GRIPS Discussion Paper 13-01

Japanese Manufacturing Facing the Power Crisis after Fukushima: A Dynamic Computable General Equilibrium Analysis with Foreign Direct Investment

Nobuhiro Hosoe

May 2013

GRIPS
NATIONAL GRADUATE INSTITUTE
FOR POLICY STUDIES

National Graduate Institute for Policy Studies
7-22-1 Roppongi, Minato-ku,
Tokyo, Japan 106-8677

Japanese Manufacturing Facing the Power Crisis after Fukushima:
A Dynamic Computable General Equilibrium Analysis with Foreign Direct Investment

May 7, 2013

Nobuhiro Hosoe*

National Graduate Institute for Policy Studies (GRIPS)

Abstract

The Great East Japan Earthquake and the subsequent tsunami hit and destroyed the Fukushima Daiichi Nuclear Power Station. People lost trust in the safety of nuclear power plants, and the regulatory authority became reluctant to permit power companies to restart their nuclear power plants. To make up for the lost nuclear power supply, thermal power plants started operating more. They consume more fossil fuels, which raises power charges. This power crisis is anticipated to raise energy input costs and to force the domestic manufacturing industries to move out to, for example, China through foreign direct investment (FDI). Using a world trade computable general equilibrium model, with recursive dynamics installed to describe both domestic investment and FDI from Japan to China, we simulate the power crisis by assuming lost capital stock and intensified fossil fuel use by the power sector to investigate its impact on the Japanese manufacturing sectors. We found that the power crisis would adversely affect several sectors that use power intensively but would benefit the transportation equipment, electric equipment, and machinery sectors, despite the common expectation that these sectors would undergo a so-called "hollowing-out."

---

* Corresponding author. 7-22-1 Roppongi, Minato, Tokyo 106-8677, Japan. E-mail: nhosoe@grips.ac.jp.

1. Introduction

The Great East Japan Earthquake (hereinafter, "the earthquake") and the subsequent tsunami that hit the Fukushima Daiichi Nuclear Power Station owned by Tokyo Electric Power Company (TEPCO) in 2011 revealed the vulnerability of the nuclear power stations in Japan to earthquakes and tsunami. People lost trust in the safety of the nuclear power plants, and the regulatory authority became reluctant to permit power companies to restart the nuclear power plants held not only by TEPCO but also other power companies in Japan. To make up for the lost nuclear power supply, the power companies had no choice but to operate thermal power plants with fossil fuels such as coal, petroleum, and liquefied natural gas (LNG) more often. These fuel costs pushed up the power generation costs and, thus, power charges.

Domestic industries are suffering with the increases of their production costs by the power charge rise in addition to the persistent appreciation of the Japanese yen triggered by the European sovereign debt crisis in 2010. This adverse business environment is anticipated to cause relocation of domestic manufacturing industries to other countries, such as China, through foreign direct investment (FDI). While FDI indicates the emergence and integration of the Asian economies, it also symbolizes a fall of the Japanese economy because it is often presumed to cause "hollowing-out" of manufacturing sectors, in which Japan has had a strong comparative advantage.

Empirically, Fukao and Yuan (2001) estimated the impact of FDI on employment among Japanese industries and found that FDI created domestic jobs by exploiting resources and expanding markets abroad while FDI caused domestic job losses by reducing export opportunities and increasing imports from the foreign affiliates. The overall impact on job-creation was found to be negative but not as marked as people often anticipate. Yamazaki and Ochiai (2011), Ishikura and Ishikawa (2011), and Tachi and Ochiai (2011) investigated the impact of the power shortage on the regional economies with a multi-regional static computable general equilibrium (CGE) model for Japan. Tsutsumi (2012)

employed a GTAP-based world trade CGE model to quantify the macroeconomic impact of a power crisis on industrial output but did not examine its impact on the hollowing-out of the Japanese industries to overseas.

From a microeconomic viewpoint, sales and sourcing patterns of foreign affiliates of multinational enterprises (MNEs) are different among industries (Baldwin and Okubo (2012)). Industries like steel may be very susceptible to an energy price rise; others can expand by absorbing resources released by those exiting from Japan. What industries would be adversely affected and move overseas in a power crisis? To identify the industries susceptible to the electric power crisis and quantify its impact on Japanese industries and on Japan's FDI to China, we developed a dynamic world trade CGE model. In this analysis, FDI plays a crucial role in describing the pattern and magnitude of reallocation of capital between Japan and China in reaction to the power crisis. Our simulation analysis shows that the food, pottery, steel, and non-ferrous metal sectors as well as the wood, paper, and printing sectors are expected to decline and that the transportation equipment, electric equipment, and other manufacturing sectors would expand their domestic output in Japan, although people are often concerned about their hollowing-out through FDI due to the power crisis.

This paper proceeds as follows. The next section describes the structure of our CGE model by focusing on a dynamic structure that considers FDI. Our simulation scenarios and results are shown in Section 3. Section 4 is the wrap-up section and discusses the implications of our simulation results, followed by an appendix for the sensitivity analysis with respect to crucial elasticities and by an annex describing the detailed model system.
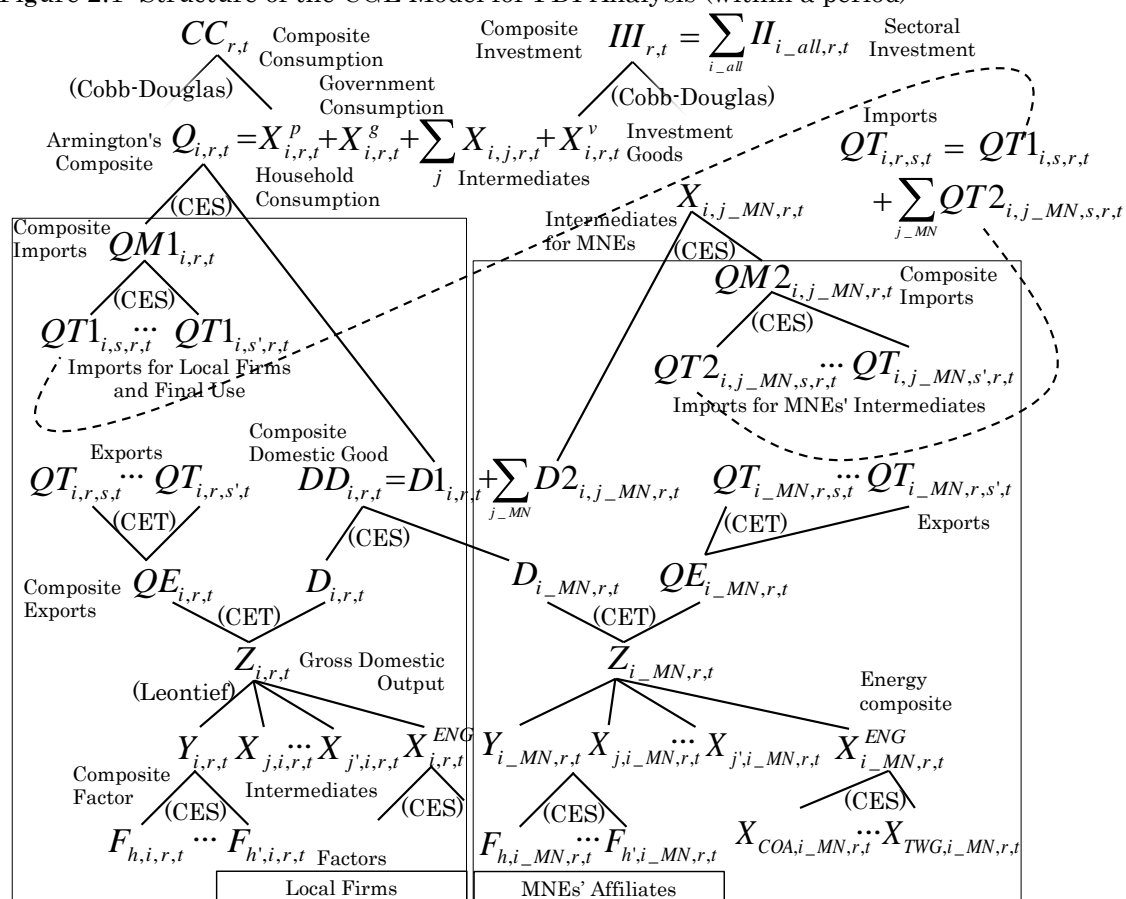
2.   Model

2.1   Structure for Trade Analysis

To quantify the impact of the power crisis on manufacturing sectors and FDI by

Japan, we developed a world trade dynamic CGE model based on the static standard CGE model by Hosoe et al. (2010). There are three regions (Japan, China, and the rest of the world (ROW)) and three primary factors (skilled labor, unskilled labor, and capital) distinguished. The model uses the nested Armington (1969) structure, which is standard for world trade CGE models (Figure 2.1). For a detailed analysis of the electric power shortage, we elaborated the model by describing substitution by various energy sources, such as coal, oil, gas, petroleum and coal product, electricity, and town gas, with a constant elasticity of substitution (CES) aggregation technology.

Figure 2.1: Structure of the CGE Model for FDI Analysis (within a period)

$CC_{r,t}$ Composite Consumption (Cobb-Douglas)

Government Consumption

Composite Investment $III_{r,t} = \sum_{i\_all} II_{i\_all,r,t}$ Sectoral Investment (Cobb-Douglas)

Armington's Composite $Q_{i,r,t} = X^{p}_{i,r,t} + X^{g}_{i,r,t} + \sum_{j} X_{i,j,r,t} + X^{v}_{i,r,t}$

Household Consumption Intermediates Investment Goods

Imports $QT_{i,r,s,t} = QT1_{i,s,r,t} + \sum_{j\_MN} QT2_{i,j\_MN,s,r,t}$

Intermediates for MNEs $X_{i,j\_MN,r,t}$ (CES)

(CES)

Composite Imports $QM1_{i,r,t}$ (CES)

$QT1_{i,s,r,t} \cdots QT1_{i,s',r,t}$ Imports for Local Firms and Final Use

$QM2_{i,j\_MN,r,t}$ Composite Imports (CES)

$QT2_{i,j\_MN,s,r,t} \cdots QT_{i,j\_MN,s',r,t}$ Imports for MNEs' Intermediates

Exports $QT_{i,r,s,t} \cdots QT_{i,r,s',t}$ (CET)

Composite Domestic Good $DD_{i,r,t} = D1_{i,r,t} + \sum_{j\_MN} D2_{i,j\_MN,r,t}$ (CES)

$QT_{i\_MN,r,s,t} \cdots QT_{i\_MN,r,s',t}$ (CET) Exports

Composite Exports $QE_{i,r,t}$ (CET) $D_{i,r,t}$

$D_{i\_MN,r,t}$ (CET) $QE_{i\_MN,r,t}$

$Z_{i,r,t}$ Gross Domestic Output (Leontief)

$Z_{i\_MN,r,t}$

$Y_{i,r,t}$ $X_{j,i,r,t} \cdots X_{j',i,r,t}$ $X^{ENG}_{i,r,t}$ (CES)

Composite Factor Intermediates

$Y_{i\_MN,r,t}$ $X_{j,i\_MN,r,t} \cdots X_{j',i\_MN,r,t}$ $X^{ENG}_{i\_MN,r,t}$ Energy composite (CES)

(CES)

$F_{h,i,r,t} \cdots F_{h',i,r,t}$ Factors

$F_{h,i\_MN,r,t} \cdots F_{h',i\_MN,r,t}$ $X_{COA,i\_MN,r,t} \cdots X_{TWG,i\_MN,r,t}$

Local Firms MNEs' Affiliates

Note: Detailed symbol and equation lists are shown in the Annex.

There are 20 sectors distinguished, among which, only in China, 12 manufacturing sectors are further split into two: those for local firms and those for the Japanese MNEs'

affiliates (Table 2.1). No MNE affiliates operate in either Japan or the ROW; only China hosts MNE affiliates established by Japanese FDI for simplicity. The model structure for Japan and the ROW is conventional; thus, detailed description is made only for China as follows.

Table 2.1: Aggregation of Sector, Region, and Factor

Abbreviation	Sector	Abbreviation	Region
AGR	Agriculture	JPN	Japan
COA[a]	Coal (mining)	CHN	China
OIL[a]	Oil (mining)	ROW	The rest of the world
GAS[a]	Gas (mining)		
FOD, FOD2[b]	Food	Abbreviation	Factor
TXA, TXA2[b]	Textiles and apparel	CAP	Capital
WPP, WPP2[b]	Wood, paper, and printing	SLB	Skilled labor
CHM, CHM2[b]	Chemical	ULB	Unskilled labor
PTC[a], PTC2[b]	Petroleum and coal product		
POT, POT2[b]	Pottery		
STL, STL2[b]	Steel		
NFM, NFM2[b]	Nonferrous metal		
MET, MET2[b]	Metal product		
TEQ, TEQ2[b]	Transport equipment		
EEQ, EEQ2[b]	Electric equipment		
MAN, MAN2[b]	Other manufacturing		
ELY[a]	Electricity (energy)		
TWG[a]	Town gas (energy)		
TRS	Transportation		
SRV	Service		

a: Energy goods used to produce energy composite
b: Sectors hosting Japanese MNEs' affiliates in China

In China, the gross domestic output $Z_{i,CHN,t}$ by the local firms and $Z_{i\_MN,CHN,t}$ by the MNEs' affiliates are respectively transformed into the composite exports $QE_{i,CHN,t}$ and $QE_{i\_MN,CHN,t}$ and the domestic goods $D_{i,CHN,t}$ and $D_{i\_MN,CHN,t}$ with a constant elasticity of transformation (CET) technology, respectively. We assumed these two separate CET structures for the local firms and the MNEs' affiliates reflect their different sales patterns (Table 2.2, the right panel of Figure 2.2). The domestic good produced by the local firms $D_{i,CHN,t}$ and that of the MNEs' affiliates $D_{i\_MN,CHN,t}$ in the corresponding sector, if

any, are combined into a composite domestic good $DD_{i,CHN,t}$ using a CES function, according to the sectoral correspondence between the local and the foreign firms as shown in Table 2.1. For this CES function, we used the elasticity of substitution often assumed for that between imports and domestic goods, following Latorre et al. (2009).

Table 2.2: Sales and Share of Japanese MNEs' Affiliates in Mainland China

Sector	Sales [mil. JPY]	Share [%]
FOD2	566,320	1.0
TXA2	368,773	0.7
WPP2	70,382	0.2
CHM2	761,871	0.9
PTC2	31,756	0.1
POT2	125,163	0.3
STL2	605,860	1.1
NFM2	191,994	0.7
MET2	171,904	0.7
TEQ2	5,338,184	12.7
EEQ2	3,568,637	6.2
MAN2	4,412,727	3.2

Source: METI and GTAP Database.
Note: Abbreviations of sectors are shown in Table 2.1

Figure 2.2: MNE Affiliates' Input and Sales Composition by Origin and Destination [%]
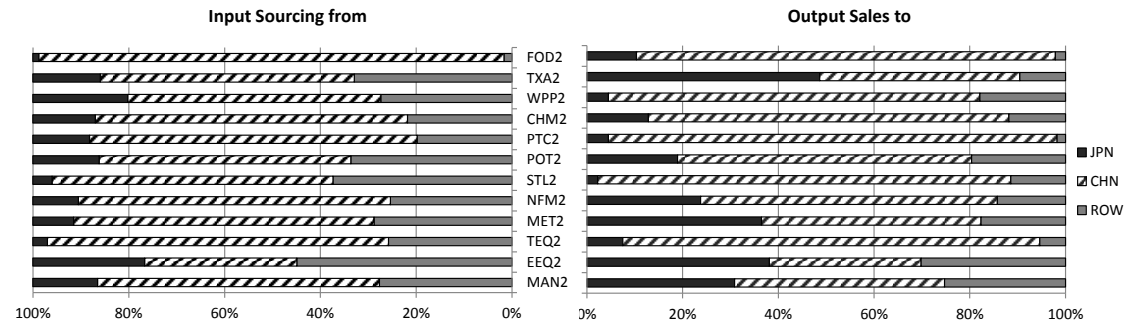
Source: METI, compiled by the author.

The Armington's (1969) composite goods for local firms' intermediate input and final uses are produced by combining the composite imports $QM1_{i,CHN,t}$ and the domestic goods $D1_{i,CHN,t}$. Armington's composites for MNEs' intermediate uses $X_{i,j\_MN,CHN,t}$ are

made separately from the one for local agents' uses $Q_{i,CHN,t}$ to reflect their different sourcing patterns, which indicate the linkages between MNEs' headquarters in Japan and their affiliates established in China (left panel of Figure 2.2).

2.2   Structure for Energy Analysis

To describe substitution among various energy sources (COA, ..., TWG), we assumed an energy composite made from these energy goods with CES technology. The energy composite for the households $X_{r,t}^{pENG}$ appears in the Cobb-Douglas type production function for a composite consumption $CC_{r,t}$ (Figure 2.3); the one for industries $X_{i\_ENG,r,t}^{ENG}$ appears in the Leontief-type production function for all the sectors but the electricity sector (Figure 2.1). The electricity sector uses these energy goods directly with fixed coefficients, not through the energy composite.

Figure 2.3: Household Consumption
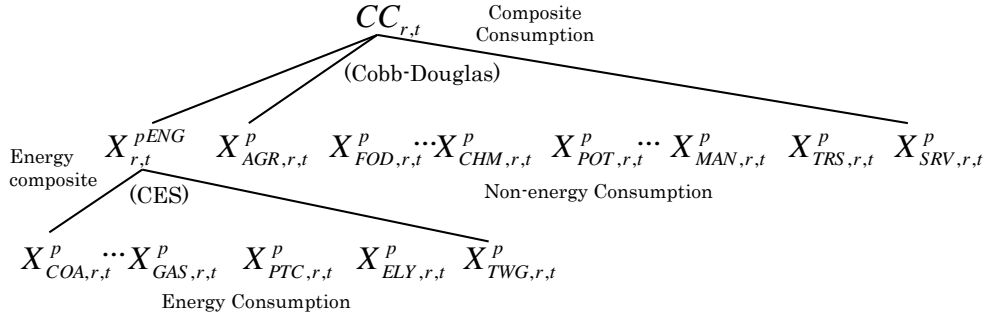
Note: Detailed symbol and equation lists are shown in the Annex.

2.3   Structure for Dynamic Analysis with FDI

We installed recursive dynamics in the static model by Hosoe et al. (2010) in a savings-driven manner. The domestic savings $S_{r,t}^{p}$ are generated with a constant propensity to save in each region ss_{r}^{p} and combined with foreign savings $S_{r,t}^{f}$, which are

exogenous but growing constantly at the rate of pop, to purchase investment goods for the domestic firms $II_{j,r,t}$ and the Japanese MNEs' affiliates (only in China) $II_{j\_MN,CHN,t}$ (Figure 2.4). We assumed a putty-clay type model for investment.

Figure 2.4: Dynamic Model Structure for the j-th Sector in Japan
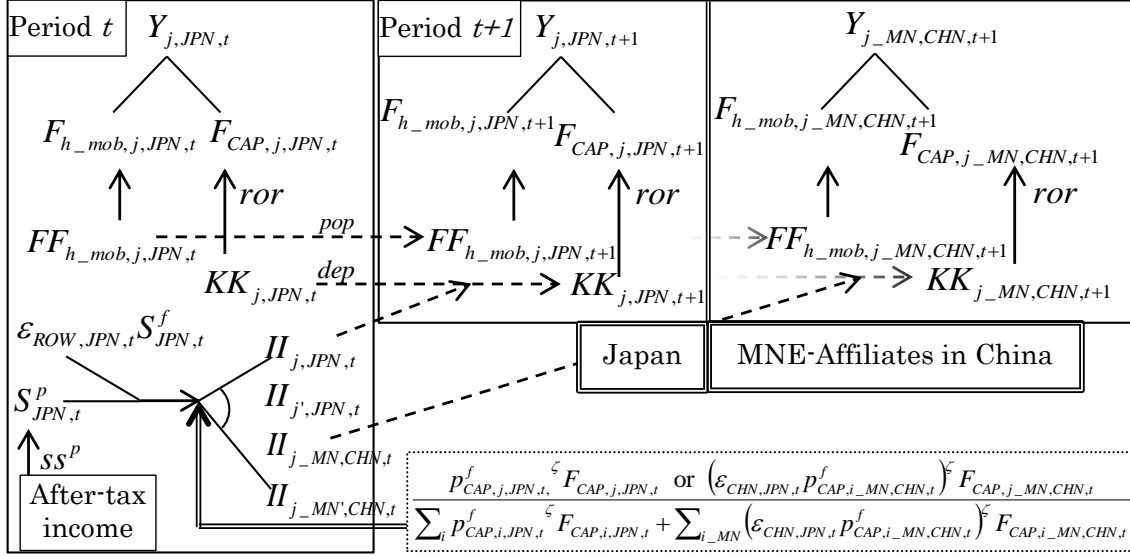
Note: Detailed symbol and equation lists are shown in the Annex.

The fund for investment is allocated among sectors according to the share of their expected sectoral operating surplus $\hat{p}_{CAP,j,r,t}^{f}{}^{\zeta}\,\hat{F}_{CAP,j,r,t}$ or $\hat{\varepsilon}_{s,r,t}\,\hat{p}_{CAP,j\_MN,s,t}^{f}{}^{\zeta}\,\hat{F}_{CAP,j\_MN,s,t}$.[2] These values are replaced with the observed (or solved) ones for the current period by assuming myopic expectations as shown in Figure 2.4. The composite investment goods (or new capital) $III_{JPN,t}$ are made from various investment goods $X_{i,r,t}^{v}$ with a Cobb-Douglas type production technology and used for the sectoral investment $II_{j\_all,r,t}$. The sectoral

---

[2] ζ is a weight parameter for the capital service price (or the rate of returns of capital) $p_{CAP,\bullet,r,t}^{f}$. A larger value for ζ accelerates convergence of capital service prices among sectors, which can deviate from each other in the short run as we assume putty-clay type capital. In this simulation, we assume ζ =1. $\varepsilon_{s,r,t}$ denotes an exchange rate converting the s-th currency into the r-th one.

investment for the MNEs' affiliates in China $II_{j\_MN,CHN,t}$ accumulates capital stocks

$KK_{j\_MN,CHN,t}$ while these MNE sectors employ local labor forces in China.

There are various types of FDI proposed in the theories. One is horizontal FDI, in which a firm establishes its affiliates located close to their local customers to save transportation costs or to avoid high trade barriers. Another is vertical FDI, in which a firm locates its affiliates abroad for cheap input (often labor) and imports the finished goods or parts back home. FDI becomes more complicated in the multi-country setup, such as export-platform FDI, complex FDI (Yeaple (2003)), and networked FDI (Baldwin and Okubo (2012)). While they assumed a detailed FDI strategy in a specific context, we described FDI, as a rule of thumb, by assuming the above-mentioned rule for new capital allocation as well as the nested Armington (1969) structure in our CGE model. Our model can depict the mixture of those patterns of cross-border investment, sales, and sourcing.

2.4 Model Estimation

Our model was calibrated to the GTAP Database version 8 for 2007 (Hertel (1997)). We assumed a business-as-usual (BAU) growth path driven by a population growth rate (pop =2%), a rate of returns of capital (ror =10%), and a depreciation rate (dep =4%). Because the composite investment and the sectoral capital service input recorded in the GTAP database are not consistent with the amount of investment required to achieve that assumed growth path, we adjusted the investment and government consumption data so that our desired BAU growth path was generated, following Ban (2007).[3]

The data for the Japanese MNEs' affiliates in China were obtained from *Survey of Overseas Business Activities* by METI for 2007 (Table 2.2, Figure 2.2). They were used to split the Chinese manufacturing sectors, originally reported in the GTAP database, into the Chinese local sectors (FOD, …, MAN) and the MNEs' affiliate sectors (FOD2, …, MAN2),

---

[3] See, Hosoe (2012) for details.

following Latorre et al. (2009). The Armington (1969) elasticities were obtained from the GTAP Database while the elasticity of substitution among various energy sources was assumed at 0.9.[4]

3.   Simulation

3.1   Simulation Scenario

We simulated the power shortage caused by the earthquake and the subsequent nuclear power accident. We assumed (1) productivity declines of the electric power sector in Japan due to the increase of its fuel input requirement by 100% for petroleum input and 20% for coal and LNG input to substitute thermal for nuclear power and (2) the loss of capital stock in this electricity sector by 5%. This approximates the fraction of the nuclear capacity destroyed by the earthquake and the tsunami or forced to be idle for safety reasons to protect against further possible natural disasters.[5]

Incidentally, Ishikura and Ishikawa (2011) and Tsutsumi (2012) simulated the power shortage by assuming a decline of total factor productivity of the electric power sector. Yamazaki and Ochiai (2011) assumed a reduction of factor inputs that were physically hindered from operating by the scheduled blackout. Tachi and Ochiai (2011) manipulated the amount of the sector-specific input for the power sectors to simulate the idle nuclear power plants and their substitution by thermal ones.

---

[4] Sensitivity analysis was conducted with respect to these elasticities. Its results are shown in the Appendix.

[5] TEPCO's fuel consumption during August 2011–July 2012 increased by 118% for heavy oil, 85% for crude oil, 19% for liquefied natural gas, and 15% for coal compared with that during March 2010-February 2011. <URL: http://www.tepco.co.jp/tepconews/pressroom/consumption-j.html> TEPCO's financial report shows that the nuclear capacity constitutes 5.7% of its total assets for fiscal 2010.

3.2   Simulation Results

Our simulation showed that the power crisis would affect the Japanese economy in the following three ways. One would be through a household income reduction partly due to the lost or idle capital stock and partly due to the overall efficiency deterioration in Japanese industries through the power charge rises. This would adversely affect FOD, as food has the second largest share of household consumption (Figure 3.1). The second shock would occur in the fuel consumption patterns of ELY. As nuclear power plants are unavailable, uses of the fossil fuels would be intensified for power generation. This would significantly increase demand for PTC and other energy sectors.

Figure 3.1: Output of Manufacturing Sectors [Deviations from the BAU, %]
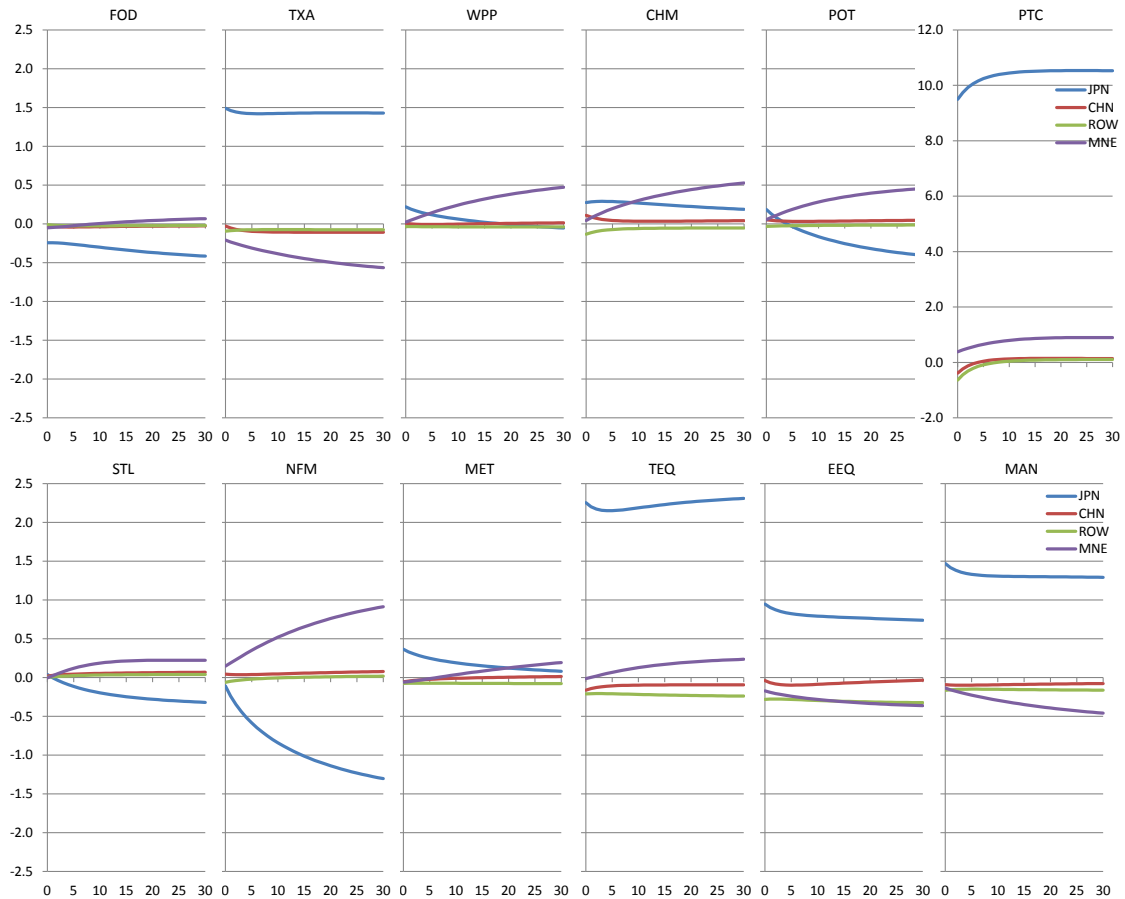
The third shock would be an indirect one through the raised power charges. This impact explains the changes in the other ten sectors, which can be divided into three groups.

One group consists of heavy power eaters (POT, STL, and NFM). They would suffer so seriously from the increase in power charges that their output could be reduced. The second group consists of moderate power eaters (WPP and MET). Their production would show a temporal expansion just after the shock but, then, a slowdown toward the BAU level. The third group of light power eaters (TXA, CHM, TEQ, EEQ, and MAN) would benefit from the crisis. They could use more domestic resources, released by the declining sectors, and increase their output. Although CHM falls in the bin of the moderate power eaters considering its electricity input intensity, it would not significantly suffer from the power charge rise owing to its tight forward linkage to these other expanding sectors.

The contraction of WPP, POT, STL, and NFM in Japan would be accompanied by the expansion of their foreign affiliates in China (Figure 3.2). TEQ would not only increase its domestic output but also expand its business further by accelerating FDI. Its increase of FDI would not cause any "hollowing-out" of this industry. EEQ and MAN, as well as TXA, would also find better business environments in Japan despite the power shortage, and they would decrease their FDI to have their foreign affiliates return home. The evolution of output of EEQ, MAN, and TXA shows that their output would be complementary to that of their foreign affiliates. That is, their FDI appears to be vertical. This is consistent with their sales-sourcing patterns showing their tight linkages between Japan and China (Figure 2.2).

Figure 3.2: Sectoral FDI by the MNEs' Affiliates [Deviations from BAU, %]
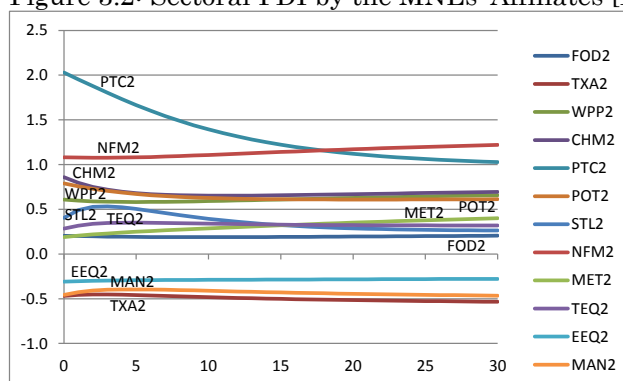
These impacts on local Japanese firms and foreign affiliates would also affect the Chinese economy. The relocation of Japanese industries to China through FDI would cause more severe competition between the Chinese local firms and the Japanese MNEs' affiliates for such resources as primary factors and investment goods in China. The competition would raise prices of local factors and goods in China. The Chinese local firms cannot relocate despite their price rises; however, Japanese MNEs' affiliates have the option to relocate back to Japan as observed for TXA, EEQ, and MAN (Figure 3.2).

In a long run, the output of heavy power users (WPP, POT, STL, and NFM) would be replaced with imports from their foreign affiliates or foreign local suppliers (Table 3.1). Light power users (TXA, EEQ, and MAN) would move back home to exploit the cheaper primary factor prices in Japan. The impact on CHM, MET, and TEQ would be complex. While they would increase their output and exports thanks to the cheaper primary factor prices, they would accelerate their FDI. The FDI by CHM and MET appears to be vertical FDI as both imports and exports would be increased. The large share of MNEs' sales to Japan, especially in MET, would enable further supply chain fragmentation by FDI in China under the power crisis (Figure 2.2). TEQ would also increase its output, exports, and FDI but would decrease its imports because the output of TEQ2 is shipped mostly to the Chinese local market.

Table 3.1: Summary of the Long-run Impact on Japanese Manufacturing

	Output	FDI	Exports	Imports	Note
FOD	-	+	+	-	Domestic income loss
TXA	+	-	+	-	Moving back home
WPP	-	+	+	-	Moving out
CHM	+	+	+	+	
PTC	+	+	+	+	Fossil fuel demand
POT	-	+	-	+	Moving out
STL	-	+	-	+	Moving out
NFM	-	+	-	+	Moving out
MET	+	+	+	+	
TEQ	+	+	+	-	
EEQ	+	-	+	-	Moving back home
MAN	+	-	+	-	Moving back home

Note: Signs indicate the deviations from the BAU path in t =30.

3.3 Sensitivity of Simulation Results

The simulation results can vary depending on our assumptions for some key parameters, especially elasticity of substitution. When we assumed 30% larger elasticity for the Armington elasticity than that assumed in the central case shown in Section 3.2, little qualitative difference was found.[6] The 30% smaller elasticity case showed qualitatively similar evolution of output to that in the central case in all the sectors but STL and POT (Figure 3.3). Although these two sectors would severely decline in the central case, this smaller elasticity case does not predict their declines, thanks to a high degree of difference between their products and foreign ones, which is represented by this small elasticity. This suggests that product differentiation could provide good survivability to these Japanese manufacturing sectors even with the adverse business environment due to the power crisis.[7]

---

[6] Details are shown in the Appendix.

[7] Indeed, we install difference of products between origins by Armington's (1969) assumption in our CGE model but do not install any structure describing product differentiation à la Dixit and Stiglitz (1977).

Figure 3.3: Output of Manufacturing Sectors with Alternative Elasticity (30% Smaller Armington Elasticity) [Deviations from the BAU, %]
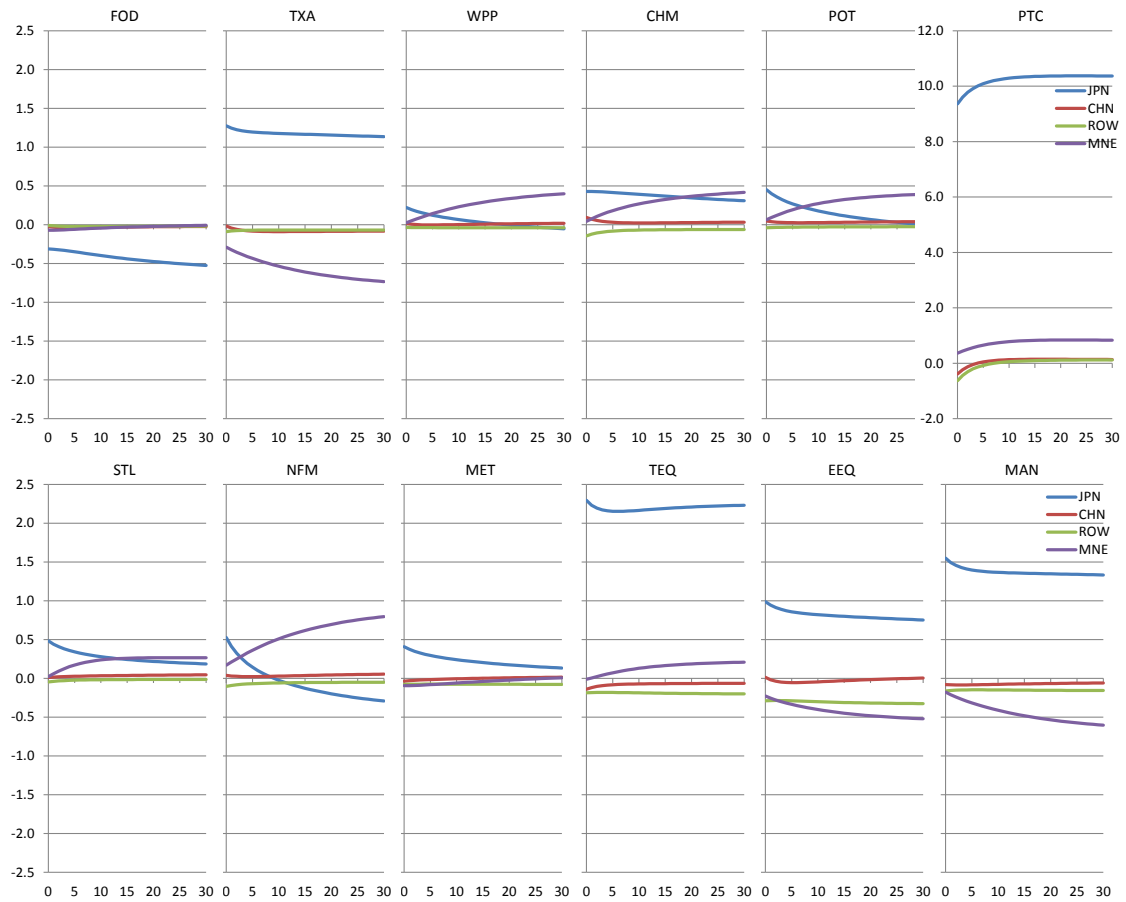
We conducted the same simulations alternatively assuming 0.5 and 0.9 for the elasticity of substitution among various energy sources σ^e. They showed qualitatively similar results. This implies that even if we succeed in investing in technologies that allow 44% larger flexibility in terms of the elasticity of substitution between electricity and other energy sources, we are not likely to be able to avoid contraction of those power eaters identified in Section 3.2.[8]

---

[8] We assumed these alternative elasticities for all the three countries/regions in our sensitivity analysis. Even if we assumed those alternative elasticities only for Japan, the conclusion is affected little.

4.   Conclusion

Our simulation showed that the power crisis would decrease the output of heavy power-using sectors (wood, paper and printing, pottery, steel, and non-ferrous metal) and the food sector in Japan and would accelerate their FDI. In this sense, hollowing-out in these sectors would indeed be a serious problem. In contrast, there would be sectors (textiles and apparel, transportation equipment, electric equipment, and other manufacturing) increasing their output by employing more factors released by those declining sectors. People anticipate and are concerned about hollowing-out in such key industries as the transportation equipment and electric equipment sectors as well as the machinery sector (this is included in the other manufacturing sector (MAN) in our model). However, these sectors would not experience any hollowing-out but would increase their output markedly.

In our simulation, we assumed a power crisis only in Japan, but China also suffers from similar power shortages due to its poor power system management. Anti-Japan movements in 2012 have caused Japanese MNEs to realize a so-called "China risk" in their international businesses and have discouraged them from investing (only) in China further. The MNEs can trigger withdrawals of their FDI from China, or accelerate the movement of their FDI to other countries. Further general equilibrium analysis can be done in this regard by installing a similar FDI mechanism in the model not only for FDI from Japan to China but also for that among Japan, China, and a third country.

Acknowledgements

References

Armington, P. (1969) "A Theory of Demand for Products Distinguished by Place of Production," *IMF Staff Papers* 16(1), 159–178.

Baldwin, R., Okubo, T. (2012) "Networked FDI: Sales and Sourcing Patterns of Japanese Foreign Affiliates," *RIETI Discussion Paper Series* 12-E-027, Research Institute of Economy, Trade and Industry, Tokyo.

Ban, K. (2007) "Nihon-keizai-no Tachiiki-dogaku-teki Oyo-ippan-kinko-moderu-no Kaihatsu [Developing a Multi-regional Dynamic Computable General Equilibrium Model for Japan]," *RIETI Discussion Paper* 07-J-043, Research Institute of Economy, Trade and Industry, Tokyo.

Dixit, A., Stiglitz, J. E. (1977) "Monopolistic Competition and Optimum Product Variety," *American Economic Review* 67(3), 297–308.

Fukao, K., Yuan, T. (2001) "Nihon-no Taigai-chokusetsu-toshi-to Kuudo-ka [Japanese Foreign Direct Investment and the Hollowing-out]," *RIETI Discussion Paper* 01-J-003 (in Japanese).

Hertel, T. W., (1997) *Global Trade Analysis: Modeling and Applications*, Cambridge.

Hosoe, N. (2012) "Note on a World Trade Recursive Dynamic CGE Model," mimeo.

Hosoe, N., Gasawa, K., Hashimoto, H. (2010) *Textbook of Computable General Equilibrium Modelling: Programming and Simulations*, Palgrave Macmillan.

Ishikura, T., Ishikawa, Y. (2011) "Higashi-nihon-daishinsai-ni-tomonau Hatsudensho-hisai-ga-motarasu Denyoku-kiki-to Hakyu-teki-higai [The Power Crisis by the Damages of the Great East Japan Earthquake to Power Stations and the Resulting Impact]," *Sangyo Renkan* 19(3), 51–59 (in Japanese).

Latorre, M. C., Bajo-Rubio, O., Gómez-Plana, A. G. (2009) "The Effects of Multinationals on Host Economies: A CGE Approach," *Economic Modelling* 26(5), 851–864.

Ministry of Economy, Trade and Industry (METI), *Survey of Overseas Business Activities*. http://www.meti.go.jp/english/statistics/tyo/kaigaizi/index.html

Tachi, Y., Ochiai, K. (2011) "Genshi-ryoku-hatsuden-zen-teishi-ni-yoru Chiiki-sangyobetsu-eikyo-no Shisan [Estimating Regional and Sectoral Impacts of Nuclear Power Plants Shutdown]," *JCER Discussion Paper* No. 132, Japan Center for Economic Research (in Japanese).

Tsutsumi, M. (2012) "CGE Moderu-ni-yoru Denryoku-kyokyu-seiyaku-no Eikyo-shisan [A CGE Analysis of the Impact of the Power Shortage]," *Keizai-zaisei-bunseki Discussion Paper* DP/12-02, Economic Research Bureau, Cabinet Office, Government of Japan (in Japanese).

Yamazaki, M., Ochiai, K. (2011) "Higashi-nihon-daishinsai Oyobi Kanto-chiho-ni-okeru Denryoku-seiyaku-no Keizaieikyo [Economic Impact of the Great East Japan Earthquake and the Power Shortage in Kanto-area]," *JCER Discussion Paper* No. 131, Japan Center for Economic Research (in Japanese).

Yeaple, S. R. (2003) "The Complex Integration Strategies of Multinationals and Cross Country Dependencies in the Structure of Foreign Direct Investment," *Journal of International Economics* 60(2), 293–314.

Appendix   Sensitivity Analysis

As is often the case with CGE simulation analysis, our simulation results depend on the assumptions for key parameters, especially elasticity of substitution/transformation in CES/CET functions. To examine the robustness of our results, we conducted a sensitivity analysis with respect to these elasticities. We alternatively assumed 30% smaller or larger elasticity of substitution for the Armington (1969) functions. The larger elasticity case yielded results quantitatively smaller than but qualitatively similar to those in the central case shown in the main text (Figure A.1). In contrast, the smaller elasticity case showed some qualitative exceptions for POT and STL (Figure 3.3). Although they are heavy power eaters and, thus, expected to be adversely affected by the power crisis in the central case, they could avoid their contraction in this smaller elasticity case as discussed in Section 3.3.

Figure A.1: Output of Manufacturing Sectors with Alternative Elasticity (30% Larger Armington Elasticity) [Deviations from the BAU, %]
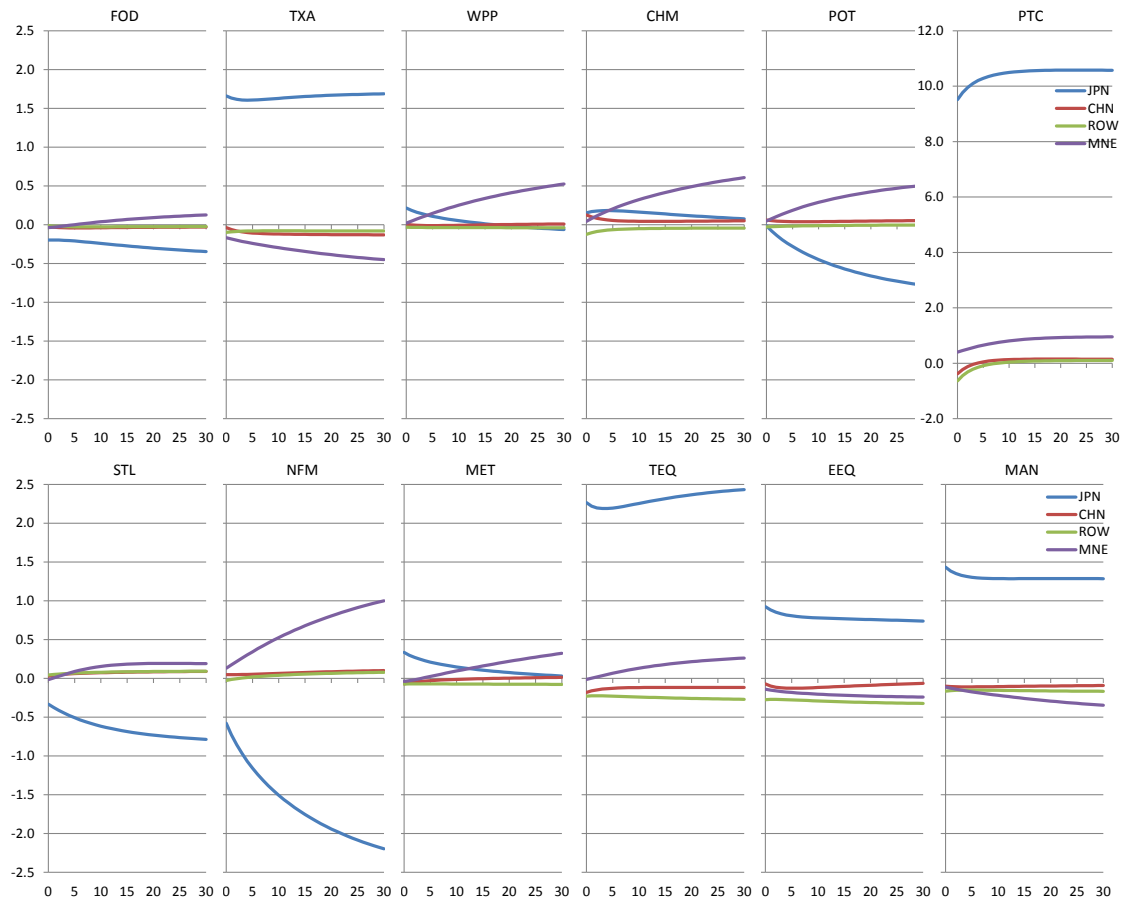
The other crucial parameter is the elasticity of substitution for the energy composite, which describes flexibility of substitution among various energy sources. The two alternative cases with σ^e =0.5 and 1.3 show that the impact of the power crisis is similar to that found in the central case (Figures A.2–A.3).

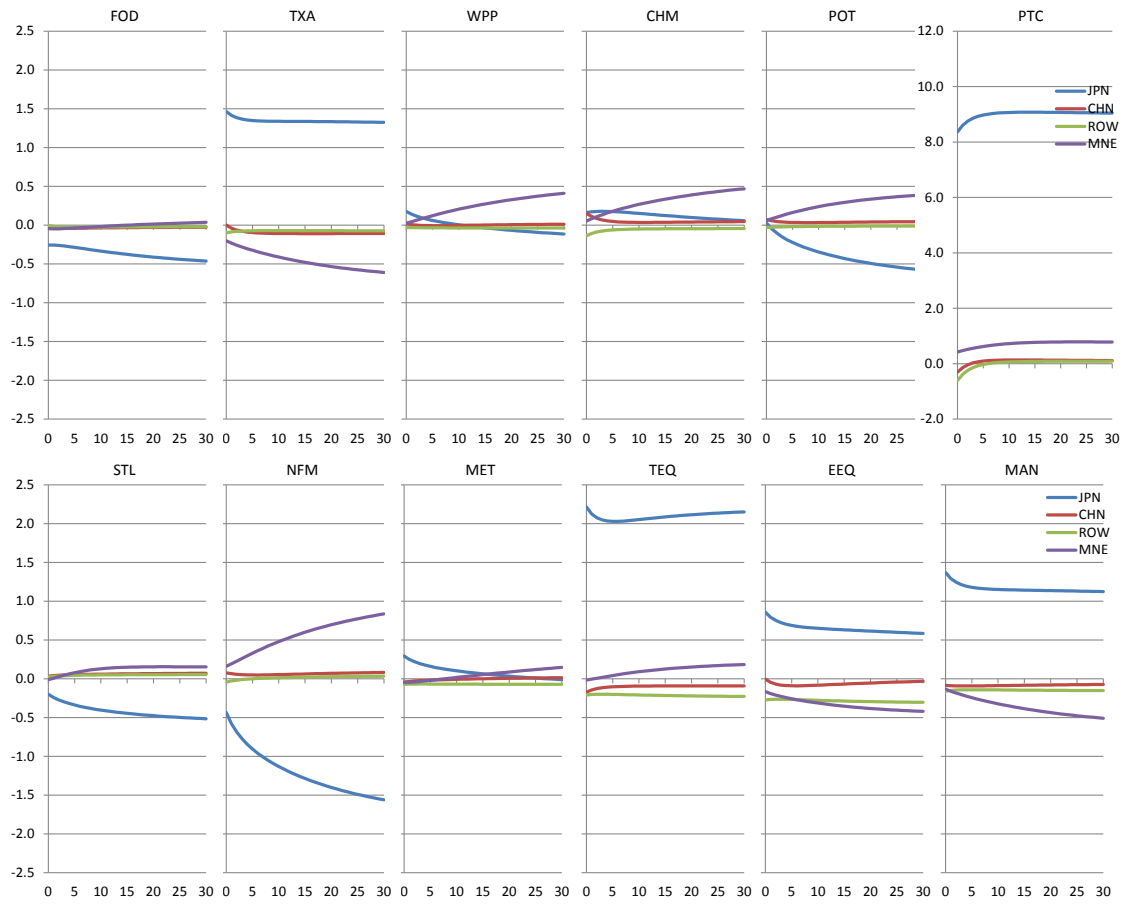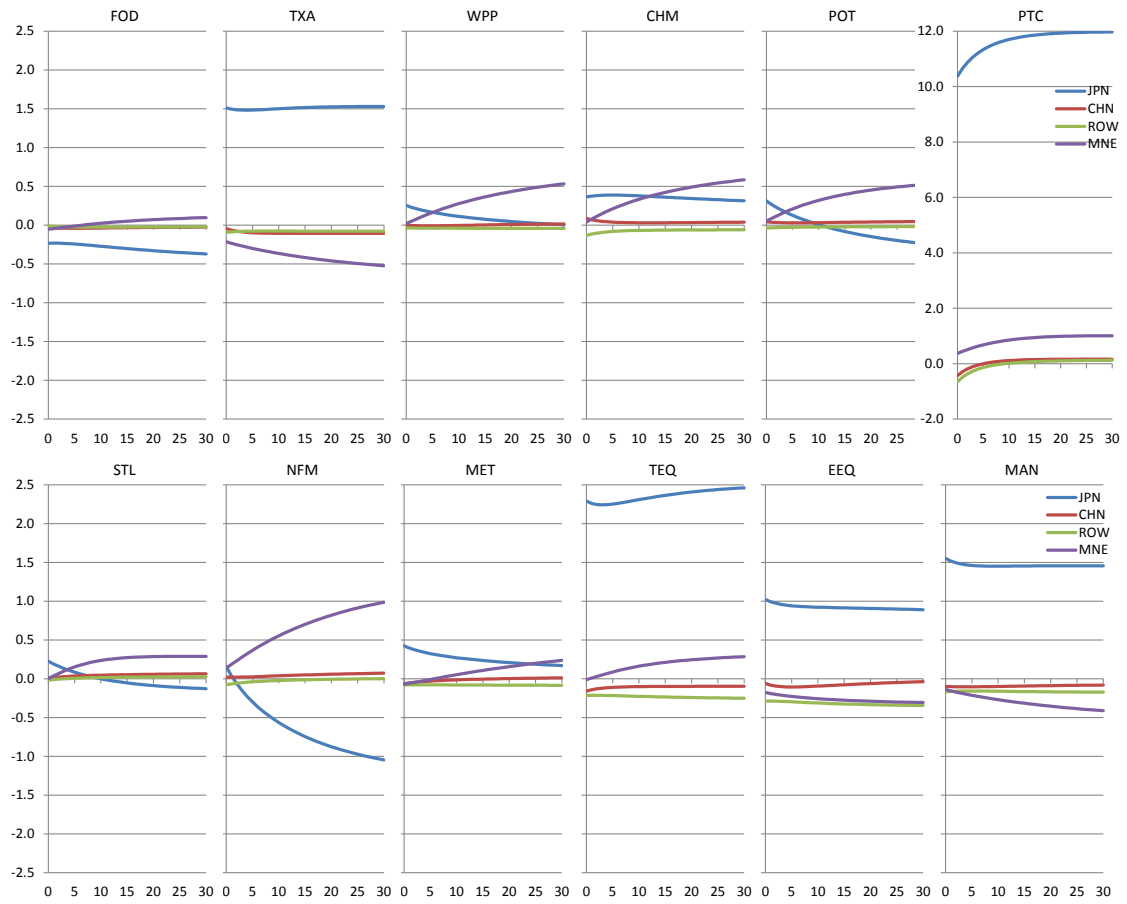Figure A.2: Output of Manufacturing Sectors with Alternative Elasticity (σ^e =0.5) [Deviations from the BAU, %]

Figure A.3: Output of Manufacturing Sectors with Alternative Elasticity (σ^e =1.3) [Deviations from the BAU, %]

Annex   Details of the Model

The index t representing time periods is omitted in the following symbol and equation lists for simplicity as long as no confusion can occur.

Sets

i_all, j_all sectors

$$\{AGR,...,GAS,FOD,...,MAN,FOD2,...,MAN2,ELY,...,SRV\}$$

i, j sectors not hosting MNEs

$$\{AGR,...,GAS,FOD,...,MAN,ELY,...,SRV\}$$

i_MN, j_MN manufacturing sectors hosting MNEs

$$\{FOD2,...,MAN2\}$$

i_nonMN, j_nonMN manufacturing sectors competing with MNEs

$$\{FOD,...,MAN\}$$

i_ENG, j_ENG energy sectors $\{COA,...,GAS,PTC,ELY,TWG\}$

i_nonELY, j_nonELY non-electricity sectors

i_nonENG, j_nonENG non-energy sectors

$i\_MAP(i,i\_all), j\_MAP(i,i\_all)$ MNE-local firms' aggregation

$$\{AGR.AGR\},$$

$$...,$$

$$\{GAS.GAS\},$$

$$\{FOD.(FOD,FOD2)\},$$

$$...,$$

$$\{MAN.(MAN,MAN2)\},$$

$$\{ELY.ELY\},$$

$$...,$$

$$\{SRV.SRV\}$$

h,k	factors	$\{CAP, SLB, ULB\}$
h_mob	mobile factors	$\{SLB, ULB\}$
t	time period	$\{0, 1, 2, ..., 30\}$

Endogenous variables

$Y_{j\_all,r}$	composite factor
$F_{h,j\_all,r}$	factor input
$X_{i,j\_all,r}$	intermediate input
$X^{ENG}_{j\_all,r}$	energy composite for intermediates
$Z_{j\_all,r}$	gross domestic output (local firms and MNE affiliates)
$DD_{j,r}$	composite domestic good
$X^{p}_{i,r}$	household consumption
X^{pENG}_{r}	household energy composite consumption
$X^{v}_{i,r}$	investment demand
$QE_{i\_all,r}$	composite exports
$QM1_{i,r}$	composite imports for local firms' intermediate and final uses
$QM2_{i,j\_MN,r}$	composite imports for MNEs
$Q_{i,r}$	Armington's composite good
$D_{i,r}$	domestic good for local firms and final uses
$D2_{i,j\_MN,r}$	domestic good for MNEs' intermediate

$p_{h,j\_all,r}^{f}$ factor price

$p_{j\_all,r}^{y}$ composite factor price

$p_{j\_all,r}^{z}$ supply price of gross domestic output

$p_{j,r}^{dd}$ supply price of composite domestic good

$p_{i,r}^{q}$ Armington's composite good price

$p_{i,j\_MN,r}^{q2}$ Armington's composite good price for MNEs' intermediate

$p_{j\_all,r}^{xENG}$ energy composite price for intermediate

p_{r}^{xpENG} energy composite price for household consumption

$p_{i\_all,r}^{qe}$ composite export price in local currency

$p_{i,r}^{qm1}$ composite import price for local firms' intermediate and final

uses in local currency

$p_{i,j\_MN,r}^{qm2}$ composite import price for MNEs' intermediate in local currency

$p_{i\_all,r}^{d}$ domestic good price

$\varepsilon_{r,s}$ exchange rate converting r-th currency into s-th currency

$QT_{i\_all,r,s}$ imports or exports from r-th region to s-th region

$QT1_{i\_all,r,s}$ imports used by local firms and final uses

$QT2_{i,j\_MN,r,s}$ imports used by MNEs

$p_{i,r,s}^{qt}$ import or export price of $QT_{i,r}$, $QT1_{i\_all,r,s}$,

and $QT2_{i\_nonMN,r,s}$

S_{r}^{p} private savings

T_{r}^{d} direct tax revenue

$T^z_{j\_all,r}$ production tax revenue

$T^f_{h,j\_all,r}$ factor input tax revenue

$T^e_{i\_all,r,s}$ export tax revenues

$T^m_{i\_all,r,s}$ import tariff revenue

$QTS_{i,r}$ export of international transport services

QQT composite international transport services

p^{qqt} price of QQT

p^k_r investment goods or capital stock price

$II_{j\_all,r}$ sectoral investment

III_r composite investment goods (or new capital)

$FDI_{r,s}$ foreign direct investment from r to s

$PRICE_r$ price index

CC_r composite consumption (or regional felicity)

State or exogenous variables

$KK_{j\_all,r}$ capital stock

$FF_{h,j\_all,r}$ factor endowment (originally) used by the j-th sector

$Q^{00}_{i,r}$ base-year value of $Q_{i,r}$

$X^g_{i,r}$ government consumption

S^f_r foreign savings in the USD

τ^d_r direct tax rate

$\tau^{z}_{i\_all,r}$ production tax rate

$\tau^{f}_{h,j\_all,r}$ factor input tax rate

$\tau^{m}_{i\_all,r,s}$ import tariff rate

$\tau^{e}_{i\_all,r,s}$ export tax rate

$\tau^{s}_{i\_all,r,s}$ international transport service requirement

Parameters

$\sigma^{d}_{i\_all}$ elasticity of substitution/transformation between domestic and composite imports/exports

$\sigma^{m}_{i\_all}$ elasticity of substitution/transformation among import origins/export destinations

$\sigma^{y}_{j\_all,r}$ elasticity of substitution among primary factors

σ^{e}_{r} elasticity of substitution among energy sources

ζ price sensitivity parameter of investment allocation

pop population growth rate

ror rate of returns

dep depreciation rate

ss^{p} propensity to save by household

Composite factor production

$$Y_{j\_all,r} = b_{j\_all,r}\left[\beta_{h,j\_all,r} F_{h,j\_all,r}^{(\sigma^{y}_{j\_all}-1)/\sigma^{y}_{j\_all}}\right]^{\sigma^{y}_{j\_all}/(\sigma^{y}_{j\_all}-1)}, \qquad \forall j\_all, r$$

$$F_{h,j\_all,r} = \left[\frac{b_{j\_all,r}^{(\sigma^{y}_{j\_all}-1)/\sigma^{y}_{j\_all}} \beta_{h,j\_all,r} p^{y}_{j\_all,r}}{\left(1+\tau^{f}_{h,j\_all,r}\right) p^{f}_{h,j\_all,r}}\right]^{\sigma^{y}_{j\_all,r}} Y_{j\_all,r}, \qquad \forall h, j\_all, r$$

Gross domestic output

$$X_{i\_nonENG,j\_nonELY,r} = ax_{i\_nonENG,j\_nonELY,r} Z_{j\_nonELY,r}, \qquad \forall i\_nonENG, j\_nonELY, r$$

$$X_{i\_all,ELY,r} = ax_{i\_all,ELY,r} Z_{ELY,r}, \qquad \forall i\_all, r$$

$$X_{j\_nonELY,r}^{ENG} = ax_{j\_nonELY,r}^{ENG} Z_{j\_nonELY,r}, \qquad \forall j\_nonELY, r$$

$$Y_{j\_all,r} = ay_{j\_all,r} Z_{j\_all,r}, \qquad \forall j\_all, r$$

$$p_{j\_nonELY,r}^{z} = ay_{j\_nonELY,r} p_{j\_nonELY,r}^{y} + \sum_{i\_nonENG} ax_{i\_nonENG,j\_nonELY,r} p_{i,r}^{q} + ax_{j\_nonELY,r}^{ENG} p_{j\_nonELY,r}^{xENG},$$

$$\forall j\_nonELY, r$$

$$p_{ELY,r}^{z} = ay_{ELY,r} p_{ELY,r}^{y} + \sum_{i} ax_{i,ELY,r} p_{i,r}^{q}, \qquad \forall r$$

$$p_{j\_MN,r}^{z} = ay_{j\_MN,r} p_{j\_MN,r}^{y} + \sum_{i\_nonENG} ax_{i\_nonENG,j\_MN,r} p_{i\_nonENG,j\_MN,r}^{q2} + ax_{j\_MN}^{ENG} p_{j\_MN,r}^{xENG},$$

$$\forall j\_MN, r$$

Energy composite for intermediate uses

$$X_{j\_nonELY,r}^{ENG} = \chi 1_{j\_nonELY,r} \left[\sum_{i\_ENG} \chi 2_{i\_ENG,j\_nonELY,r} X_{i\_ENG,r}^{(\sigma_r^e - 1)/\sigma_r^e} \right]^{\sigma_r^e/(\sigma_r^e - 1)}, \quad \forall j\_nonELY, r$$

$$X_{i\_ENG,j\_nonELY,r} = \left[\frac{\chi 1_{j\_nonELY,r}^{(\sigma_r^e - 1)/\sigma_r^e} \chi 2_{i\_ENG,j\_nonELY,r} p_{i\_ENG,r}^{xENG}}{p_{i\_ENG,r}^{q}} \right]^{\sigma_r^e} X_{j\_nonELY,r}^{ENG},$$

$$\forall i\_ENG, j\_nonELY, r$$

Energy composite for household consumption

$$X_r^{pENG} = a2_r \left[\sum_{i\_ENG} \alpha 2_{i\_ENG,r} X_{i\_ENG,r}^{p \, (\sigma_r^e - 1)/\sigma_r^e} \right]^{\sigma_r^e/(\sigma_r^e - 1)}, \quad \forall r$$

$$X_r^{pENG} = \left[\frac{a2_r^{(\sigma_r^e - 1)/\sigma_r^e} \alpha 2_{i\_ENG,r} p_{i\_ENG,r}^{xpENG}}{p_{i\_ENG,r}^{q}} \right]^{\sigma_r^e} X_r^{pENG}, \qquad \forall i\_ENG, j\_nonELY, r$$

Domestic good aggregation

$$DD_{j,r} = c1_{j,r} \left[\sum_{j\_all \in j\_MAP(j,j\_all)} c2_{j,j\_all,r} D_{j\_all,r}^{(\sigma_j^d - 1)/\sigma_j^d} \right]^{\sigma_j^d/(\sigma_j^d - 1)}, \qquad \forall j, r$$

$$D_{j\_all,r} = \left[\frac{c1_{j,r}^{(\sigma_j^d - 1)/\sigma_j^d} p_{j,r}^{dd} c2_{j,j\_all,r}}{p_{j\_all,r}^d} \right]^{\sigma_j^d} DD_{j,r}, \qquad \forall j, r, j\_all \in j\_MAP(j,j\_all)$$

Government

$$T_r^d = \sum_i p_{i,r}^q X_{i,r}^g - \left(\sum_{j\_all,s} T_{j\_all,s,r}^z + \sum_{j\_all} T_{j\_all,r}^m + \sum_{h,j\_all} T_{h,j\_all,r}^f + \sum_{j\_all,s} T_{j\_all,r,s}^e \right), \qquad \forall r$$

$$T_{j\_all,r}^z = \tau_r^z p_{j\_all,r}^z Z_{j\_all,r}, \qquad \forall j\_all, r$$

$$T_{h,j\_all,r}^f = \tau_{h,j\_all,r}^f p_{h,j\_all,r}^f F_{h,j\_all,r}, \qquad \forall h, j\_all, r$$

$$T_{i\_all,r,s}^m = \tau_{i\_all,r,s}^m \left[\left(1 + \tau_{i\_all,r,s}^e \right) \varepsilon_{r,s} p_{i\_all,r,s}^{qt} + \tau_{i\_all,r,s}^s p^{qqt} \varepsilon_{ROW,s} \right] QT_{i\_all,r,s}, \quad \forall i\_all, r, s$$

$$T_{i\_all,r,s}^e = \tau_{i\_all,r,s}^e p_{i\_all,r,s}^{qt} QT_{i\_all,r,s}, \qquad \forall i\_all, r, s$$

Investment and savings

$$p_{i,r}^q X_{i,r}^v = \lambda_{i,r} p_r^k III_r, \qquad \forall i, r$$

$$III_r = \iota_r \prod_i X_{i,r}^{v^{\lambda_{i,r}}}, \qquad \forall r$$

$$S_r^p = \begin{cases} ss_r^p \left(\sum_{h,j} p_{h,j,r}^f F_{h,j,r} + \sum_{j\_MN} \varepsilon_{CHN,r} p_{CAP,j\_MN,CHN}^f F_{CAP,j\_MN,CHN} - T_r^d \right), & r = JPN \\ ss_r^p \left(\sum_{h,j} p_{h,j,r}^f F_{h,j,r} + \sum_{h\_mob,j\_MN} p_{h\_mob,j\_MN,r}^f F_{h\_mob,j\_MN,r} - T_r^d \right), & r = CHN \\ ss_r^p \left(\sum_{h,j} p_{h,j,r}^f F_{h,j,r} - T_r^d \right), & r = ROW \end{cases}$$

FDI from Japan to China in USD

$$FDI_{JPN,CHN} = \sum_{i\_MN} \varepsilon_{CHN,ROW} p_{CHN}^k II_{i\_MN,CHN}$$

Household consumption

$$p_{i,r}^{q} X_{i,r}^{p} = \begin{cases} \alpha_{i,r}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} + \sum_{j\_MN} \varepsilon_{CHN,r} p_{CAP,j\_MN,CHN}^{f} F_{CAP,j\_MN,CHN} - T_r^d - S_r^p\right), & r = JPN, \forall i \\[2em] \alpha_{i,r}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} + \sum_{h\_mob,j\_MN} p_{h\_mob,j\_MN,r}^{f} F_{h\_mob,j\_MN,r} - T_r^d - S_r^p\right), & r = CHN, \forall i \\[2em] \alpha_{i,r}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} - T_r^d - S_r^p\right), & r = ROW, \forall i \end{cases}$$

$$p_r^{xpENG} X_r^{pENG}$$

$$= \begin{cases} \alpha_r^{ENG}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} + \sum_{j\_MN} \varepsilon_{CHN,r} p_{CAP,j\_MN,CHN}^{f} F_{CAP,j\_MN,CHN} - T_r^d - S_r^p\right), & r = JPN \\[2em] \alpha_r^{ENG}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} + \sum_{h\_mob,j\_MN} p_{h\_mob,j\_MN,r}^{f} F_{h\_mob,j\_MN,r} - T_r^d - S_r^p\right), & r = CHN \\[2em] \alpha_r^{ENG}\left(\sum_{h,j} p_{h,j,r}^{f} F_{h,j,r} - T_r^d - S_r^p\right), & r = ROW \end{cases}$$

Balance of payment

$$\sum_i \left(1 + \tau_{i,r,s}^{e}\right) \varepsilon_{r,ROW} p_{i,r,s}^{qt} QT_{i,r,s} + \sum_i \varepsilon_{r,ROW} \left(1 + \tau_{i,r}^{z}\right) p_{i,r}^{z} QTS_{i,r}$$

$$+ S_r^f - \sum_i \left[\tau_{i,s,r}^{s} p^{qqt} + \left(1 + \tau_{i,s,r}^{e}\right) \varepsilon_{s,ROW} p_{i,s,r}^{qt}\right] QT_{i,s,r}$$

$$= \begin{cases} FDI_{JPN,CHN} - \sum_{i\_MN} \varepsilon_{CHN,ROW} p_{CAP,i\_MN,CHN}^{f} F_{CAP,i\_MN,CHN}, & r = JPN \\[2em] -FDI_{JPN,CHN} + \sum_{i\_MN} \varepsilon_{CHN,ROW} p_{CAP,i\_MN,CHN}^{f} F_{CAP,i\_MN,CHN}, & r = CHN \\[1em] 0, & r = ROW \end{cases}$$

Armington function for local firms and final uses

$$Q_{i,r} = \gamma_{i,r} \left[\delta m_{i,r} QM1_{i,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} + \delta d_{i,r} D_{i,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d}\right]^{\sigma_i^d/\left(\sigma_i^d - 1\right)}, \qquad \forall i, r$$

$$QM1_{i,r} = \left[\frac{\gamma_{i,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} \delta m_{i,r} p_{i,r}^{q}}{p_{i,r}^{qm1}}\right]^{\sigma_i^d} Q_{i,r}, \qquad \forall i, r$$

$$D_{i,r} = \left[\frac{\gamma_{i,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} \delta d_{i,r} p_{i,r}^{q}}{p_{i,r}^{d}}\right]^{\sigma_i^d} Q_{i,r}, \qquad \forall i, r$$

$$QM1_{i,r} = \omega_{i,r} \left[\sum_s \psi_{i,s,r} QT_{i,s,r}^{\left(\sigma_i^m - 1\right)/\sigma_i^m} \right]^{\sigma_i^m / \left(\sigma_i^m - 1\right)}, \qquad\qquad \forall i,r$$

$$QT1_{i,s,r} = \left\{ \frac{\omega_{i,r}^{\left(\sigma_i^m - 1\right)/\sigma_i^m} \psi_{i,s,r} p_{i,r}^{qm1}}{\left(1 + \tau_{i,s,r}^m\right)\left[\left(1 + \tau_{i,s,r}^e\right)\varepsilon_{s,r} p_{i,s,r}^{qt} + \tau_{i,s,r}^s \varepsilon_{ROW,r} p^{qqt}\right]} \right\}^{\sigma_i^m} QM1_{i,r}, \qquad \forall i,s,r$$

Armington function for MNEs

$$X_{i,j\_MN,r} = \gamma2_{i,j\_MN,r}$$
$$\left[\delta m2_{i,i\_MN,r} QM2_{i,i\_MN,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} + \delta d2_{i,i\_MN,r} D2_{i,i\_MN,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d}\right]^{\sigma_i^d / \left(\sigma_i^d - 1\right)},$$

$$\forall i, j\_MN, r$$

$$QM2_{i,i\_MN,r} = \left[\frac{\gamma2_{i,i\_MN,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} \delta m2_{i,i\_MN,r} p_{i,i\_MN,r}^{q2}}{p_{i,r}^{qm2}} \right]^{\sigma_i^d} X_{i,i\_MN,r}, \qquad \forall i, i\_MN, r$$

$$D2_{i,i\_MN,r} = \left[\frac{\gamma2_{i,i\_MN,r}^{\left(\sigma_i^d - 1\right)/\sigma_i^d} \delta d2_{i,i\_MN,r} p_{i,i\_MN,r}^{q2}}{p_{i,r}^{dd}} \right]^{\sigma_i^d} X_{i,i\_MN,r}, \quad \forall i, i\_MN, r$$

$$QM2_{i,j\_MN,r} = \omega2_{i,j\_MN,r} \left[\sum_s \phi2_{i,j\_MN,s,r} QT2_{i,j\_MN,s,r}^{\left(\sigma_i^m - 1\right)/\sigma_i^m} \right]^{\sigma_i^m / \left(\sigma_i^m - 1\right)}, \quad \forall i, j\_MN, r$$

$$QT2_{i,j\_MN,s,r} = \left[\frac{\omega2_{i,j\_MN,r}^{\left(\sigma_i^m - 1\right)/\sigma_i^m} \phi2_{i,j\_MN,s,r} p_{i,j\_MN,r}^{qm2}}{\left(1 + \tau_{i,s,r}^e\right)p_{i,s,r}^{qt}\varepsilon_{s,r} + \tau_{i,s,r}^s p^{qqt}\varepsilon_{ROW,r}\left(1 + \tau_{i,s,r}^m\right)} \right]^{\sigma_i^m} QM2_{i,j\_MN,r},$$

$$\forall i, j\_MN, s, r$$

Transformation functions

$$Z_{i\_all,r} - QTS_{i\_all,r} = \theta_{i\_all,r} \left[\xi e_{i\_all,r} QE_{i\_all,r}^{\left(\sigma_{i\_all}^d + 1\right)/\sigma_{i\_all}^d} + \xi d_{i\_all,r} D_{i\_all,r}^{\left(\sigma_{i\_all}^d + 1\right)/\sigma_{i\_all}^d} \right]^{\sigma_{i\_all}^d / \left(\sigma_{i\_all}^d + 1\right)},$$

$$\forall i\_all, r$$

$$QE_{i\_all,r} = \left[\frac{\theta_{i\_all,r}^{\left(\sigma_{i\_all}^d + 1\right)/\sigma_{i\_all}^d} \xi e_{i\_all,r}\left(1 + \tau_{i\_all,r}^z\right)p_{i\_all,r}^{zz}}{p_{i\_all,r}^{qe}} \right]^{-\sigma_{i\_all}^d} Z_{i\_all,r}, \qquad \forall i\_all, r$$

$$D_{i\_all,r} = \left[\frac{\theta_{i,r}^{\left(\sigma_{i\_all}^{d}+1\right)/\sigma_{i\_all}^{d}} \xi d_{i\_all,r} \left(1+\tau_{i\_all,r}^{z}\right) p_{i\_all,r}^{z}}{p_{i\_all,r}^{d}} \right]^{-\sigma_{i\_all}^{d}} Z_{i\_all,r}, \qquad \forall i\_all, r$$

$$QE_{i\_all,r} = \kappa_{i\_all,r} \left[\sum_s \pi_{i\_all,r,s} QT_{i\_all,r,s}^{\left(\sigma_{i\_all}^{m}+1\right)/\sigma_{i\_all}^{m}} \right]^{\sigma_{i\_all}^{m}/\left(\sigma_{i\_all}^{m}+1\right)}, \qquad \forall i\_all, r$$

$$QT_{i\_all,s,r} = \left[\kappa_{i\_all,r}^{\left(\sigma_{i\_all}^{m}+1\right)/\sigma_{i\_all}^{m}} \pi_{i\_all,r,s} p_{i\_all,r}^{qe} \right]^{-\sigma_{i\_all}^{m}} QE_{i\_all,r}, \qquad \forall i\_all, s, r$$

International transport sector

$$QQT = \rho 1 \prod_r QTS_{TRS,r}^{\rho 2_{TRS,r}},$$

$$QTS_{i,r} = \frac{\rho 2_{i,r}}{\left(1+\tau_{i,r}^{z}\right) \varepsilon_{r,ROW} \, p_{i,r}^{z}} p^{qqt} QQT, \qquad \forall i, r$$

$$QQT = \sum_{i,r,s} \tau_{i,r,s}^{s} QT_{i,r,s},$$

Market clearing condition

$$Q_{i,r} = X_{i,r}^{p} + X_{i,r}^{g} + X_{i,r}^{v} + \sum_{j\_all} X_{i,j\_all,r}, \qquad \forall i, r$$

$$DD_{j,r} = D1_{j,r} + \sum_{j\_MN} D2_{j,j\_MN,r}, \qquad \forall j, r$$

$$QT_{j\_all,r,s} = QT1_{j\_all,r,s} + \sum_{j\_MN} QT2_{j\_all,j\_MN,r,s}, \qquad \forall j\_all, r, s$$

$$\sum_{j\_all} F_{h\_mob,j\_all,r} = \sum_{j\_all} FF_{h\_mob,j\_all,r}, \qquad \forall h\_mob, r$$

$$p_{h\_mob,j\_all,r}^{f} = p_{h\_mob,i\_all,r}^{f}, \qquad \forall h\_mob, j\_all, i\_all, r$$

$$F_{CAP,j\_all,r} = rorKK_{j\_all,r}, \qquad \forall j\_all, r$$

$$III_r = \sum_{j\_all} II_{j\_all,r}, \qquad \forall r$$

Investment good allocation among sectors

$$p_r^k II_{j,r} = \frac{p_{CAP,j,r}^{f}{}^\zeta F_{CAP,j,r}}{\sum_i p_{CAP,i,r}^{f}{}^\zeta F_{CAP,i,r}} \left(S_r^p + \varepsilon_{ROW,r} S_r^f \right), \qquad \forall j, r = CHN, ROW$$

$$p_r^k II_{j,r} = \frac{p_{CAP,j,r}^{f}{}^\zeta F_{CAP,j,r} \left(S_r^p + \varepsilon_{ROW,r} S_r^f \right)}{\sum_i p_{CAP,i,r}^{f}{}^\zeta F_{CAP,i,r} + \sum_{i\_MN} \left(\varepsilon_{CHN,r} p_{CAP,i\_MN,CHN}^{f} \right)^\zeta F_{CAP,i\_MN,CHN}}, \quad \forall j, r = JPN$$

$$\varepsilon_{CHN,r} p_r^k II_{j\_MN,r} = \frac{\left(\varepsilon_{CHN,r} p_{CAP,j\_MN,CHN}^{f} \right)^\zeta F_{CAP,j\_MN,CHN} \left(S_r^p + \varepsilon_{ROW,r} S_r^f \right)}{\sum_i p_{CAP,i,r}^{f}{}^\zeta F_{CAP,i,r} + \sum_{i\_MN} \left(\varepsilon_{CHN,r} p_{CAP,i\_MN,CHN}^{f} \right)^\zeta F_{CAP,i\_MN,CHN}},$$

$$\forall j\_MN, r = JPN$$

Exchange rate arbitrage condition

$$\varepsilon_{r,s} = \varepsilon_{r,rr} \varepsilon_{rr,s}, \qquad \forall r, s, rr$$

Price index for numeraire

$$PRICE_r = \sum_j p_{j,r}^q \frac{Q_{j,r}^{00}}{\sum_i Q_{i,r}^{00}}, \qquad \forall r$$

Composite consumption

$$CC_r = a_r \prod_i X_{i,r}^{p}{}^{\alpha_{i,r}}, \qquad \forall r$$

Evolution of state variables and exogenous variables

$$KK_{j\_all,r,t+1} = (1 - dep) KK_{j\_all,r,t} + II_{j\_all,r,t}, \quad \forall j\_all, r, t$$

$$FF_{h\_mob,j\_all,r,t+1} = (1 + pop) FF_{h\_mob,j\_all,r,t}, \quad \forall h\_mob, j\_all, r, t$$

$$X_{i,r,t+1}^g = (1 + pop) X_{i,r,t}^g, \qquad \forall i, r, t$$

$$S_{r,t+1}^f = (1 + pop) S_{r,t}^f, \qquad \forall r, t$$