industry s_1 from country i for cutting-edge semiconductors from country j is given by

$$Q^{s_1 ij}_{AS,t} = \upsilon^{ij}_{AS} \left(\frac{P^{s_1 ij}_{AS,t}}{P^{s_1 i}_{SC,t}}\right)^{-\eta_{AS}} Q^{s_1 i}_{SC,t}\,. \tag{15}$$

3.3.3 Production involving semiconductors

The production of a final goods producing firm φ from industry s_1 and country i depends on semiconductors with an elasticity of $\eta^{s_1}_{SC}$. For labor and other intermediate goods, we assume the standard Cobb-Douglas form:

$$\begin{aligned} Y^{i}_{s_1,t}(\varphi) \; &= \; zZ^{i}\left[\left(1-\varrho_2^{s_1 i}\right)^{\frac{1}{\eta_{SC}^{s_1}}}\left(\left(M^{s_1 i}_{OI,t}(\varphi)\right)^{\varrho_1}\;\left(L^{s_1 i}_{t}(\varphi)\right)^{(1-\varrho_1)}\right)^{\frac{\eta_{SC}^{s_1}-1}{\eta_{SC}^{s_1}}} + \left(\varrho_2^{s_1 i}\right)^{\frac{1}{\eta_{SC}^{s_1}}}\left(M^{s_1 i}_{SC,t}(\varphi)\right)^{\frac{\eta_{SC}^{s_1}-1}{\eta_{SC}^{s_1}}}\right]^{\frac{\eta_{SC}^{s_1}}{\eta_{SC}^{s_1}-1}} \\ &= zZ^{i}\,\Lambda^{i}_{s_1,t} \end{aligned} \tag{16}$$

where $\varrho_2^{s_1 i}$ is the weight of semiconductors in the production of industry s_1 in country i.[16] The other intermediate goods and labor enter the production function with the weight $\left(1-\varrho_2^{s_1 i}\right)$, and the partial weight of the other intermediate goods is ϱ_1. Z^{i} is aggregate total factor productivity of country i, z is relative productivity of the individual firm and $L_t^{s_1 i}(\varphi)$ denotes the labor demand of firm φ from country i and industry s_1. $\Lambda^{i}_{s_1,t}(\varphi)$ denotes the input bundle. As is standard in the literature, the firm productivities are drawn from a probability distribution as characterized below. By minimizing costs, we can derive the following input price ratios:

$$\frac{P^{s_1 i}_{OI,t}}{P^{s_1 i}_{SC,t}} = \left[\left(\frac{1-\varrho_1^{s_1}}{\varrho_1^{s_1}}\frac{P^{s_1 i}_{OI,t}}{w^{s_1 i}_{t}}\right)^{1-\varrho_1}\right]^{\frac{\eta_{SC}^{s_1}-1}{\eta_{SC}^{s_1}}} \varrho_1\left(\frac{1-\varrho_2^{s_1 i}}{\varrho_2^{s_1 i}}\frac{M^{s_1 i}_{SC,t}(\varphi)}{M^{s_1 i}_{OI,t}(\varphi)}\right)^{\frac{1}{\eta_{SC}^{s_1}}}, \tag{17}$$

$$\frac{w^{s_1 i}_{t}}{P^{s_1 i}_{SC,t}} = \left[\left(\frac{1-\varrho_1^{s_1}}{\varrho_1^{s_1}}\frac{P^{s_1 i}_{OI,t}}{w^{s_1 i}_{t}}\right)^{-\varrho_1}\right]^{\frac{\eta_{SC}^{s_1}-1}{\eta_{SC}^{s_1}}} (1-\varrho_1)\left(\frac{1-\varrho_2^{s_1 i}}{\varrho_2^{s_1 i}}\frac{M^{s_1 i}_{SC,t}(\varphi)}{L^{s_1 i}_{t}(\varphi)}\right)^{\frac{1}{\eta_{SC}^{s_1}}}. \tag{18}$$

By combining equations (16), (17), and (18) and the first-order condition of the cost minimization problem with respect to semiconductors, we derive the following expression for the marginal cost of an additional unit of the input bundle:

$$mc^{i}_{s_1,t} = \left[\left(1-\varrho_2^{s_1 i}\right)\left(\left(\frac{P^{s_1 i}_{OI,t}}{\varrho_1}\right)^{\varrho_1}\left(\frac{w^{s_1 i}_{t}}{(1-\varrho_1)}\right)^{1-\varrho_1}\right)^{1-\eta_{SC}^{s_1}} + \varrho_2^{s_1 i}\left(P^{s_1 i}_{SC,t}\right)^{1-\eta_{SC}^{s_1}}\right]^{\frac{1}{1-\eta_{SC}^{s_1}}} \tag{19}$$

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[16] Although the input share of semiconductors is not large, this sector is a crucial upstream supplier. Any semiconductor bottleneck is likely to extend to many other sectors in the economy.

where $mc^i_{s_1,t}$ is defined as the Lagrangian multiplier multiplied by zZ^i. As can be seen, the marginal cost of an additional unit of the input bundle is the same for all firms in industry s_1, which implies that all firms of this industry buy the same input bundle.

The production function of all intermediate goods producing firms in industry s_2 takes the form $Y^i_{s_2,t}(z) = zZ^i L^i_{s_2,t}(z)$ implying that marginal costs equal the wage: $mc^i_{s_2,t} = w^i_{s_2,t}$. Firms in country i set their domestic price as a mark-up over their marginal costs of producing an additional unit of output:

$$p^i_{Ds,t}(z) = \frac{p^{i,n}_{Ds,t}(z)}{P^i_t} = \frac{\theta^i_s}{\theta^i_s - 1}\frac{mc^i_{s,t}}{zZ^i_t}, \tag{20}$$

where $p^{i,n}_{D,st}(z)$ is the nominal domestic price of a firm with productivity z, and P^i_t, the price index of final goods, serves as numeraire. Firms in the semiconductor industry are equally productive with $z = 1,$ so that equation (20) also applies. If a firm with productivity z from country j exports to country i, its price in terms of the price index of the destination market is given by

$$p^{ij}_{Xs,t}(z) = \frac{p^{ij,n}_{Xs,t}(z)}{P^i_t} = \frac{1}{\varepsilon^{ij}_t}\tau^{ji}_{IBs,t}\, p^j_{Ds,t}(z), \tag{21}$$

where $\tau^{ij}_{IB,t} > 1$ denotes the iceberg trade costs of exporting from country i to country j. In the industries producing final and other intermediate goods, a firm in country i with productivity z makes profits from domestic sales and from exporting to country j:

$$d^i_{Ds,t}(z) = \frac{1}{\theta}\left[p^i_{Ds,t}(z)\right]^{1-\theta}\left(P^i_{Ds,t}\right)^{\theta-\omega}\left(P^i_{s,t}\right)^{\omega}\left(1-\alpha^i_s\right)Q^i_{s,t} \qquad \forall\, s \in \{HT, LT, OI\}, \tag{22}$$

$$\begin{aligned} &d^{ij}_{Xs,t}(z) \\ &= \begin{cases} \dfrac{\varepsilon^{ij}_t}{\theta}\left(1+\tau^{ji}_{s,t}\right)^{-\theta}\left[p^{ji}_{Xs,t}(z)\right]^{1-\theta}\left(P^i_{Xs,t}\right)^{\theta-\omega}\left(P^i_{s,t}\right)^{\omega}\alpha^j\kappa^{ij}Q^j_{s,t} - mc^i_{s,t}\dfrac{f^{ij}_{Xs,t}}{Z^i_t}, & \text{if firm } z \text{ exports to } j \\ 0 & \text{otherwise,} \end{cases} \\ &\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \forall\, s \in \{HT, LT, OI\}\,. \end{aligned} \tag{23}$$

$f_{Xs,t}^{ij}$ are the usual fixed costs of exporting from country i to country j. In the case of firms producing other intermediate goods, we assume that the fixed export costs are country-specific, not buyer-specific. The profits of firms selling semiconductors to industry s_1 depend on whether they produce cutting-edge (AS) or lower-grade (BS) products:

$$d_{DAS,t}^{s_1 i}(z) = \frac{1}{\theta_{AS}}\left[p_{DAS,t}^{i}\right]^{1-\theta_{AS}}\left(P_{DAS,t}^{i}\right)^{\theta_{AS}-\eta_{AS}}\left(P_{SC,t}^{s_1 i}\right)^{\eta_{AS}} \upsilon_{AS}^{ii}\, Q_{AS,t}^{s_1 i}, \tag{24}$$

$$d_{DBS,t}^{s_1 i}(z) = \frac{1}{\theta_{BS}}\left[p_{DBS,t}^{i}\right]^{1-\theta_{BS}}\left(P_{DBS,t}^{i}\right)^{\theta_{BS}-\eta_{BS}}\left(P_{BS,t}^{s_1 i}\right)^{\eta_{BS}-\eta_{AS}}\left(P_{SC,t}^{s_1 i}\right)^{\eta_{AS}} \upsilon_{BS}^{i}\upsilon_{BS}^{ii}\, Q_{BS,t}^{s_1 i}, \tag{25}$$

$$d_{Xs_3,t}^{ij} = \begin{cases} \dfrac{\varepsilon_t^{ij}}{\theta_{s_3}}\left(1+\tau_{s_3,t}^{ji}+\tau_{s_3,t}^{exji}\right)^{-\theta_{s_3}}\left[p_{Xs_3,t}^{ji}\right]^{1-\theta_{s_3}}\left(P_{Xs_3,t}^{ji}\right)^{\eta_{AS}}\left(Q_{xs_3,t}^{LTji}+Q_{xs_3,t}^{HTji}\right), & \text{if firm } \varphi \text{ exports to } j \\ 0 & \text{otherwise} \end{cases} \tag{26}$$

We assume that there are no fixed costs of exporting in the semiconductor industry. Average total profits of the industries producing final and other intermediate goods in country i can be calculated as

$$\tilde{d}_{s,t}^{i} = d_{Ds,t}^{i}\left(\tilde{z}_{Ds,t}^{i}\right) + \sum\nolimits_{j\neq i}\frac{N_{Xs,t}^{ij}}{N_{s,t}^{i}} d_{Xs,t}^{ij}\left(\tilde{z}_{Xs,t}^{ij}\right)\ \forall\ \mathrm{s} \in \{HT, LT, OI\};\ \tilde{d}_{s_3,t}^{i} = \sum\nolimits_{s_1} \mathrm{d}_{Ds_3,t}^{s_1 i} + \sum\nolimits_{j\neq i}\frac{N_{Xs_3,t}^{ij}}{N_{s_3,t}^{i}} d_{Xs_3,t}^{ij}. \tag{27}$$

Since in the semiconductor industry $z = 1$ holds for all firms, their prices and profits do not depend on z. The average productivities in the other industries $\tilde{z}_{Ds,t}^{i}$ and $\tilde{z}_{Xs,t}^{ij}$ depend on distributional assumptions that will be described in Section 3.3.4.

New firms can enter the domestic market in any industry but, apart from the semiconductor industry, do not yet know how productive they will be. Prospective entrants calculate the present value of the expected stream of average profits starting in period $t + 1$ that we denote by $\tilde{v}_{s,t}^{i}$. In doing so, firms face up-front sunk entry costs f_E^i. Solving for the free entry condition, we obtain

$$\tilde{v}_{s,t}^{i} = \frac{mc_{s,t}^{i} f_E^i}{Z_t^i}. \tag{28}$$

Firms that plan semiconductor market entry in period t, start to produce new semiconductor varieties in period $t+\tau$, where τ is the time until production starts. The probability of firms' survival is $(1-\delta)$ each period. Thus, there are also firms that exit without starting to produce. The number of firms (products) in industry s of country i is hence given by

$$N_{s,t}^{i}=(1-\delta)\left(N_{s,t-1}^{i}+N_{Es,t-\tau}^{i}\right). \tag{29}$$

In the following, we take a closer look at the shape of the productivity distribution in the heterogeneous firm model.

3.3.4 Firm averages

For all $s \notin s_3$, the equilibrium prices at the micro level are, similar as in Melitz (2003), given by $P_{Ds,t}^{i}=\left(\int_{z_{min}}^{\infty}\left[p_{Ds,t}^{i}(z)\right]^{1-\theta}N_{s,t}^{i}\,g(z)\,dz\right)^{1/(1-\theta)}$ and $P_{Xs,t}^{i}=\left(\int_{z_{Xs,t}^{ji}}^{\infty}\left[\left(1+\tau_{t}^{ij}\right)p_{Xs,t}^{i}(z)\right]^{1-\theta}N_{Xs,t}^{ji}\,g(z)\,dz\right)^{1/(1-\theta)}$, where $z_{Xs,t}^{ij}$ is the productivity cutoff. Using this and equations (20) and (21), we can derive the following aggregate prices in terms of the price index of the destination market:

$$P_{Ds,t}^{i}=\frac{P_{Ds,t}^{i,n}}{P_{t}^{i}}=N_{s,t}^{i}{}^{\frac{1}{1-\theta}}p_{Ds,t}^{i}\left(\tilde{z}_{Ds,t}^{i}\right), \tag{30}$$

$$P_{Xs,t}^{ij}=\frac{P_{Xs,t}^{ij,n}}{P_{t}^{i}}=\left(1+\tau_{s}^{ij}\right)N_{Xs,t}^{ji}{}^{\frac{1}{1-\theta}}p_{Ds,t}^{j}\left(\tilde{z}_{Xs,t}^{ji}\right), \tag{31}$$

where $\tilde{z}_{Ds,t}^{i}=\left(\int_{z_{min}}^{\infty}z^{\theta-1}g(z)\,dz\right)^{1/(\theta-1)}$ and $\tilde{z}_{Xs,t}^{ji}=\left(\frac{1}{1-G(z_{Xs,t}^{ij})}\int_{z_{Xs,t}^{ij}}^{\infty}z^{\theta-1}g(z)\,dz\right)^{1/(\theta-1)}$ are the average productivities of the firms that serve the domestic market and those that also export, respectively. z_{min} is the minimum productivity that can be assigned to new firms. Generally, the same equations also apply in the semiconductor industry of our model, but with $\tilde{z}_{Ds,t}^{i}=\tilde{z}_{Xs,t}^{ji}=z=1$ and considering a possible export tariff. Since the relative productivity of firms in the semiconductor industry in our model is always equal to 1, the average values are equal to the equilibrium values for the representative firm. Moreover, the share of exporting firms is policy determined or is also 1. Thus, the equilibrium conditions for the semiconductor industry are complete. For the remaining industries, however, average productivities and the endogenous productivity cutoff still need to be determined. We now assume that firm productivity is drawn from a Pareto distribution so that $G(z) = 1 - (z_{min}/z)^k$ where z_{min} is the lower bound of the support and the shape parameter $k > \theta - 1$ indexes dispersion (lower values of k are associated with greater productivity dispersion). Given this distribution, the average productivities $\forall\ s \notin s_3$ are as follows:

$$\tilde{z}^{i}_{Ds,t} = \left[\frac{k}{k-\theta+1}\right]^{\frac{1}{\theta-1}} z_{min} \ ; \qquad \tilde{z}^{ij}_{Xs,t} = \left[\frac{k}{k-\theta+1}\right]^{\frac{1}{\theta-1}} z^{ij}_{Xs,t}. \tag{32}$$

We now combine the above, the profits from exporting and the condition $d^{ij}_{Xs,t}\left(z^{ij}_{Xs,t}\right) = 0\ \ \forall\ s \notin s_3$ to solve for the productivity cutoffs. Only firms that draw a productivity above the cutoff will export. For final goods producing firms, the cutoff is given by

$$z^{ij}_{Xs_1,t} = \left[\frac{k}{k-\theta+1}\right]^{\frac{1}{\theta-1}} \left(\frac{\theta}{\theta-1}\right) \tau^{ij}_{IBs_1,t} \left(\frac{\left(1+\tau^{ji}_{s_1,t}\right) mc^{i}_{s_1,t}}{\varepsilon^{ij}_{t} Z^{i}_{t}}\right)^{\frac{\theta}{\theta-1}} \left(\frac{\kappa^{ij} \alpha^{i}_{s_1} \left(P^{j}_{s_1,t}\right)^{\omega} \left(P^{i}_{Xs_1,t}\right)^{\theta-\omega} Q^{j}_{s_1,t}}{\theta f^{ij}_{X,t}}\right)^{\frac{1}{1-\theta}}, \tag{33}$$

and for firms producing other intermediate goods the cutoff can be written as

$$z^{ij}_{XOIt} = \left[\frac{k}{k-\theta+1}\right]^{\frac{1}{\theta-1}} \left(\frac{\theta}{\theta-1}\right) \tau^{ij}_{IBOI,t} \left(\frac{\left(1+\tau^{ji}_{OI,t}\right) mc^{i}_{OI,t}}{\varepsilon^{ij}_{t} Z^{i}_{t}}\right)^{\frac{\theta}{\theta-1}} \left[\frac{1}{\theta f^{ij}_{X,t}} \left(P^{ji}_{XOI,t}\right)^{\theta} \left(Q^{LTji}_{OI,t} + Q^{HTji}_{OI,t}\right)\right]^{\frac{1}{1-\theta}}. \tag{34}$$

Given the results above average profits can be determined by inserting the average productivities to get average domestic profits, i.e., $\tilde{d}^{i}_{Ds,t} = d^{i}_{Ds,t}(\tilde{z}^{i}_{Ds,t})$, and average profits from exporting can be expressed as

$$\tilde{d}^{ij}_{Xs,t} = \left(\frac{\theta-1}{k-\theta+1}\right) \frac{mc^{i}_{s,t} f^{ij}_{Xs}}{Z^{i}_{t}} \ \ \forall\ \ \mathrm{s} \in \{HT, LT, OI\}\ . \tag{35}$$

Note that this equation also holds for the intermediate goods industry which sells its goods to the two final goods industries. In every industry s $\in \{HT, LT, OI\}$ of country i there are $N^{i}_{s,t}$

firms, but only $N_{Xs,t}^{ij}$ firms decide to export to country j. The share of firms serving the export market is given by

$$\frac{N_{Xs,t}^{ij}}{N_{s,t}^{i}} = \left(\frac{z_{min}}{\tilde{z}_{Xs,t}^{ij}}\right)^{k} \left(\frac{k}{k-\theta+1}\right)^{\frac{k}{\theta-1}} \quad \forall \quad s \in \{HT, LT, OI\}\,, \tag{36}$$

which links back to equation (1) which determines the same share for the semiconductor industry.

3.4 Consumers

There is a continuum of identical and infinitely-lived households, so we can focus on a representative agent. The representative household in country i maximizes the present value of its lifetime CRRA utility given by

$$V_0 = E_0\left(\sum_{t=0}^{\infty} \beta^t \frac{\left[C_t^i\left(1-L_t^i\right)^{\nu^i}\right]^{1-\gamma} - 1}{1-\gamma}\right), \tag{37}$$

where the expectation conditional on the information set available at the end of period $t = 0$ is denoted by $E_0(\cdot)$, β is the discount factor, C_t^i is the index of consumed varieties, ν^i is a preference parameter used to calibrate the amount of time the household in country i devotes to leisure and the parameter γ ($\gamma \geq 0;\ \gamma \neq 1$) measures the degree of relative risk aversion that is implicit in the utility function. The aggregate labor index takes the form

$$L_t^i = \left[\sum_s \left(L_{s,t}^i\right)^{\frac{1+\zeta}{\zeta}}\right]^{\frac{\zeta}{1+\zeta}}, \tag{38}$$

where ζ is the sectoral labor supply elasticity and $L_{s,t}^i$ is labor supplied in sector s. The household faces the budget constraint

$$\sum_{j\neq i} B_{i,t}^{ij} + \sum_{j\neq i} \varepsilon_t^{ij} B_{j,t}^{ij} + \sum_{s} \tilde{v}_{s,t}^{i}\left(N_{s,t}^i + N_{Es,t}^i\right) x_{s,t}^i + C_t^i =$$

$$\sum_{j\neq i} R_{t-1}^{i} B_{i,t-1}^{ij} + \sum_{j\neq i} R_{t-1}^{ij} \varepsilon_t^{ij} B_{j,t-1}^{ij} + \sum_s \left(\tilde{d}_{s,t}^{i} + \tilde{v}_{s,t}^{i}\right) \left(N_{s,t}^{i} + N_{Es,t}^{i}\right) x_{s,t-1}^{i} + \sum_s w_{s,t}^{i} L_{s,t}^{i} + \Gamma_t^{i}, \quad (39)$$

where $B_{i,t}^{ij}$ are bonds denominated in domestic currency, $B_{j,t}^{ij}$ are bonds denominated in foreign currency, R_{t-1}^{i} and R_{t-1}^{ij} are the interest rates of bonds denominated in domestic currency and bonds denominated in the currency of country j, respectively. $w_{s,t}^{i}$ is the real wage paid in industry s of country i, L_s^i is fixed labor supply in the respecting industry and Γ_t^i is a lump-sum rebate of government's tariff revenues. In period t, the household buys $x_{s,t}^{i}$ shares in a mutual fund of domestic firms of industry s. The price of the shares is equal to the above-mentioned present value of the expected stream of average profits of the domestic firms $\tilde{v}_{s,t}^{i}$. The dividends paid to the shareholders in period t are in turn equal to the average profits $\tilde{d}_{s,t}^{i}$.

Let λ_t^i be the Lagrangian multiplier of the budget constraint, then at the optimum it must be equal to the first derivative of the utility function. Moreover, let ξ^i be the size of the model economy i, where we weight it relative to the US, i.e., relative to ξ^{US}. Then the corresponding first-order condition in the aggregate is given by

$$\lambda_t^i = \left(\frac{\xi^{US}}{\xi^i} C_t^i \left(1 - \frac{\xi^{US}}{\xi^i} L_t^i\right)^{\nu^i}\right)^{-\gamma}. \quad (40)$$

The remaining first-order conditions of the utility maximization problem are given by

$$w_{s,t}^{i} = \nu^i \frac{C_t^i}{\frac{\xi^i}{\xi^{US}} - L_t^i} \left(\frac{L_{s,t}^{i}}{L_t^i}\right)^{\frac{1}{\zeta}} \quad (41)$$

$$R_t^i = \frac{1}{\beta} E_t\left(\frac{\lambda_t^i}{\lambda_{t+1}^i}\right) \quad (42)$$

$$R_t^{ij} = \frac{1}{\beta} E_t\left(\frac{\varepsilon_t^{ij}}{\varepsilon_{t+1}^{ij}} \frac{\lambda_t^i}{\lambda_{t+1}^i}\right) \quad (43)$$

$$\tilde{v}_{s,t}^{i} = \beta(1-\delta)\, E_t\left(\frac{\lambda_{t+1}^i}{\lambda_t^i}\left(\tilde{d}_{s,t+1}^{i} + \tilde{v}_{s,t+1}^{i}\right)\right). \quad (44)$$

Equation (41) is the first-order condition for sectoral labor supply, the Equations (42) and (43) are the usual Euler equations for trading in domestic and foreign bonds and equation (44) is the Euler equation for trading in fund shares.

3.5 Market clearing

The model is completed by conditions for clearing in bond and goods markets. To ensure that our model has only one well-defined steady state, we assume a convex risk premium for owning bonds:

$$R_{i,t}^{j} = R_{i,t}^{i} + \Upsilon\, e^{\bar{B}_{i,t}^{j} - B_{i,t}^{j}}. \tag{45}$$

Market clearing for bonds in the currency of country i implies

$$B_{i,t}^{US} + B_{i,t}^{CN} + B_{i,t}^{RW} = 0 \tag{46}$$

Market clearing in the market of final goods, intermediate goods, and semiconductors requires

$$\Lambda_{s_1,t}^{i} = \frac{(\theta-1)}{mc_{s_1,t}^{i}}\left(N_{s_1,t}^{i}\tilde{d}_{Ds_1,t}^{i} + \sum\nolimits_{j\neq i} N_{Xs_1,t}^{ij}\tilde{d}_{Xs_1,t}^{ij}\right) + \frac{1}{Z_t^i}\left(\theta \sum\nolimits_{j\neq i} N_{Xs_1,t}^{ij} f_{Xs_1}^{ij} + N_{Es_1,t}^{i} f_E^{i}\right), \tag{47}$$

$$L_{OI,t}^{i} = \frac{(\theta-1)}{mc_{OI,t}^{i}}\left(\sum\nolimits_{s_1} N_{OI,t}^{i}\tilde{d}_{DOI,t}^{s_1 i} + \sum\nolimits_{j\neq i} N_{XOI,t}^{ij}\tilde{d}_{XOI,t}^{ij}\right) + \frac{1}{Z_t^i}\left(\theta \sum\nolimits_{j\neq i} N_{XOI,t}^{ij} f_{XOI}^{ij} + N_{EOI,t}^{i} f_E^{i}\right), \tag{48}$$

and

$$L_{s_3,t}^{i} = \frac{(\theta-1)}{mc_{s_3,t}^{i}}\left(\sum\nolimits_{s_1} N_{s_3,t}^{i}\tilde{d}_{Ds_3,t}^{s_1 i} + \sum\nolimits_{j\neq i} N_{Xs_3,t}^{ij}\tilde{d}_{Xs_3,t}^{ij}\right) + \frac{1}{Z_t^i} N_{Es_3,t}^{i} f_E^{i} \quad . \tag{49}$$

respectively. Moreover, the net assets of two out of the three countries are needed to close the model. For example, the equation for the net asset position of the US is given by

$$B_{US,t}^{US} + \varepsilon_t^{USCN} B_{CN,t}^{US} + \varepsilon_t^{USRW} B_{RW,t}^{US} = \frac{1}{2}\Big[R_{US,t-1}^{US} B_{US,t-1}^{US} - \sum\nolimits_{j\neq US} R_{US,t-1}^{j} B_{US,t-1}^{j} +$$
$$\varepsilon_t^{USCN}\left(R_{CN,t-1}^{US} B_{CN,t-1}^{US} - \sum\nolimits_{j\neq US} R_{CN,t-1}^{j} B_{CN,t-1}^{j}\right) + \varepsilon_t^{USRW}\big(R_{RW,t-1}^{US} B_{RW,t-1}^{US} -$$

$$\sum\nolimits_{j\neq US} R^{j}_{RW,t-1} B^{j}_{RW,t-1}\big) + \sum\nolimits_{s} w^{US}_{s,t}\, L^{US}_{s,t} + \Gamma^{US}_{t} + \big(\sum\nolimits_{s} N^{US}_{s,t}\tilde{d}^{US}_{s,t} - N^{US}_{Es,t}\tilde{v}^{US}_{s,t}\big) - C^{US}_{t} -$$

$$\sum\nolimits_{j\neq US}\, \varepsilon^{USj}_{t}\big(\sum\nolimits_{s} w^{j}_{s,t}\, L^{j}_{s,t} + \Gamma^{j}_{t} + \big(\sum\nolimits_{s} N^{US}_{s,t}\tilde{d}^{US}_{s,t} - N^{CN}_{Es,t}\tilde{v}^{CN}_{s,t}\big) - C^{j}_{t}\big)\big] \tag{50}$$

4. Mapping the model to the data

We describe here our two-stage strategy for parameterizing the model. First, we set several parameters according to conventions and estimates from the literature or take them directly from actual data. Second, the remaining 87 parameters are set such that the model equilibrium matches the steady-state ratios. Our approach is similar to that of Kehoe et al. (2018) and Steinberg (2019). For all steady-state ratios for which actual data are available, a perfect match is achieved by means of this procedure. For parameters without direct empirical evidence, their plausibility is ensured.

As described above, we first choose some parameters according to conventions in the literature (e.g. Ghironi and Melitz 2005, Barattieri et al., 2021). The discount factor is set to $\beta = 0.99$, the coefficient of relative risk aversion is set to $\gamma = 2$, and the exit rate is set at $\delta = 0.025$. The Pareto shape parameter for firm productivity is assumed to be $k = 3.4$. We normalize the minimum relative productivity, the aggregate productivity and the market entry costs to 1. The risk premium parameter is set to $\Upsilon = 0.001$ which ensures a unique steady state but has no influence on the model simulations. In line with the recent estimates of Bajzik et al. (2020), we take a value of 3.8 for the micro elasticity, θ. For the macro elasticity, ω, we assume that it is 1.9, half as large as the micro elasticity, i.e. “the rule of two” (Feenstra et al., 2018). Of particular importance to our results are the trade elasticities of the semiconductor industry. The semiconductor micro elasticity is estimated by Ahmad and Riker (2020) to be 2.25 for 2017, and 2.09 for 2012 US data. It should be noted that we assume that there are easy-to-substitute lower-grade semiconductors and hard-to-substitute cutting-edge semiconductors. For lower-grade semiconductors, we assume $\eta_{BS} = \theta_{BS} = 3.8$, while for cutting-edge semiconductors we assume $\eta_{AS} = \theta_{AS} = 2.2$. We also examine the cases of easier within- or between-country substitutability (see Section 3.3.1). In the case that cutting-edge semiconductors are more easily substitutable within a country than between different countries, we assume a micro elasticity of $\theta_{AS} = 2.5$ and a cutting-edge semiconductor elasticity of $\eta_{AS} = 1.9$. In the case that semiconductors are more easily substitutable across countries than within a country, we assume exactly the opposite, $\theta_{AS} = 1.9$ and $\eta_{AS} = 2.5$. Moreover, we set the material share of the production function to $\varrho_1 = 0.6$. The elasticity of substitution between semiconductors and other factors of production is set to $\eta_{SC}^{s_2} = 0.5$. This reflects the quintessential character of semiconductors.[17] The latest tariff rates of China and the US are $\tau_t^{USCN} = 0.193$, $\tau_t^{USRW} = 0.030$, $\tau_t^{CNUS} = 0.207$, $\tau_t^{CNRW} = 0.061$ and originate from Bown (2021). For the tariffs of the rest of the world, we take the EU-China tariff rates $\tau_t^{RWUS} = \tau_t^{RWCN} = 0.0435$ as provided by the WTO (http://tao.wto.org, HS subheading average method). The tabular summary of the baseline parameters is given in Table 2.

Table 2: Calibration: First-stage parameters

Parameter	**Definition**	**Value**
Production, costs and capital		
ϱ_1	Material share	0.6
Z^i	Aggregate Productivity	1.0
δ	Exit probability of firms	0.025
f_E^i	Entry cost	1
Trade elasticities		
Cutting-edge semiconductor trade elasticity cases		
$\eta_{AS} = \theta_{AS}$	Baseline: Firm-specific substitutability	2.2
$\eta_{AS} > \theta_{AS}$	Within-country substitutability	$2.5 > 1.9$
$\eta_{AS} < \theta_{AS}$	Between-country substitutability	$1.9 < 2.5$
Trade elasticities of lower-grade semiconductors and other goods		
$\eta_{BS} = \theta_{BS}$	Lower-grade semiconductor trade elasticity	3.8
$\theta_s \forall s \notin \{AS\}$	Micro elasticity	3.8
ω	Macro elasticity	1.9
Households		
β	Discount factor	0.99
γ	Coefficient of relative risk aversion	2
ζ	Sectoral labor elasticity	1
Firm distribution and other structural parameters		
z_{min}	Minimum relative productivity	1
k	Pareto shape parameter	3.4
Υ	Risk premium parameter	0.001

The remaining parameters are set such that the model steady state matches the actual data listed in Table 3. For all steady state ratios for which actual data are available, a perfect match is achieved. For parameters without direct empirical evidence, their plausibility is ensured.

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[17] As an alternative to the modeling approach chosen here, Atalay (2017) assumes a CES bundle of intermediate goods, which has an elasticity of substitution with the other production factors. He estimates this to be 1, which is also our assumption for the Cobb-Douglas production function with respect to the intermediate goods without semiconductors.

Table 3: Calibration: Second-stage parameters

	US	China	Rest of the World
A. GDP and US-China Trade Ratios			
GDP as ratio of world GDP (in %)	24.7[1]	17.4[1]	57.9[1]
Trade as ratio of GDP (in %)	23.4[1]	34.5[1]	17.8
US-China trade as ratio of overall US trade (in %)	12.5[2]	-	-
Ratio of US imports from China to exports to China	2.7[2]	-	-
B. Trade of Final Consumer vs. Intermediate Goods			
Share of final consumer goods in total exports to the US (in %)	-	45.8[3]	37.2[3]
Share of final consumer goods in total exports to China (in %)	18.3[3]	-	16.0[3]
Share of final consumer goods in total exports to the RW (in %)	26.2[3]	36.1[3]	-
C. Semiconductor and High-Tech Industry			
Contribution of the semiconductor industry (SI) to GDP (in %)	0.74[5]	0.27	0.51
Ratio of US SI imports from China to SI exports to China	0.20[2]	-	-
Share of global semiconductor purchases (in %)	21.7[6]	34.4[6]	43.9[6]
High (and medium) tech manufacturing value added (% of GDP)	5.2[4]	10.7[4]	7.0
High (and medium) tech exports (% of GDP)	4.4	6.5	4.1
D. Other			
Ratio of time allocated to work (in %)	20[7]	20	20
Ratio of exporting firms (in %)	23[8]	23	12.7

Notes: For all data marked with a superscript, a perfect match with the actual numerical data is given in the model. Data not marked with a superscript have been determined by approximation. Sources: [1] World Bank, 2020; [2] US Census Bureau, 2020; China's General Administration of Customs; [3] World Bank, 2019 (for RW, we take the world values); [4] World Bank, 2019; [5] value added of the semiconductor industry is taken from Oxford Economics (2021), direct plus indirect impact, and divided by GDP taken from the World Bank; [6] Semiconductor Industry Association (for the US, we take the number for America); [7] Prescott (1986); [8] Bernard et al. (2003).

Looking in more detail at our choice of parameters to obtain the steady state ratios given in Table 3, we note that each parameter affects many steady state values. Thus, only an approximate description is possible. To match the country-specific GDP to world GDP ratios, we employ the country weights ξ^i. The trade to GDP ratios have been matched by means of α_s^{US}, α_s^{CN} and α_s^{RW}. For matching the ratio of US imports from China to exports to China, final versus intermediate goods trade and the high-tech GDP shares the Armington shares κ_s^{ij} are used. We set iceberg trade costs τ_{IBs}^{ij} to 1, which means that the Armington shares capture the impact of non-tariff barriers and transport costs. The contribution of the semiconductor industry to GDP of country i is matched by the Armington share of country j of semiconductors from country i. To get a unique solution we assume that all countries have the same Armington shares with respect to cutting-edge semiconductors, i.e. $\upsilon_{AS}^{ii} = \upsilon_{AS}^{ji} = \upsilon_{AS}^{ki}$. Moreover, we use υ_{BS}^{USCN} to match the ratio of US semiconductor imports from China to exports to China and the respective shares of China and the rest of the world to ensure that the rest of the world cutting-edge is half as large as the lower-grade semiconductor industry. To match the share of global semiconductor purchases of each country, we use the semiconductor shares in the production function $\varrho_2^{s_2 i}$. Moreover, we assume that the semiconductor weight of the low-tech industry is only 10 % of that of the high-tech industry, that is $\varrho_2^{LTi} = 0.1\varrho_2^{HTi}$. We adjust the size of the high-tech sector of our model by υ_{HT}^{i} to reflect the value added of high- and medium-tech manufacturing according to World Bank data. Finally, we use ν^{i} to ensure that steady-state households spend 20 % of their time on working and fixed costs of exporting f_{XS}^{i}, so that 23 % of firms export both in line with the US data.

5. Quantifying the effects of semiconductor trade restrictions

The modeling framework provides a rich laboratory for the analysis of trade policies. To delve deeper into the modelling framework, we next explore numerically the properties of the model.[18] We also conduct various policy experiments. The simulations should be considered as an illustration of the mechanisms embedded in our framework.

Several variables depicted in the subsequent graphs need to be defined before we present the impact channels and numerical results. Semiconductors are a universally required intermediate product. Therefore, in the case of protectionist measures, the unavailability of certain semiconductor varieties is likely to hurt importers more than higher prices. For our modeling and analysis, the separation between intensive and extensive margin is therefore of particular importance. To illustrate the intensive margin adjustments, we present semiconductor industry average revenue of exporting from country i to country j in terms of the price index of the former, which can be easily calculated from export profits (see Section 3.3.2):

$$\tilde{r}_{xs_3,t}^{ij} = \frac{\tilde{r}_{xs_3,t}^{ij,n}}{P_t^{i}} = \theta_{s_3}\tilde{d}_{sx_3,t}^{ij} \tag{51}$$

This is the revenue received by the producers and, thus, calculated net of trade tariffs. As long as we examine export restrictions, this is not important, but it makes a difference when we look

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[18] Since the policies studied in this paper take some model variables far from their steady state and because parts of the model are highly nonlinear, we employ a non-linear solution method for the simulations, i.e. DYNARE’s trust-region algorithm (Adjemian et al., 2011).

at export tariffs. Export revenues outside of the semiconductor industry are $\tilde{r}_{xs,t}^{ij} = \theta_s\left(\tilde{d}_{sx,t}^{ij} + mc_t^i f_{Xs}^{ij}/Z_t^i\right) \forall\, s \in \{OI, AS, BS\}$, total export revenues can be calculated by $r_{xs,t}^{ij} = N_{xs,t}^{ij}\tilde{r}_{xs,t}^{ij}$ in all industries. Total sector-specific revenue is also of particular interest to us:

$$r_{s_3,t}^{i} = N_{s_3,t}^{i}\theta_{s_3}\tilde{d}_{s_3,t}^{i} + \sum\nolimits_{j \neq i} N_{xs_3,t}^{ij}\tilde{r}_{xs_3,t}^{ij} \tag{52}$$

$$r_{s,t}^{i} = N_{s,t}^{i}\theta_s\left(\tilde{d}_{s,t}^{LT,i} + \tilde{d}_{s,t}^{HT,i}\right) + \sum\nolimits_{j \neq i} N_{xs,t}^{ij}\tilde{r}_{xs,t}^{ij} \quad \forall\, s \in \{OI, AS, BS\} \tag{53}$$

Revenue is a common metric in the semiconductor industry both for evaluating the development of the industry as a whole and for comparing industry trends in different countries. However, since revenue can change due to both volume and price effects, we also look at average firm prices as set forth in equations (20) and (21). Here, we use average prices instead of aggregate price indices presented in equations (30) and (31), since they do not include the variety effect. We show the adjustments at the extensive margin, i.e. the change in the number of exported semiconductor varieties, separately. With these preliminaries in mind, we now consider the important impact channels.

5.1 Impact channels

From the Chinese perspective, export restrictions and export tariffs first trigger a price effect. Using equation (1), we rewrite equation (31) as

$$P_{XAS,t}^{CNj} = \left(1 + \tau_{AS,t}^{CNj} + \tau_{AS,t}^{exjCN}\right)\left[\left(1 - \aleph_{AS,t}^{iCN}\right)N_{AS,t}^{i}\right]^{1/(1-\theta_{AS})} p_{XAS,t}^{CN}\,. \tag{54}$$

Whereas an export tariff causes a direct price increase, export restrictions act via the variety effect. Both together trigger a trade destruction effect among exporters and importers. This leads to a trade diversion. To describe this trade detour effect in more detail, we combine the just used equation, the CES demand function, equation (15), and the pricing equations (20) and (21), take logs, and get

$$ln\left(\frac{Q_{AS,t}^{s_1CNj}}{Q_{AS,t}^{s_1CNk}}\right) = (-\eta_{AS})ln\left(\frac{1+\tau_{AS,t}^{CNj}+\tau_{AS,t}^{exjCN}}{1+\tau_{AS,t}^{CNk}+\tau_{AS,t}^{exUSk}}\right) - \frac{\eta_{AS}}{1-\theta_{AS}}ln\left(\frac{1-\aleph_{AS,t}^{jCN}}{1-\aleph_{AS,t}^{kCN}}\right) - \eta_{AS}\left[\frac{1}{1-\theta_{AS}}ln\left(\frac{N_{AS,t}^{j}}{N_{AS,t}^{k}}\right) + ln\left(\frac{\varepsilon_t^{CNk}}{\varepsilon_t^{CNj}}\frac{w_{AS,t}^{j}}{w_{AS,t}^{k}}\right)\right] + \left[ln\left(\frac{\upsilon_{AS}^{CNj}}{\upsilon_{AS}^{CNk}}\right) - \eta_{AS}\,ln\left(\frac{\tau_{IBs,t}^{jCN}}{\tau_{IBs,t}^{kCN}}\frac{Z_t^{k}}{Z_t^{j}}\right)\right] \tag{55}$$

From equation (55), we can infer how industry s_1 from China substitutes between cutting-edge semiconductors from the other two economies when one of them either imposes export tariffs or imposes export restrictions. The right-hand side of the equation consists of four terms. Inside the last square bracket are constants which we will not consider further here. The first and second terms describe the downsizing of the affected semiconductor companies triggered by trade tariffs and the trade restrictions, respectively. As counteracting effect, falling output, declining employment and dwindling wages let semiconductor prices to fall, as can be seen by the third term.

How do Chinese importers respond to semiconductor trade restrictions, that is, to the relative export tariff costs of both trading partners or to the relative variety restriction intensity? Not surprisingly, if relative tariff costs change, the Chinese industry s_1 substitutes between both semiconductor country bundles with elasticity η_{AS}.[19] Since the tariff is applied on all semiconductors in a specific country, there is only substitution between country bundles and no substitution within a country of origin and since the number of exporters is also constant, this effect only takes place at the intensive margin. Thus, changes in tariff costs lead to an intensive margin substitution (or trade diversion) effect.

If one trading partner imposes export restrictions increasing the ratio of banned varieties both cutting-edge country bundles are substituted with elasticity $\eta_{AS}/(1-\theta_{AS})$, which depends also on the micro elasticity of cutting-edge semiconductors.[20] The greater the micro elasticity, the easier it is to substitute between varieties, the less important it is to have a large number of varieties available, the less a reduction in varieties increases the aggregate price, the less substitution occurs. This is the variety effect on the aggregate price of semiconductors and can also be seen directly in equation (54).

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[19] Formally, $-\partial ln\big(Q_{AS,t}^{s_1CNj}/Q_{AS,t}^{s_1CNk}\big)/\partial ln\big(1+\tau_{AS,t}^{CNj}+\tau_{AS,t}^{exjCN}/1+\tau_{AS,t}^{CNk}+\tau_{AS,t}^{exUSk}\big) = \eta_{AS}$ holding $N_{AS,t}^{j}/N_{AS,t}^{k}$, $\varepsilon_t^{CNk}/\varepsilon_t^{CNj}$ and $w_{AS,t}^{j}/w_{AS,t}^{k}$ constant. Note that this does not hold for the other model industries. Since the firms in the latter are Pareto-distributed and only the most productive export, there would be an immediate reaction at the extensive margin also in the case of trade tariff changes.

[20] This elasticity is always negative since the condition $\theta_{AS} > 1$ is needed to have a positive and finite markup.

Next, we take the perspective of the exporting country by looking at total industry revenue. For this purpose, we combine equation (51) with the export restriction and pricing equations which yields

$$r_{xAS,t}^{iCN} = \left[\left(1 - \aleph_{s_3,t}^{iCN}\right)N_{s_3,t}^{i}\right]^{\frac{1-\eta_{AS}}{1-\theta_{AS}}}\left(1 + \tau_{s_3,t}^{CNi} + \tau_{s_3,t}^{exCNi}\right)^{-\eta_{AS}}\left[\left(\frac{p_{XAS,t}^{CNi}}{P_{SC,t}^{s_1CN}}\right)^{1-\eta_{AS}} \upsilon_{AS}^{CNi}\,\varepsilon_{t}^{iCN} P_{SC,t}^{s_1CN} Q_{SC,t}^{s_1CN}\right]. \quad (56)$$

We can divide the right side of the equation into three parts. First, the last part (in square brackets) contains a Chinese import demand function for cutting-edge semiconductors of country i that shows the indirect effects of trade policy. The price received by the producers, $p_{Xs_3,t}^{CNi}$, depends only on the wage $w_{AS,t}^{i}$ and exogenous parameters. Measured is the demand function in the currency of country i, which introduces exchange rate effects into the equation. And besides substitution effects to other semiconductors, trade policy targeting the Chinese import demand can of course also affect the total demand for semiconductors measured by $P_{SC,t}^{s_1CN} Q_{SC,t}^{s_1CN}$. Second, the term $\left(1 + \tau_{s_3,t}^{CNi} + \tau_{s_3,t}^{exCNi}\right)^{-\eta_{AS}}$ again shows the intensive margin substitution effect with elasticity η_{AS} induced by tariff changes. Note that $r_{xAS,t}^{iCN}$ denotes the revenue received, i.e. net of tariffs. Not visible in the equation, but existing is of course also an income effect due to tariffs shown already in equation (2). For example, an export tariff leads to a transfer of income to households in country of origin i. This income effect is also a major mechanism. Finally, $\left[\left(1 - \aleph_{s_3,t}^{iCN}\right)N_{s_3,t}^{i}\right]^{(1-\eta_{AS})/(1-\theta)}$ captures the direct effect of export restrictions on total industry revenue at the extensive margin. Assuming $\eta_{AS} = \theta_{AS}$ holds, banning exports of a given percentage of varieties leads to a direct reduction in industry revenue by the same percentage. But export restrictions do not only act at the extensive margin. If $\eta_{AS} > \theta_{AS}$ applies, an additional intensive margin trade diversion effect is triggered from semiconductors not affected by the export restriction to cutting-edge semiconductors from other countries. On the other hand, if $\eta_{AS} < \theta_{AS}$ an additional intensive margin substitution effect to the domestic semiconductors not affected by the export restriction is initiated. However, even if $\eta_{AS} = \theta_{AS}$, export restrictions will lower domestic marginal costs and thus prices, causing an intensive margin substitution effect to domestic semiconductors not affected as well as an intensive margin trade diversion effect: The demand for domestic cutting-edge semiconductors from other countries will rise.

To summarize the six model mechanisms, both export restrictions and export tariffs have (i) a trade destruction effect and (ii) a counteracting labor demand effect lowering producer prices. Export tariffs lead to (iii) positive (negative) income effects for the country imposing the tariff (destination country) and (iv) negative intensive margin substitution effects (trade diversion). Export restrictions also lead to intensive margin substitution effects, but their direction depends on the assumed elasticities. Either the intensive margin trade diversion effect to other countries or the substitution effect to the varieties not affected by the export restriction can prevail. However, the unambiguous effects of export restrictions are (v) an extensive margin reduction of producer revenues and (vi) a negative variety effect on the import price for buyers.

Finally, while it is important to emphasize that our model includes further general equilibrium impacts due to optimizing households, the specific effects mentioned are quantitatively most dominant.

In the next stage of the analysis, we analyze how semiconductor trade barriers aimed at technological decoupling reverberate throughout the countries involved. In our baseline calibration, we assume that top-end semiconductors are difficult to substitute regardless of the origin ($\eta_{AS} = \theta_{AS} = 2.2$), after which we explore the alternatives that semiconductors either exhibit country-specific technology differences ($\eta_{AS} = 1.9 < \theta_{AS} = 2.5$) or have to a greater extent business-specific features ($\eta_{AS} = 2.5 > \theta_{AS} = 1.9$).

5.2 The baseline calibration $\boldsymbol{\eta_{AS} = \theta_{AS} = 2.2}$

Figure 4 shows the impulse responses of the targeted export restrictions on GDP and total revenue on the different model industries. Thereby, quarters are drawn on the horizontal axis. The four cases considered here include (i) an unilateral export restriction that lead to a ban of 50 % of US semiconductor products exported to China (black dashed line), (ii) an unilateral export ban of 80 % of US semiconductor products exported to China (black solid line), (iii) an internationally coordinated export ban of 80 % of US and RW cutting-edge semiconductor varieties exported to China (gray dotted line), and (iv) an internationally coordinated US export ban of 80 % of US semiconductor varieties combined with an 400 % export trade tariff on RW semiconductors (gray solid line).[21] This combined approach arises because of the export tariff

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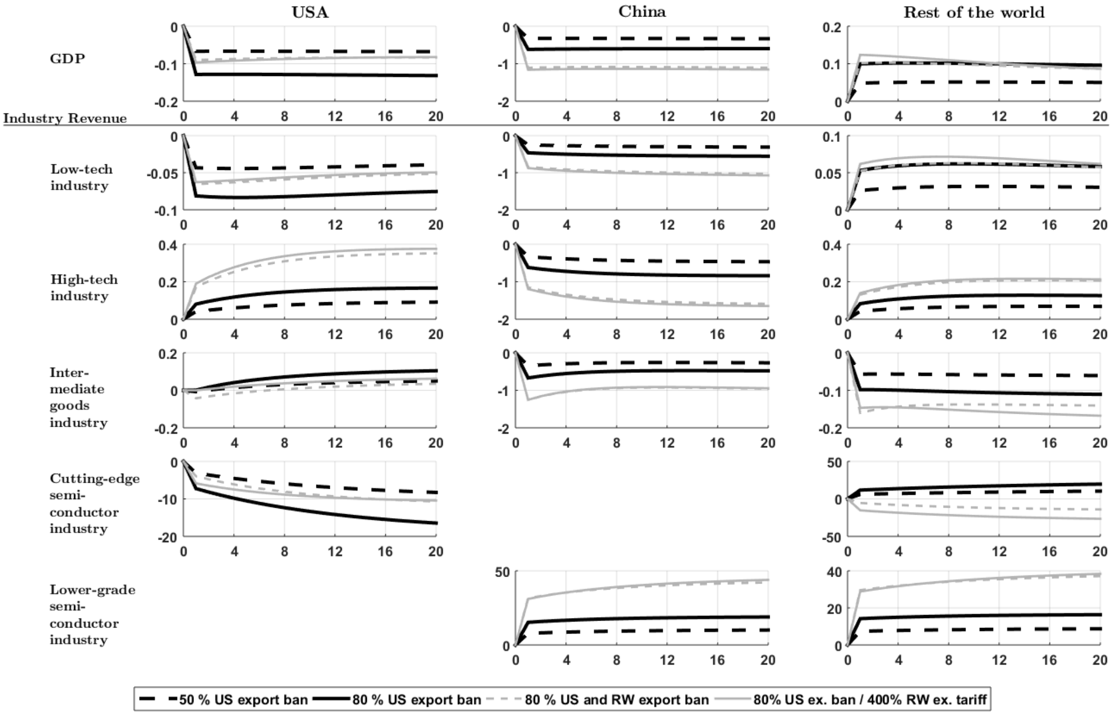
[21] In contrast to the first two variants (i) and (ii), policy variants (iii) and (iv) assume that the US works with Japan, South Korea, and the Netherlands in an alliance-centered strategy to bar exports to China of advanced semiconductors and semiconductor factories to prevent China from manufacturing advanced semiconductors

prohibitions in the US Constitution detailed above. For a given import budget, an export tariff of 400 % implies an import decline of 80 %. Accordingly, the first two cases are situations in which the US presses ahead independently with trade restrictions. In the remaining two cases, the US acts in an internationally coordinated manner with allied countries complying with US controls targeting China.

Figure 4: The impact of cutting-edge semiconductor export bans and tariffs on GDP and total sectoral industry revenue ($\boldsymbol{\eta_{AS} = \theta_{AS} = 2.2}$)



Notes: Shown are the percentage deviations of the variables from their initial steady state, with the variables denominated in domestic currency.

Unsurprisingly, Chinese GDP falls in all cases, with the effect being greatest in the case of internationally coordinated semiconductor trade restrictions. If the US and RW countries impose trade restrictions on 80 % of semiconductor varieties, Chinese GDP falls by almost 1.1 % in the year after introduction. If only the US were to introduce trade restrictions on 80% (50%) of semiconductor varieties, Chinese GDP falls by just over 0.6% (0.3%). The loss is slightly larger if RW countries impose an export tariff instead.

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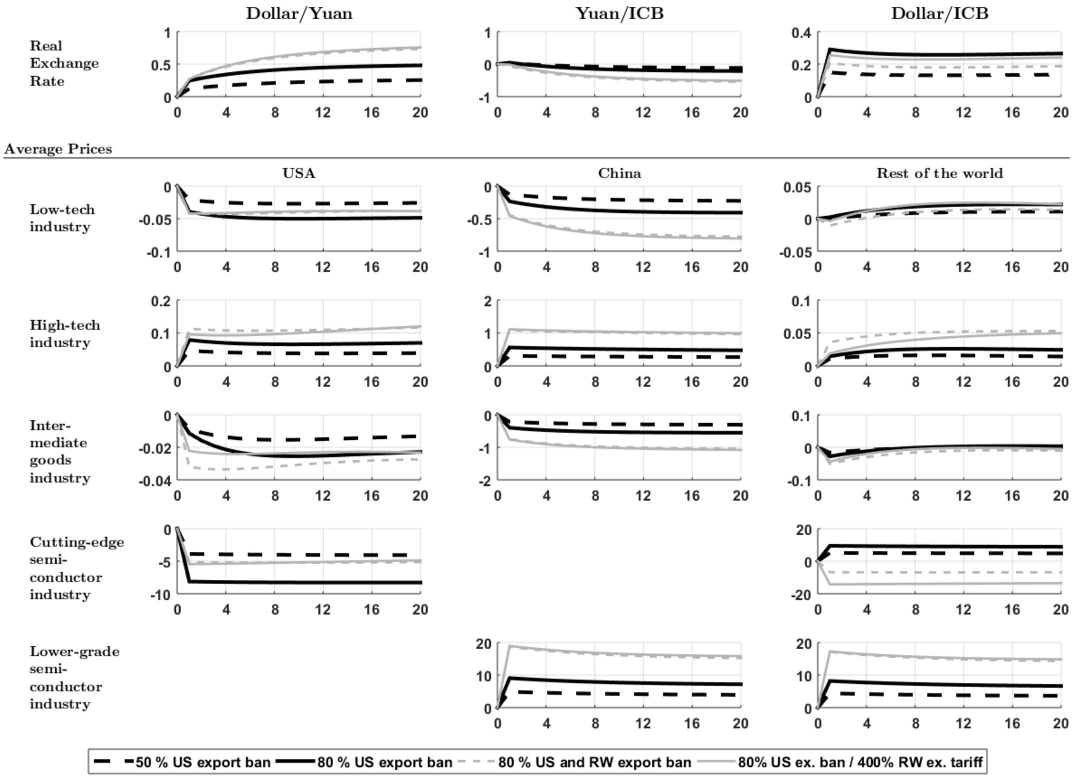
domestically. The two alternatives (i) and (ii) versus (iii) and (iv) highlight the *diversification principle*. By diversifying the sources of demand and supply across countries, countries can reduce volatility when country-specific shocks are important (Caselli et al., 2020). This is less likely to be relevant in the case of the current semiconductor trade dispute, however, because of the extraterritorial effect of US trade restrictions, i.e. the trade shock is more global in nature.

To our knowledge, no directly comparable estimates exist in the literature. However, we can compare the impact with those in Cerdeiro et al. (2021) for decoupling of the entire high-tech sectors of the US and China. The authors find that China's real GDP decline by about 1 % within 5 years in the case of a decoupling limited to the US and China. In the case of an internationally coordinated "coalition of caution," China's GDP loss increases to about 3 %. The orders of magnitude are thus comparable. The US also loses, with the GDP loss being largest if a unilateral approach is taken. On the contrary, the RW countries gain from trade diversion. Summing up over all three countries (China, the US and the RW countries), a decline in global GDP results.

In addition to these aggregate GDP effects, the tech sanctions also entail sector specific impacts. Given the varying degrees of technological intensity across sectors, one can even say that semiconductor trade restrictions are intrinsically a sectoral shock. The cheaper availability of US semiconductors leads to a revenue increase in the American final goods producing high-tech industry, while the Chinese high-tech industry shrinks due to the limited access to semiconductors. Among the losers is also the American semiconductor industry. Production volumes fall over time due to the lower number of semiconductor varieties produced in the US. This is shown by the fact that total revenue of the semiconductor industry falls by about the same amount as its average prices immediately after the introduction of the export bans.

Fewer cutting-edge semiconductor varieties are produced in the US, while cutting-edge semiconductor production in the rest of the world increases. The revenues of Chinese lower-grade semiconductor producers also rise. Figure 5 highlights that this effect is not due mainly to a genuine increase in production, but to price increases caused by semiconductor supply constraints and disruptions. The price and exchange rate changes in Figure 5 also convey three further insights. First, the trade restrictions degrade the price competitiveness of China's high-tech industry as this is where prices rise most. Second, on the global scale, the price of high-tech products tends to increase relative to prices of low-tech products. Third, according to our model, US semiconductor export restrictions result in a depreciation of the real USD exchange rate, which is consistent with the literature findings. For example, Itskhoki and Mukhin (2022) show that sanctions that restrict exports lead to a depreciation of the exchange rate.

Figure 5. **The impact of cutting-edge semiconductor export bans and tariffs on domestic average prices ($\eta_{AS} = \theta_{AS} = 2.2$)**



Notes: Shown are the percentage deviations of the variables from their initial steady state, with the variables denominated in domestic currency.

Figure 6 looks at the adjustment processes from a third viewpoint by looking at the intensive margin (average revenue) and the extensive margin (number of exporters and thus the number of varieties exported).

The first two rows illustrate the loss of competition in the US cutting-edge semiconductor industry, where the number of exporting businesses is declining, as is the number of varieties. This also applies to their revenues, although rising prices have a stabilizing impact.[22] The third and fourth rows describe the evolution of the Chinese lower-grade semiconductor industry. This industry benefits from a partial substitution towards lower-grade semiconductors. The number of corresponding exporters and varieties increases, while average revenues and thus total export revenues decrease. The last two rows describe the adjustment dynamics in the RW countries. If the US only imposes a unilateral export ban (black lines), cutting-edge trade diversion occurs. In the case of a coordinated export ban (gray dashed lines), semiconductor

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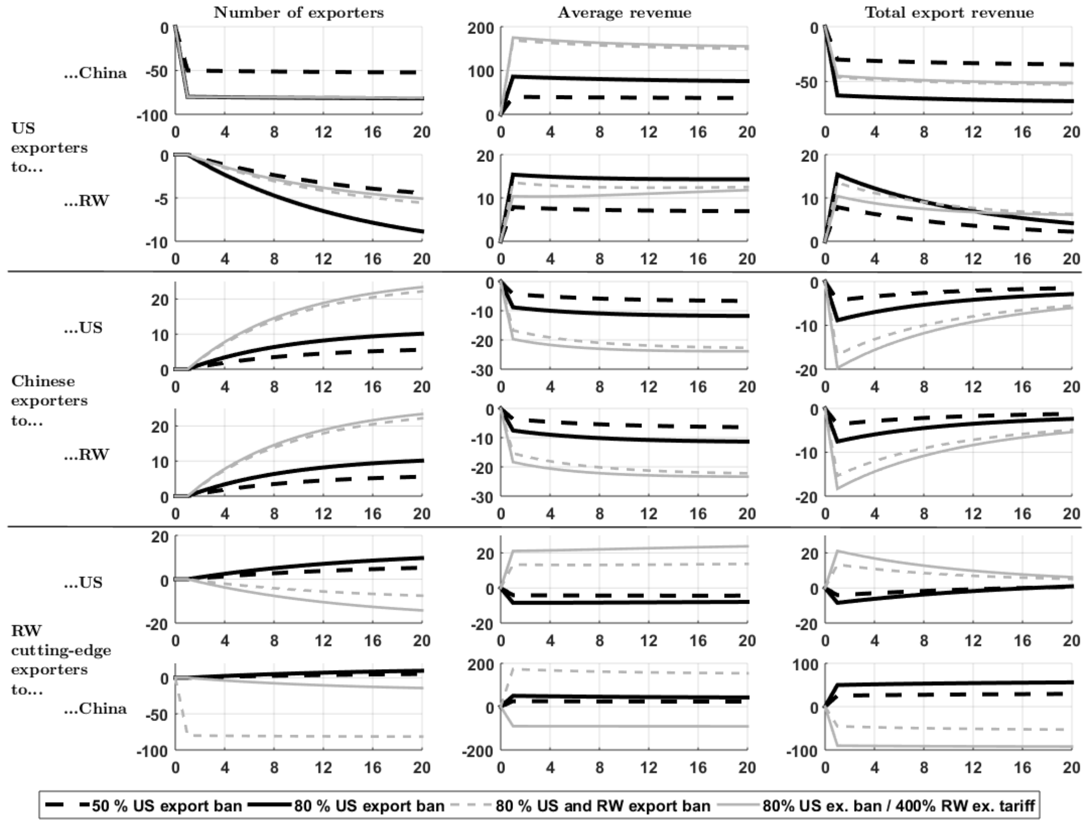
[22] This coincides with fears that the semiconductor trade restrictions could lead to a loss of technological leadership in the sector in the industrial policy arms race (Varas and Varadarajan, 2020).

profits decrease and thus the number of semiconductor firms or varieties in the rest of the world also shrink. Finally, the last two rows allow a direct comparison of an export tariff and an export ban. The export tariff has an indirectly operating effect on the number of exporters as it becomes less lucrative to produce domestically. This reduces the number of domestic semiconductor varieties (or firms) over time. At the same time, the export tariff directly causes a sharp decline on the average revenues of exporters, i.e. the intensive margin of exports. In the case of export bans, the opposite is true. They have a direct effect on the extensive margin and an indirect opposite effect on the intensive margin. The affected varieties may no longer be exported, but the average sales revenue of the remaining, unaffected exporters increases strongly.

Figure 6: The impact of cutting-edge semiconductor export bans and tariffs on the number of semiconductor exporters and their average revenue ($\eta_{AS} = \theta_{AS} = 2.2$).

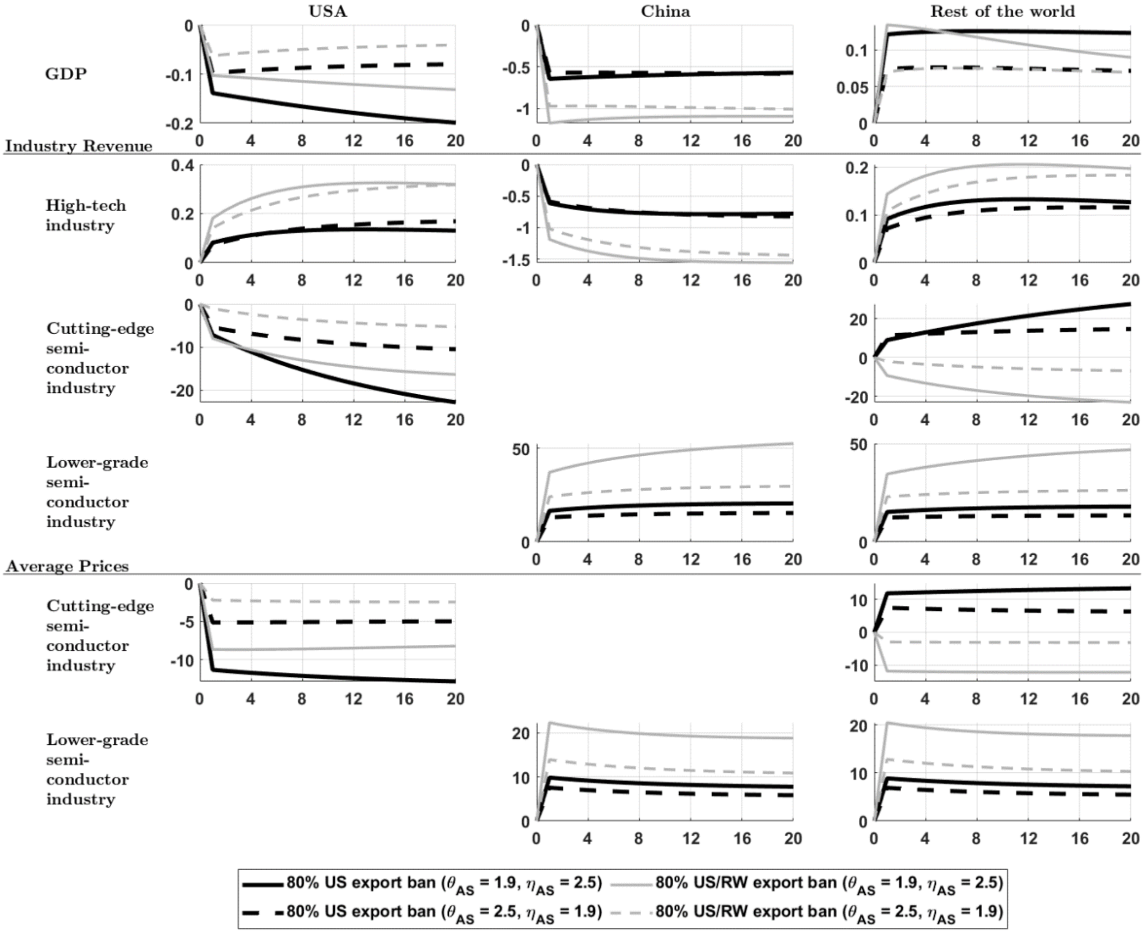


Notes: Shown are the percentage deviations of the variables from their initial steady state, with the revenues denominated in domestic currency.

5.3 Augmented model evaluations for $\boldsymbol{\eta_{AS} < \theta_{AS}}$ and $\boldsymbol{\eta_{AS} > \theta_{AS}}$

To complement the above analysis, we perform a robustness and sensitivity analysis to shed light on the transmission channels of technology-focused trade policies. In the previous model evaluations, we assumed that cutting-edge semiconductor substitution opportunities are independent of the geographic area of origin ($\eta_{AS} = \theta_{AS}$). What if this equivalence assumption is not satisfied, however? In the case of $\eta_{AS} < \theta_{AS}$ ($\eta_{AS} > \theta_{AS}$), it is more difficult (easier) to substitute cutting-edge semiconductors from different countries than from the same country. How do these alternative parameter configurations affect the magnitude and distribution of trade restriction costs? In the interest of a compact analysis, we restrict ourselves to the cases of a unilateral or internationally coordinated export ban on 80 % of cutting-edge semiconductors.

Figure 7. The impact of cutting-edge semiconductor export bans on GDP and total sectoral industry revenue for alternative trade elasticity calibrations



Notes: Shown are the percentage deviations of the variables from their initial steady state, with the revenues denominated in domestic currency.

Figure 7 compares the GDP, industry revenue and average price impulse response functions for $\eta_{AS} < \theta_{AS}$ (dashed lines) with $\eta_{AS} > \theta_{AS}$ (solid lines). The black lines present the unilateral US export ban, the gray lines show the internationally coordinated ban. Generally speaking, the qualitative results of trade policy remain unchanged, implying that the results presented earlier are robust. There is, however, a shift in burden-sharing across countries. In the two scenarios with $\eta_{AS} < \theta_{AS}$, the US faces a higher decoupling GDP loss compared to the baseline case as Chinese companies can more easily switch to other international suppliers. In a somewhat weaker form, this applies in a mirror image to China in the case of $\eta_{AS} > \theta_{AS}$.

6. Welfare

The welfare effects arising from the semiconductor trade restrictions can be expressed as the percentage of consumption that households are willing to give up in order to be as well off under the corresponding trade policy as under the reference policy. Like in Schmitt-Grohé and Uribe (2007), the consumption-equivalent total welfare cost in percentage terms is given by

$$Welfare\ cost = \left[1 - \left(\frac{(1-\gamma)V_0^a + (1-\beta)^{-1}}{(1-\gamma)V_0^r + (1-\beta)^{-1}}\right)^{\frac{1}{1-\gamma}}\right] \times 100 \tag{57}$$

where V_0^a is the welfare of the respective policy measure implemented in $t = 0$ and V_0^r is the welfare without the policy measure. The welfare of both V_0^a and V_0^r, i.e. their net present value of utility, is calculated according to equation (37) for a time horizon of 100 periods.

Table 4 reports the welfare costs for all policy scenarios considered above. In the baseline calibration ($\eta_{AS} = \theta_{AS} = 2.2$), an export ban of 50 % of US semiconductor varieties hurts both China and the US, albeit Chinese households are suffering nearly six times as much. The rest of the world gains slightly because of trade diversion effects. A US export ban of 80 % of semiconductor varieties almost doubles the effects. Provided that the 80 % semiconductor variety export ban is coordinated internationally, the Chinese welfare loss increases to over 1 %. The US welfare loss falls slightly, as does the RW welfare gain. There is a significantly higher welfare gain for the RW countries in the case of export tariffs.

What mechanisms drive these outcomes? The literature suggest that a country can increase its welfare to a certain degree by unilaterally raising export tariffs (Gros, 1987). How does the export tariff differ from the export ban? In the case of an export tariff, the importing country makes a welfare-enhancing income transfer to the country imposing the export tariff.

Furthermore, different variety effects arise. In the case of the export tariff changes primarily take place at the intensive margin, i.e. the semiconductor trade volume decreases but the number of available varieties remains as before. The export ban, however, leads to a decrease of imports at the extensive margin, so there is an additional negative variety effect. In technical parlance, the welfare loss from the export tariff is higher than from the export ban when the income effect is larger than the variety effect.

Table 4: Welfare cost in percent (negative values indicate welfare gains)

		USA	**China**	**Rest of the World**
50% US export ban	$\eta_{AS} = \theta_{AS} = 2.2$	0.0550	0.3101	-0.0329
	$\eta_{AS} = 1.9 < \theta_{AS} = 2.5$	0.0305	0.2676	-0.0216
	$\eta_{AS} = 2.5 > \theta_{AS} = 1.9$	0.1035	0.3529	-0.0469
80% US export ban	$\eta_{AS} = \theta_{AS} = 2.2$	0.1076	0.5525	-0.0621
	$\eta_{AS} = 1.9 < \theta_{AS} = 2.5$	0.0677	0.5394	-0.0462
	$\eta_{AS} = 2.5 > \theta_{AS} = 1.9$	0.1624	0.5152	-0.0704
80% US and RW export ban	$\eta_{AS} = \theta_{AS} = 2.2$	0.0777	1.0152	-0.0419
	$\eta_{AS} = 1.9 < \theta_{AS} = 2.5$	0.0413	0.9183	-0.0359
	$\eta_{AS} = 2.5 > \theta_{AS} = 1.9$	0.1196	1.0144	-0.0168
80% US export ban and 400% RW export tariff	$\eta_{AS} = \theta_{AS} = 2.2$	0.1031	1.0900	-0.1986
	$\eta_{AS} = 1.9 < \theta_{AS} = 2.5$	0.0701	1.0704	-0.2432
	$\eta_{AS} = 2.5 > \theta_{AS} = 1.9$	0.1374	1.0224	-0.1508

Notes: Further extensions of the time horizon have only marginal effects on the welfare effects shown.

Table 4 also presents the welfare effects for the two alternative parameter configurations $\eta_{AS} = 2.5 > \theta_{AS} = 1.9$ and $\eta_{AS} = 1.9 < \theta_{AS} = 2.5$, respectively. Comparison of the numerical values shows that the qualitative welfare effects reported for the baseline case are robust. Quantitatively, the interaction of the assumed microelasticies (η_{AS}) and macroelasticities (θ_{AS}) results in differences in magnitude. These are due to the different substitution opportunities in each case. In other words, the alternative parameter configurations provide a quantification of the possible range of welfare effects.

7. Conclusion

In recent years, the Chinese government has made several announcements signaling heightened efforts to invest in and quickly advance a range of advanced technologies. Against this background, the strategic significance of semiconductors and their ever-increasing importance for economic competitiveness has become a focus for governments worldwide.[23] Given that the US seems committed to an extended period of high-technology trade restrictions, our tripolar (US, China, and the rest of the world) multi-sector general equilibrium model provides a framework for thinking about the economic effects of semiconductor trade restrictions. The extension capturing the semiconductor value chain adds realism and provides a means to analyze the critical trade restrictions at the heart of the current trade conflict.

There are three aspects of this framework relevant for our study. First, by explicitly modeling semiconductor supply chain linkages across sectors and countries, the framework allows us to assess the transmission of sectoral shocks within the domestic economy and across borders. Second, the general equilibrium framework allows us to investigate semiconductor trade shocks via both supply and demand channels. Description of the upstream supply channel is rather straightforward in the case of production networks. The transmission via the demand side is less trivial as it occurs via price effects that eventually determine demand in both final and intermediate usage in the model, making our general equilibrium framework particularly relevant. Finally, the paper sheds light on the normative implications of the semiconductor trade dispute.

Given the multiple scenarios in the numerical analysis above, we draw two conclusions. The first takeaway, as mentioned earlier, is that cutting-edge semiconductors represent a stranglehold on China's further technological advancement. The flip side is that locking China out of cutting-edge semiconductors eventually leads to lower growth and welfare in the US. Rest-of-the-world (RW) countries benefit from the partial trade diversion.

While the model incorporates empirically relevant transmission mechanisms, further enhancements are warranted. One issue not addressed is the impact of the trade-related creation and absorption of digital technologies on the long-run growth of economies. See, for example,

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[23] The Economic Complexity Index (ECI) shaping multiple dimensions of economic development and growth, provides information of China's technological advancement. The ECI ranked China 17th, 24th, and 39th globally in the years 2020, 2010, and 2000, respectively. The gap between China and the US, which was ranked globally 6th, 12th, and 12th in 2000, 2010, and 2020, has thus decreased noticeably. See https://atlas.cid.harvard.edu/rankings.

Aghion et al. (2021) and Cai et al. (2021).[24] More recently, the role of uncertainty has attracted new interest in the context of trade policy and trade agreements. The evidence suggests that the relationship between trade policy uncertainty and trade is robustly negative, implying that trade policy uncertainty has an adverse effect on trade and growth performance of countries (Handley and Limão, 2015 and 2017). Furthermore, Handley and Limão (2015) show that policy uncertainty limits entry of firms into foreign trade due to the sunk costs involved in entry and trade commitments.

It is also worth noting that the model does not include physical capital and business strategies aimed at diversifying production sites to reduce dependency on China and foster supply-chain resilience. Modeling foreign direct investment and the transition from globalizing to regionalizing to reshoring in the presence of country-specific geopolitical risks is beyond the scope of the paper (Caldara and Iacoviello, 2022).

The proposed model can be augmented with further China-specific features. This includes a model-theoretical analysis of China's "dual-circulation" strategy. Underlying this technical-sounding phrase is China's long-standing push to make economic growth more self-reliant, i.e. policymakers seek ways to move beyond China's current export-led growth paradigm through diversification of the country's supply chains.[25] While tantalizing, we must leave these issues for future research.

Acknowledgement

We thank the participants of the Workshop on the Impact of Global Trade Shocks (University of Luxembourg, August 2023), the Annual Meeting of the Austrian Economic Association (University of Salzburg, September 2023) and the Centre for European Policy Studies Annual Conference 2023 (CEPS, Brussels, March 2023) for providing helpful comments on an earlier draft. We also benefitted from discussions with participants at various seminars. A previous version of the paper has been published as Bank of Finland BOFIT Discussion Paper No. 2022/13. This paper presents the authors' personal opinions and does not necessarily reflect the views of the Bank of Finland and the Eurosystem. All remaining errors are ours.

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[24] We view the longer-run perspective to be complementary to our medium-run modeling approach, which follows the time horizon set forth in China's current five-year plan (2021–2025). A theme of the plan is building China into a self-reliant technological and manufacturing powerhouse (Mallapaty, 2021).

[25] Ultimately, this may lead to a bifurcated economy. One realm ("external circulation") would remain in contact with the rest of the world, while a second realm ("internal circulation") gradually supplants it by cultivating domestic demand, capital, and ideas.

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