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Investigating Fiscal and Social Costs of Recovery Policy: A Dynamic General Equilibrium Analysis of a Compound Disaster in Northern Taiwan

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Abstract

We investigate a long-run impact of a compound disaster in northern Taiwan by describing a recovery process from the disaster with a dynamic computable general equilibrium model. After simulating losses of capital and labor in combination with a nuclear power shutdown, we conduct policy experiments that are aimed at recovery of Taiwan's major industries by subsidizing their output or capital use. We found that the semiconductor industry could recover but need a huge amount of subsidies while the electronic equipment sector could almost recover even without subsidies. Capital-use subsidies would cost less than output subsidies. When we use two-year longer duration for a recovery program of semiconductors, we could save the subsidy costs by 7–10%.

Keywords: Compound Disaster, Nuclear Power Shutdown, Taiwan, Disaster Recovery, Dynamic Computable General Equilibrium Model

JEL Classification: Q54, C68, Q43

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1. Introduction

Asia and the Pacific is the most natural hazard prone region owing to its geological environment and its rapid (Davis, 2014). Taiwan is one of the most vulnerable areas among many that are prone to natural disasters, especially earthquakes. It is a small island of 36,000 km^2 with 23 million people and hosts world-leading industrial sectors, such as semiconductors and electronic equipment. They are located in the Hsinchu Science Park in the northern area close to the capital, Taipei City. This area has two risk factors of disasters. First, the Shan-jiao fault runs through the semiconductor complex area. The second risk factor is nuclear power stations, which are located at coastal areas within 30 km from the capital. As we have learned in the Great East Japan Earthquake (GEJE) in 2011, a destructive tsunami caused by a huge earthquake can trigger a nuclear disaster and a power crisis, which could be termed a “compound disaster” (McEntire, 2006; Kawata, 2011).

Electricity has long been indispensable input in Taiwan (Fukushige and Yamawaki, 2015), and it is important for modern industries, especially semiconductors, which is the flagship industry. On September 21, 1999, a magnitude (ML) 7.6 earthquake (hereinafter, the 921 earthquake) hit northern Taiwan, causing serious damage to communities and facilities, including the power network, and disrupting industrial activities for two weeks. The disaster incurred costs as high as 14 billion USD or 3.3% of Taiwan’s GDP (Prater and Wu, 2002). The loss of semiconductor and electronic equipment manufacturing in the Hsinchu Science Park exceeded 10 billion TWD (Hsinchu Science Park, 2011). Taiwan has achieved further high growth after the 921 earthquake and thus could lose more from another compound disaster.

Some impact analysis of actual and potential disasters have been made for Taiwan. Mai et al. (1999) quantified the macroeconomic impacts of the 921 Earthquake. Tsai and Chen (2011) conducted risk analysis of potential disasters for Taiwan’s tourism industry from an engineering viewpoint by using a geographic information system. Huang and Hosoe (2014) assessed the economic impact of a hypothetical ML 7.5 earthquake and a power crisis hitting manufacturing sectors of northern Taiwan by using a static computable general equilibrium (CGE) model. They found that the semiconductor, chemical, and pottery sectors, which are capital and/or energy intensive, would be affected most severely, the machinery and transportation equipment sectors would be affected much less, and the power crisis would push up power prices by 27% to add up to an additional 16% of losses caused by the assumed earthquake alone.

These estimates of damages and losses by disasters are useful for us to develop disaster-impact mitigation plans and to examine their investment values. However, no matter how deeply and precisely we study the impact of a disaster, it cannot be prevented and thus would have some negative impacts on the economy. Given the occurrence of a disaster, we have to develop a recovery plan by studying recovery processes and policies that can minimize the disaster-induced losses and/or achieve a recovery goal at a minimum cost. After the 921 Earthquake, the Taiwanese government set up a 2-year recovery plan with a special budget of 200 billion TWD (Shieh, 2004). In a future disaster case, a similar amount would be requested. We have to assess what would happen in a recovery process after a disaster and what would need to be done for a better recovery. That is, we question what type of policy could achieve a recovery, how much fiscal costs would be needed, and how much social costs an economy would bear in the recovery process.

On top of these questions, there is another issue about the timeframe for the recovery program. While people often prefer intensive and thus quick recovery, additional funds and social cots may be needed. In the case of the GEJE, a large portion of the special recovery budget was prepared after the event; the Board of Audit of Japan (2013) reported that about 10% of the budget for the first 2 years was misused or abused. In addition, inefficiency would result from interventions for recovery, and an intensive recovery program would bring about even larger distortions. Therefore, finally, the study addresses the question of how long recovery program duration should be.

Studies on recovery process and policies *after* a disaster are scant for Taiwan although it potentially faces risks of various and serious disasters. Chen (2013) simulated a no-nuclear situation (but without considering any disasters) with a dynamic CGE model for Taiwan. Huang and Min (2002) investigated a recovery of inbound tourist flows after the 921 earthquake. While no economy-wide study for these questions exists for Taiwan's disaster and recovery, the GEJE strongly motivated researchers to study recovery processes and policies for Japan. Okiyama et al. (2014) used a spatial CGE model to simulate the GEJE and studied efficient financing measures of reconstruction funds. Akune et al. (2013) used a dynamic CGE model to predict recovery time needed for the fishery and the marine products industries, which were severely affected by the GEJE-induced compound disaster. These dynamic analyses for Japan, however, did not consider long-run effects of either a recovery program or its duration.

To answer these questions, we develop a dynamic CGE model for Taiwan and simulate a huge earthquake that causes losses in capital and labor as well as a nuclear power shutdown in a compound disaster. To examine the costs and effectiveness of recovery policies, we consider two types of subsidies—a production subsidy and a capital-use subsidy—that are aimed at achieving a recovery of output levels in a few major industries in 10 years. We evaluate these policy interventions by measuring their fiscal and social costs by varying program duration.

The rest of the paper proceeds as follows. Section 2 describes our dynamic CGE model for Taiwan. Section 3 explains our simulation scenarios and simulation results. Section 4 summarizes our findings and their implications for a better recovery policy.

2. Dynamic CGE Model and Simulation Method

2.1 Intratemporal Model Structure

We use a recursive dynamic CGE model for Taiwan that is developed on the basis of the static model by Huang and Hosoe (2014) with an extension made for recursive dynamics, à la Hosoe (2014). The model is explained in detail in these two articles, we explain only its major features below. The model distinguishes 22 sectors (Table 2.1). Figure 2.1 describes activities *within* a period with nested-constant elasticity of substitution/transformation (CES/CET) functions. They describe (1) substitution between capital and labor, (2) intermediate input and composite factor input with energy composite input for a production function of gross output, (3) transformation for domestic goods supply and exports, and (4) substitution between the domestic goods and imports, à la Armington (1969). (5) The Armington composite goods are used by a representative household and the government as well as for investment and intermediate input. (6) The household utility depends on consumption of various non-energy goods and an energy composite.

Table 2.1: Sectors and their Estimated Loss of Capital Stock and Total Labor Endowment

Sector and its Abbreviation		Damages on Capital in Period 0
Capital Loss		
Agriculture	AGR	−1.3%
Crude oil and natural gas[a,b]	PAG	−4.2%
Mining	MIN	−1.9%
Coal[a]	COA	−5.7%
Food	FOD	−3.9%
Textiles and apparel	TXA	−7.1%
Wood and paper	WPP	−9.6%
Petroleum[a,b]	PET	−4.9%
Chemical	CHM	−7.4%
Pottery	POT	−6.3%
Steel	STL	−5.8%
Metal products	MET	−6.4%
Semiconductors	SEC	−11.6%
Electronic equipment	EEQ	−11.0%
Machinery	MCH	−6.1%
Transportation equipment	TEQ	−4.1%
Manufacturing	MAN	−5.6%
Electricity[a,b]	ELY	−16.3%[c]
Town gas[a,b]	TWG	−5.8%
Construction	CON	−6.8%
Transportation	TRS	−13.5%
Service	SRV	−8.2%
Labor Loss[d]		−7.4%

Note. Estimated by Huang and Hosoe (2014).

[a] Energy sectors whose energy input is determined by fixed coefficients. In addition, their output is used for the production of energy composite goods for industries

[b] Energy goods used for energy composite goods for households

[c] This loss consists of the direct loss by the earthquake and the loss reflecting the nuclear power shutdown.

[d] The labor loss is assumed to recover gradually in five periods.

To describe substitution of electricity with other energy sources, which can be crucial in a power crisis induced by the nuclear power shutdown, we assume that (7) the energy composite for non-energy sectors is developed from the five energy goods indicated in Table 2.1, while we assume the conventional Leontief's fixed coefficient technology for the five energy sectors. (8) In the energy composite for the household, petroleum, natural gas, electricity, and town gas (without coal) are used. The model is calibrated to Taiwan's input-output (IO) table for 2006 (DGBAS, 2011a) with parameters summarized in Table 2.2.[1]

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[1] We conduct sensitivity analysis with respect to these assumed parameters to examine robustness of our results. Details are shown in the Appendix.

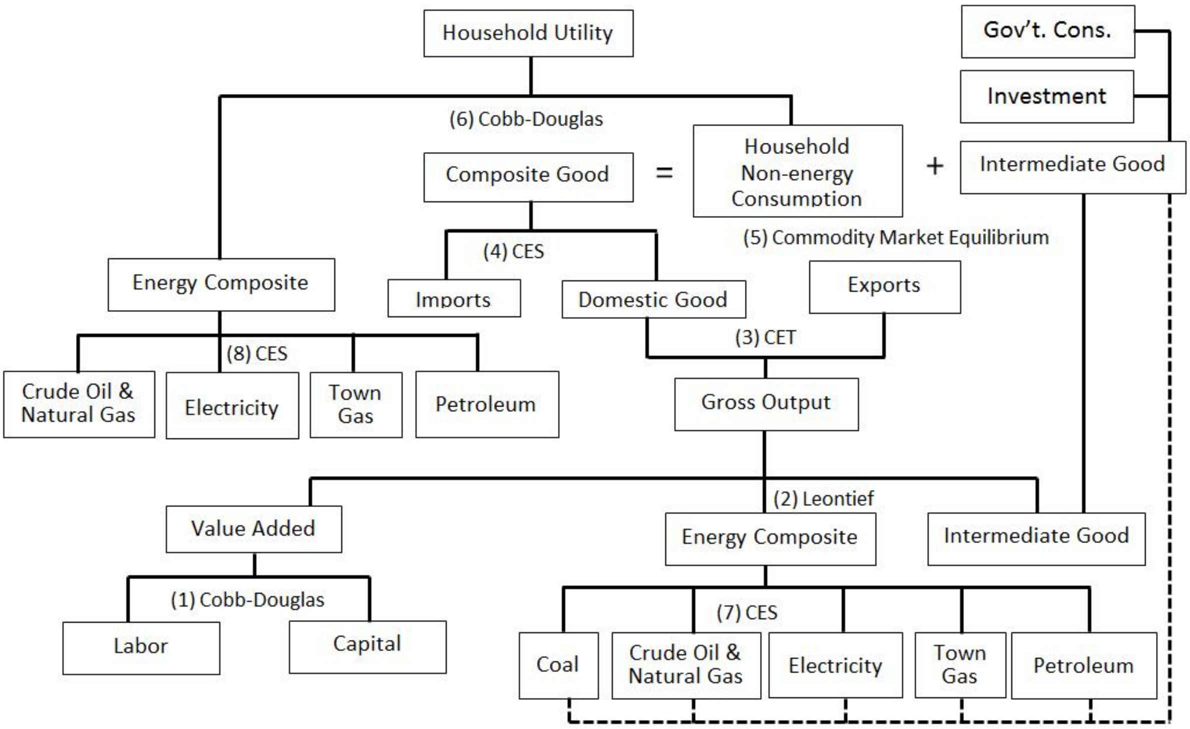

Figure 2.1: The CGE Model Structure within a Period

Table 2.2: Assumed Parameters

Parameter	Value	Source
Rate of return of capital (*ror*)	5%	Hosoe (2014)
Depreciation rate (*dep*)	4%	Chow and Lin (2002); Chang and Guan (2005)
Population growth rate (*pop*)	1%	DGBAS (2007)
Armington elasticity parameters (σ, ϕ)	0.90–7.35	GTAP Database version 8.1 (Hertel, 1997)
Elasticity of substitution among energy sources (σ^e)	1.1	Authors' assumption
Elasticity parameter in the investment function (2.1) (ς)	1.0	Hosoe (2014)

2.2 Intertemporal Model Structure

We depart from the earlier study with a static model by Huang and Hosoe (2014) by installing recursive dynamics in that model, which link economic activities *between* periods. In the t-th period, private savings S_t^p, which are generated with a constant saving propensity, and foreign savings in the foreign currency S_t^f (converted to the local currency with an exchange rate ε_t) are spent in purchasing investment goods. These savings are allocated to purchase goods for sectoral investment in the *i*-th sector $II_{i,t}$ according to its expected relative profitability among sectors in the next period, following Hosoe (2014).

$$p_t^k II_{i,t} = \frac{{p_{CAP,i,t+1}^{f}}^{\zeta} F_{CAP,i,t+1}}{\sum_j {p_{CAP,j,t+1}^{f}}^{\zeta} F_{CAP,j,t+1}} \left(S_t^p + \varepsilon_t S_t^f \right) \tag{2.1}$$

where p_t^k denotes the price of composite investment goods, and $p_{CAP,i,t+1}^f$ and $F_{CAP,i,t+1}$ denote the price and the amount of capital service in the *i*-th sector in the next period, respectively. The last two variables can be replaced with the *t*-th period variables $p_{CAP,i,t}^f$ and $(1+pop)F_{CAP,j,t}$, where *pop* denotes a population growth rate, by assuming a myopic expectation. ζ is an elasticity parameter that determines sensitivity of sectoral investment allocation to a gap of profitability among sectors. As we assume putty-clay type capital, capital cannot move from one sector to another instantaneously but moves sluggishly through capital accumulation. By contrast, labor is assumed to be mobile among sectors as assumed in many CGE models.

2.3 Growth Paths

Through calibration to the IO table data and parameters that are summarized in Table 2.2, the model generates a path that is constantly growing at the population growth rate *pop*. Hereafter, this path is called the business-as-usual (BAU) path, which experiences no exogenous shocks or policies (Figure 2.2). We assume that the first period (period 0) experiences an ML 7.5 earthquake with a nuclear power shutdown, which Huang and Hosoe (2014) assumed to quantify their short-run impacts with a static CGE model. By running the model recursively from period 0 to 30, we describe the long run consequence of the compound disaster without any policies for recovery as the base run. After computing the base run path, we compute growth paths under counter-factual scenarios with various policy interventions for recovery of some major sectors in Taiwan. Finally, we compare these counter-factual growth paths with the base run path to evaluate these policies.

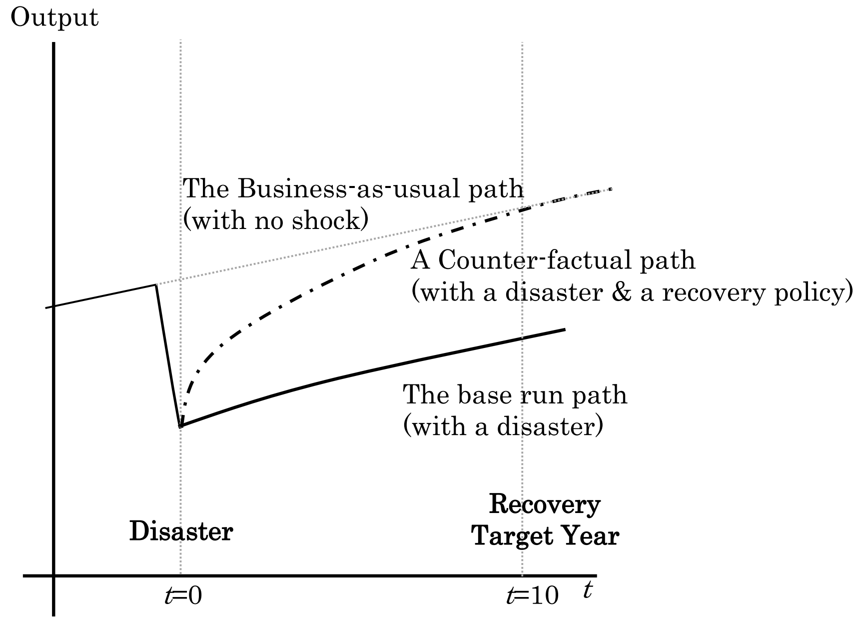

Figure 2.2: Three Growth Paths for Comparative Dynamics

2.4 Disaster Shocks: Earthquake and Nuclear Power Shutdown

The hypothetical earthquake at the Shan-jiao fault is assumed to cause destruction of capital stock and unavailability of labor force. We use the estimates of their losses made by Huang and Hosoe (2014) for period 0. They estimated the capital losses based on the regional building collapse estimated by Taiwan Seismic Scenario Database with regional concentration data of affected industries (DGBAS, 2011b).[2] The capital losses are assumed to occur exogenously only once in period 0 and can be recovered through endogenously-determined investment from period 1 as described by the sectoral investment function (2.1). The loss rates differ among sectors because capital intensity and spatial distribution are different among sectors (Table 2.1).

The labor losses are assumed to occur in period 0 by 7.4 %, which is also estimated based on the building collapse and damage. The background assumption is that building collapse and damage render workplaces unavailable and, thus, a certain proportion of the labor force is unavailable. Note that the unavailability of the labor force does not mean only expected deaths and injuries in the earthquake, which are not high enough to cause macroeconomic impacts. As the collapsed or damaged buildings, in due course, would be rebuilt or fixed, labor unavailability is to

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[2] http://teles.ncree.org.tw/tssd/

be reduced gradually in the following five periods (i.e., by 25% every year).

On top of these two factor losses, we assume a nuclear power shutdown in the compound disaster. By this assumption, it could be interpreted either that the earthquake and/or an earthquake-induced tsunami hits the nuclear power plants (but causes no serious nuclear disaster) or that the earthquake makes Taiwanese people concerned about a nuclear accident, causing them to call for the suspension or abolition of nuclear power plants. The nuclear power shutdown implies two impacts. One is further losses/unavailability of the capital stock of the nuclear power plants in the electric power sector. The assumed capital losses in the electric power industry in Table 2.1 is increased by this capital stock losses/unavailability. The other impact is increased fossil fuel uses to make up the losses of nuclear power generation just as Japan has experienced after the GEJE.[3] In our experiments, we assume that 138% more petroleum, 15% more coal, and 27% more natural gas are used to produce a unit of electricity. This is implemented in our simulations by adjusting their Leontief input coefficients in the electric power sector by this magnitude.

2.5 Recovery Policy Scenarios

After a disaster, people often call for various measures of recovery for housing, food supply, medical service, employment and industrial activities, energy supply, and so on. In our macroeconomic simulations, we focus on the recovery of economic activities. Indeed, as a standard macroeconomic growth theory shows, aggregate output cannot recover perfectly from a shock in endowments and/or technological changes. Instead, in our multisectoral setup, we investigate policies that can achieve a recovery of output in some of the major sectors for Taiwan, such as semiconductors, electronic equipment, and chemicals. In addition, we investigate the possibility of recovery in the electric power sector, which is assumed to be hit seriously by a compound disaster.

Two types of subsidies are examined in our experiments. One is a production subsidy, which is expected to stimulate sectoral output to the desired level directly. The second type is a capital-use subsidy. As the investment good allocation function (2.1) shows, the capital-use subsidy raises remuneration of capital, and, thus, attracts more investment in the target sector for quicker

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[3] Details about these loss estimates in capital, labor, and nuclear power are provided in Huang and Hosoe (2014).

recovery. We assume that these subsidies are financed by lump-sum direct taxes.

We set the recovery target year at period 10. While many periods are needed for recovery, the duration of recovery programs tend to be rather short. For example, the recovery budget was prepared only for the first 3 years, including the year when the 921 earthquake occurred in Taiwan. Three variations for the program duration are assumed: 3, 5, and 7 years. The government is assumed to provide a production subsidy or a capital-use subsidy for one of the target industries in these periods after the earthquake. For simplicity, their subsidy rates are assumed to be constant during the recovery program periods and are set high enough to achieve output recovery in each target sector at period 10 (Table 2.3). As we focus on the recovery of the four sectors from the compound disaster by means of the two types of subsidies with the three types of recovery program duration, we conduct 24 different experiments in our simulations.

Table 2.3: Subsidy Rates Required for Recovery at Period 10

	Production Subsidy Rate	Capital-use Subsidy Rate
3-year Recovery Program		
Semiconductor	12.0%	46.5%
Electronic equipment	0.4%	4.5%
Chemical	6.0%	47.9%
Electricity	93.1%	98.8%
5-year Recovery Program		
Semiconductor	7.4%	33.1%
Electronic equipment	0.2%	2.6%
Chemical	3.8%	34.5%
Electricity	84.3%	97.6%
7-year Recovery Program		
Semiconductor	5.3%	25.6%
Electronic equipment	0.1%	1.8%
Chemical	2.7%	26.7%
Electricity	76.6%	95.8%

3. Simulation Results

3.1 The Base Run–Impacts of Compound Disaster

We use a multisectoral model and, thus, can see the impacts of disasters and the effects of policies not just on the target sector but also on other sectors. In Figure 3.1, thick lines show the paths of sectoral output in the base run (i.e., only a compound disaster) in terms of deviations from their BAU paths (i.e., no shocks). Output would decline in all the sectors except PET in period 0, as Huang and Hosoe (2014) predicted with a static CGE model. We investigate what would occur in the subsequent periods with our dynamic CGE model.

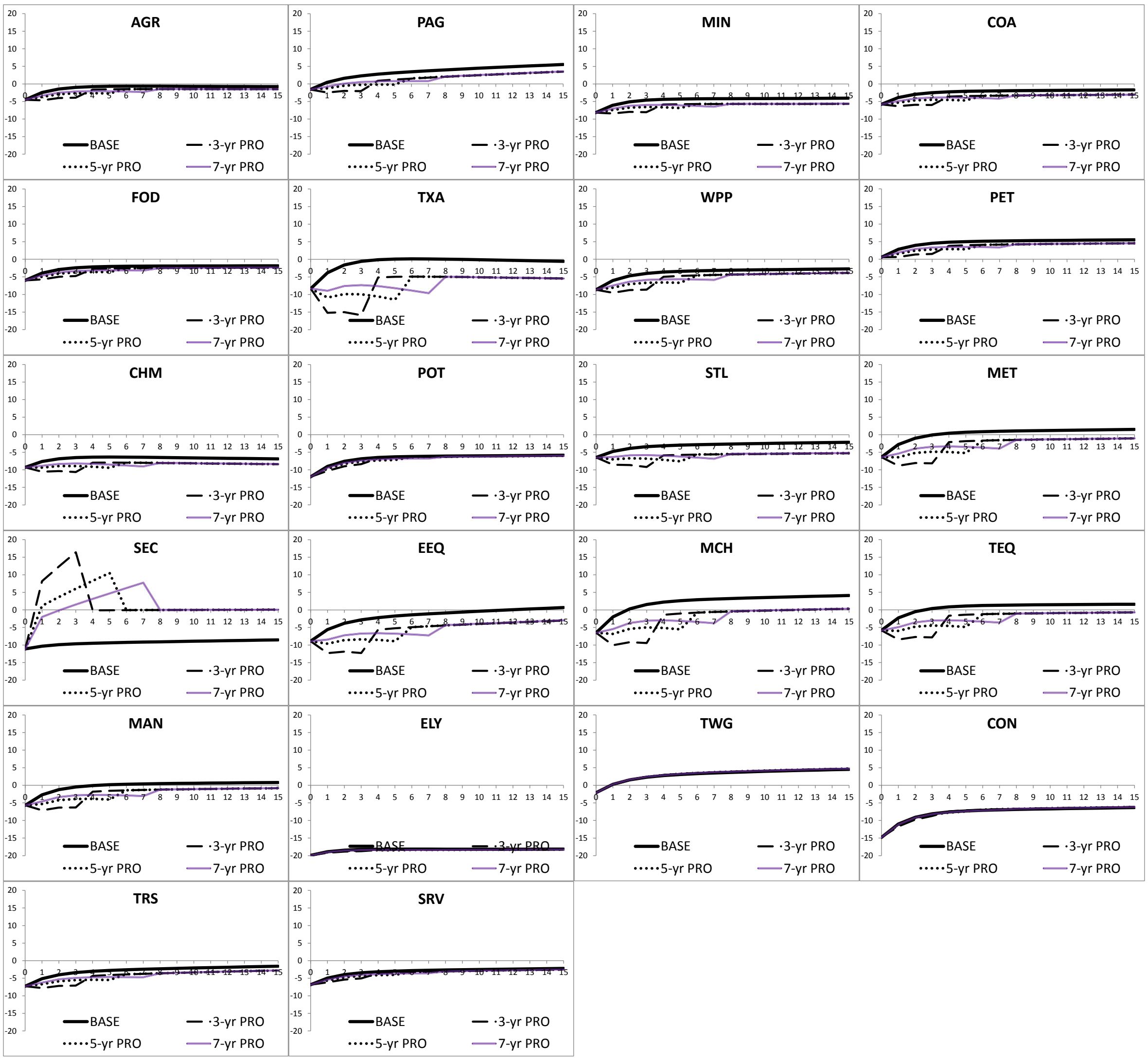

Figure 3.1: Sectoral Output with and without Production Subsidies for Semiconductor Sector [Unit: deviations from the BAU, %]

The semiconductor sector (SEC), among many others, would suffer a very severe decline of more than 10% in period 0 and even after the recovery target year of period 10. Similarly, the chemical (CHM), pottery (POT), and electric power sectors (ELY) would suffer in the long run. In contrast, the textiles and apparel (TXA), metal (MET), electronic equipment (EEQ), machinery (MCH), transportation equipment (TEQ), and other manufacturing (MAN) sectors would recover in due course without any policy interventions. The petroleum sector (PET) alone would gain throughout our simulation periods owing to increased fossil fuel demand from the nuclear power shutdown. From a macroeconomic viewpoint, the social losses, measured with the Hicksian equivalent variations, would reach 565 billion TWD in period 0 and 2.7 trillion TWD in periods 1–10, which are comparable to 4.9% and 2.7% of the BAU GDP, respectively.

3.2 Sectoral Impacts

3.2.1 Impacts of Recovery Program for Semiconductor Sector

Considering the importance of SEC in Taiwan, citizens could call for policies that would help or accelerate the sector's recovery. The production subsidy would achieve a recovery quickly, with conspicuous overshooting of its output level compared with the BAU path (the panel in the far left of the fourth row of Figure 3.1). The shorter the recovery program duration is, the more marked its overshooting would be during the recovery program. After the program finishes, the SEC output level would fall sharply and become stable at the BAU level. These interventions would affect other sectors negatively, especially TXA, STL, EEQ, and MCH. This is because recovery of one sector could be achieved only by mobilizing resources—investment goods and the labor force—from other sectors. Direct taxes, which are raised to finance subsidies, would decrease household consumption as a whole. TXA has a significant share in the household consumption and thus would also suffer through this channel. They are the side effects of the recovery program.

Alternatively, when we use a capital-use subsidy for the SEC, its recovery paths would be smooth without any overshooting (the panel in the far left of the fourth row in Figure 3.2). The impact of this on other sectors would also be negative but smaller. As the capital-use subsidy can recover lost capital through the investment mechanism (2.1) directly, it works more efficiently than the production subsidy.

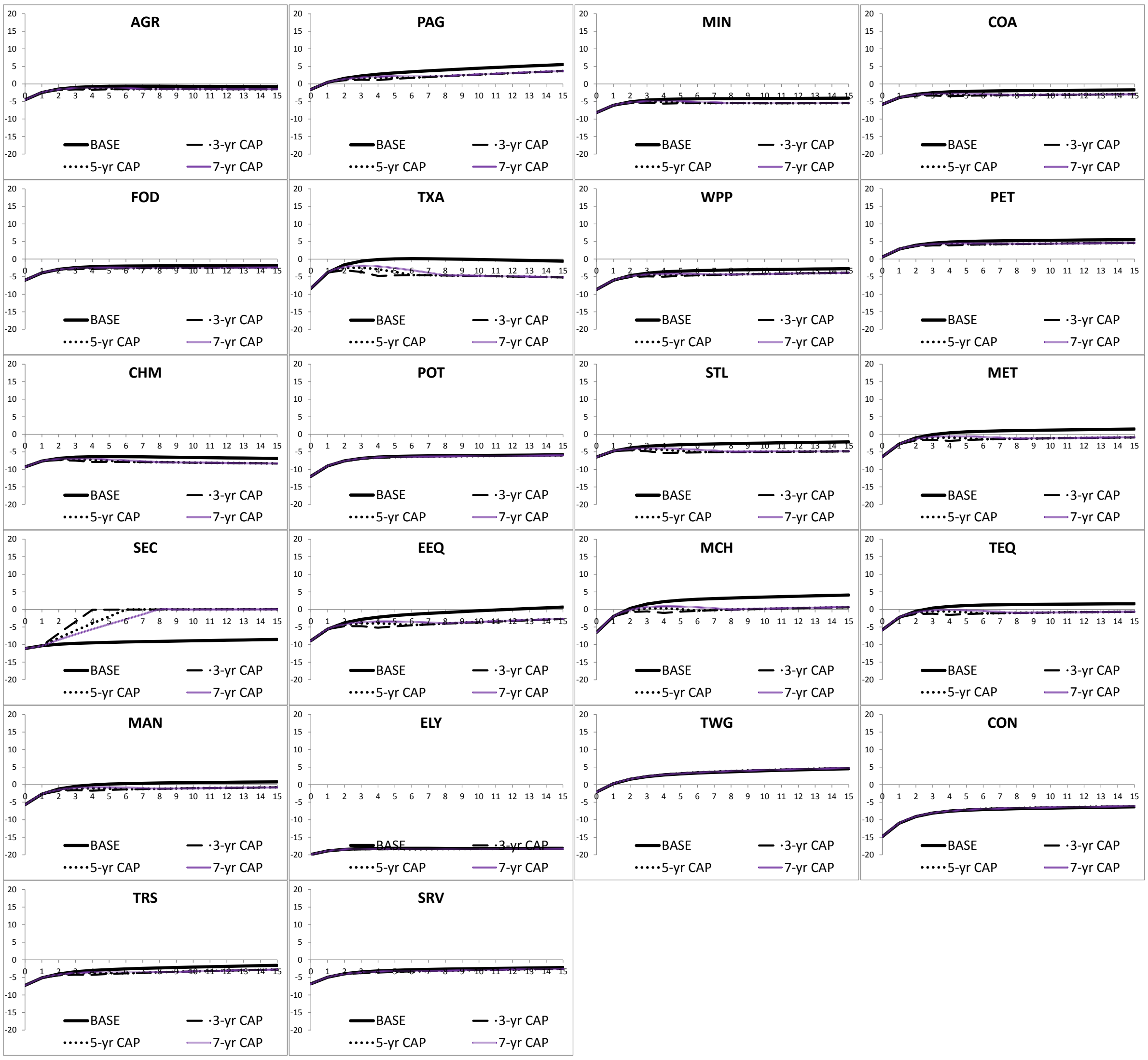

Figure 3.2: Sectoral Output with and without Capital-use Subsidies for Semiconductor Sector [Unit: deviations from the BAU, %]

By comparing costs of these different recovery programs, we can see efficiency of these programs (the left panel of Figure 3.3). A recovery program with longer duration, which requires lower subsidy rates, costs less. When we extend the program duration with production subsidies and capital-use subsidies from 3 years to 5 years, we could reduce its fiscal burden by 10% and 7%, respectively. The saved total fiscal costs of production subsidies (139 billion TWD) and capital-use subsidies (113 billion TWD) by extending the program duration from 3 years to 5 years are comparable to 0.1% of the BAU GDP in periods 1–10. Another extension of the program duration from 5 years to 7 years would cut the fiscal costs further in a similar magnitude.

The capital-use subsidy would costs 10, 8, and 7% less than the production subsidy in the 3-, 5-, and 7-year programs, respectively. Finally, it should be noted that the total fiscal burden for this single sector of SEC would exceed 1 trillion TWD while the annual government budget is 1.9 trillion TWD in 2013, when no serious disaster hit Taiwan.

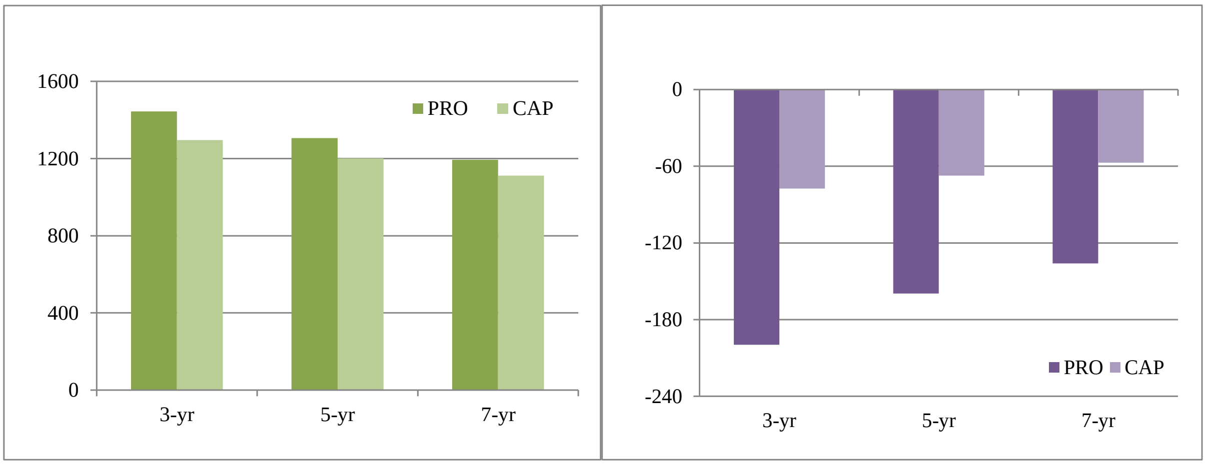

Figure 3.3: Total Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP)
[unit: billion TWD]

Source: Authors' calculation.
Note: The total fiscal costs and social costs measured by the Hicksian equivalent variations in Periods 1–10 discounted at a rate of 4%.

The higher subsidy rates in the shorter recovery programs cause larger distortions in resource allocation and therefore incur additional social costs on top of those in the base run (the right panel of Figure 3.3). These subsidy programs would increase the social losses by more than 5%.

3.2.2 Impacts of Recovery Programs for Three Other Sectors

The output paths indicates that EEQ would achieve a recovery in period 11 (i.e., one period after the target period) without subsidies and, thus, would require only a little acceleration of its recovery by subsidies (Figures 3.4 and 3.5). The impact of subsidies for EEQ would be qualitatively similar to that discussed in the previous section for SEC. The smaller policy interventions would incur smaller fiscal and social costs (Figure 3.6).

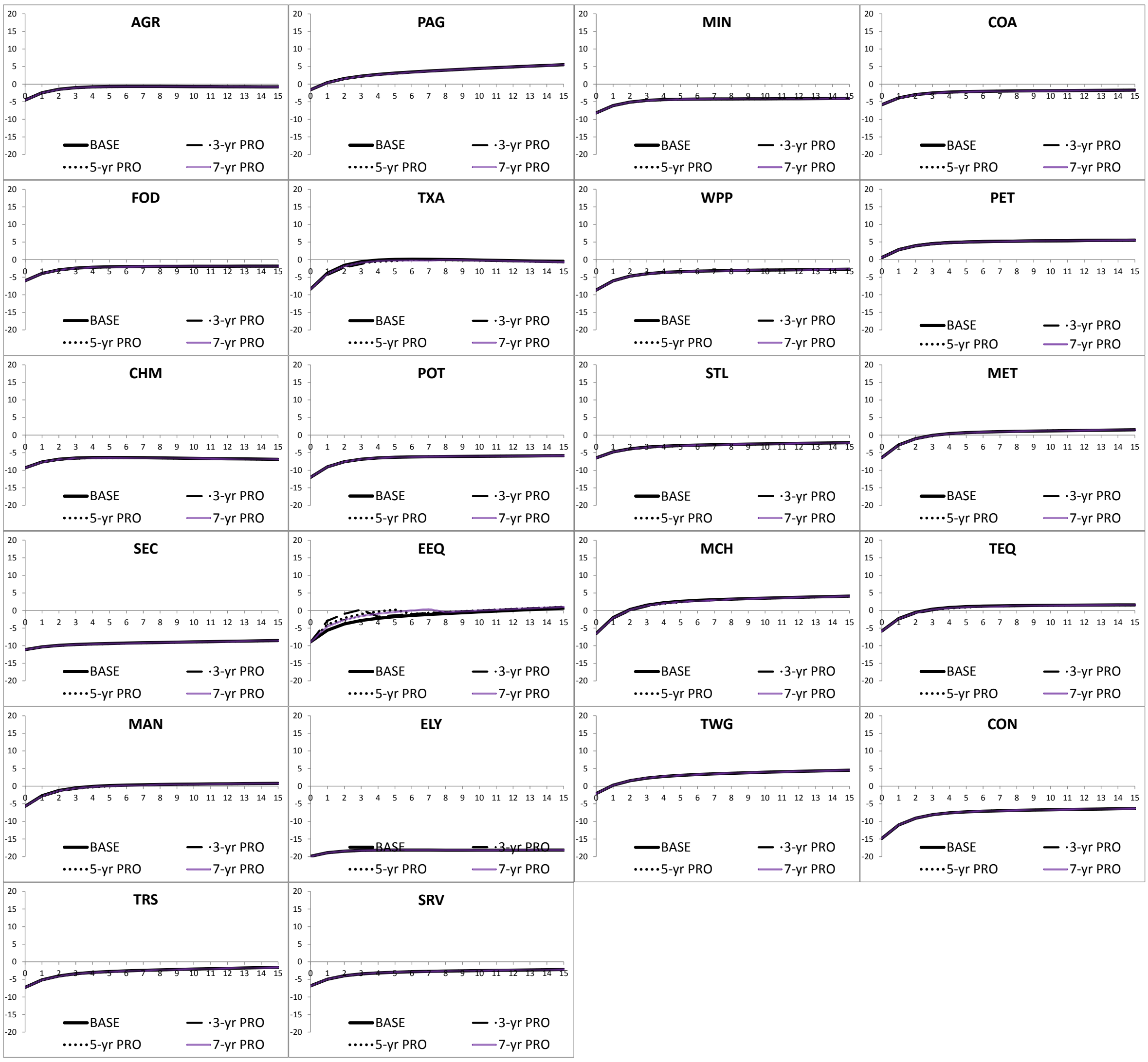

Figure 3.4: Sectoral Output with and without Production Subsidies for Electronic Equipment Sector [Unit: deviations from the BAU, %]

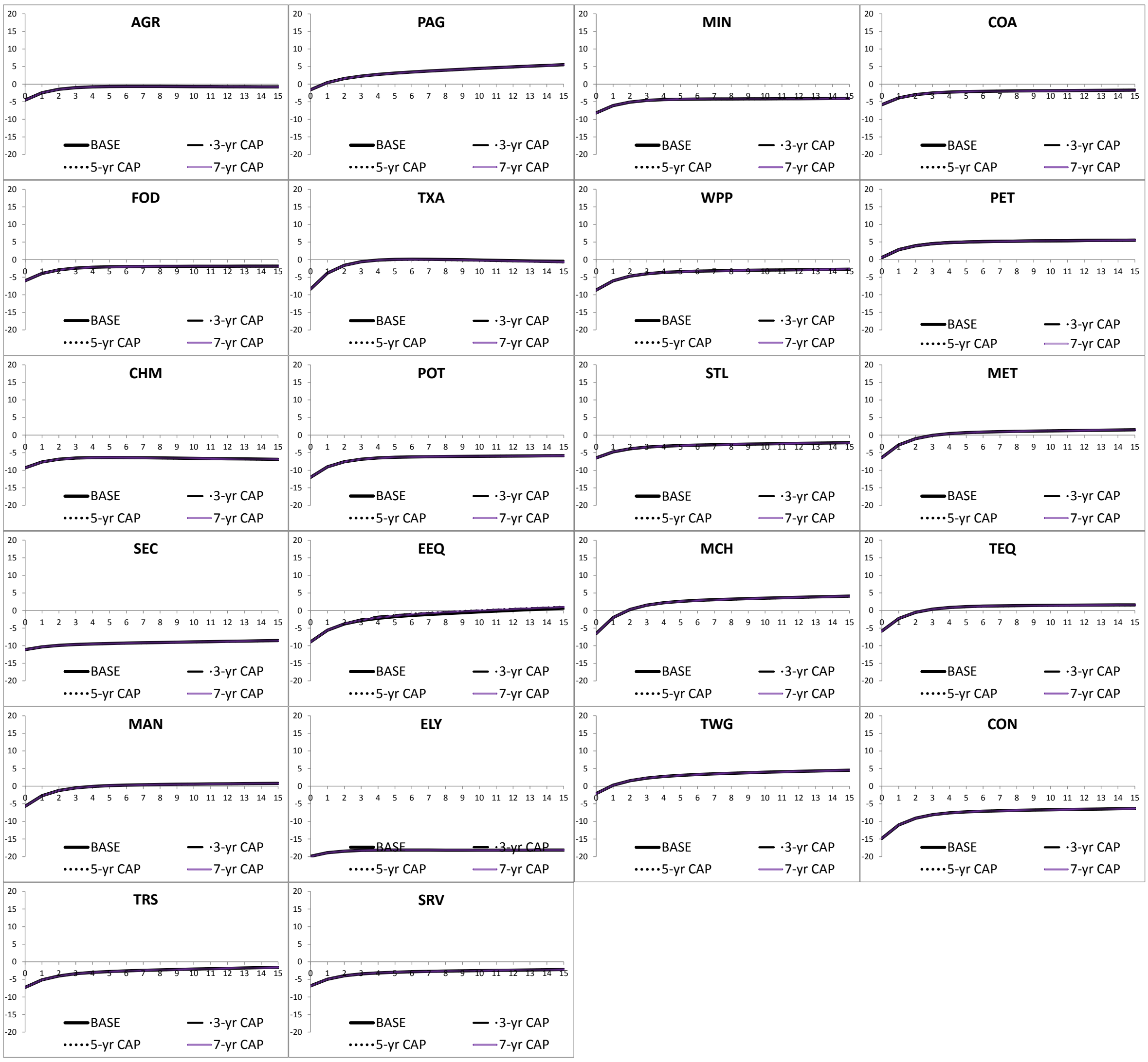

Figure 3.5: Sectoral Output with and without Capital-use Subsidies for Electronic Equipment Sector
[Unit: deviations from the BAU, %]

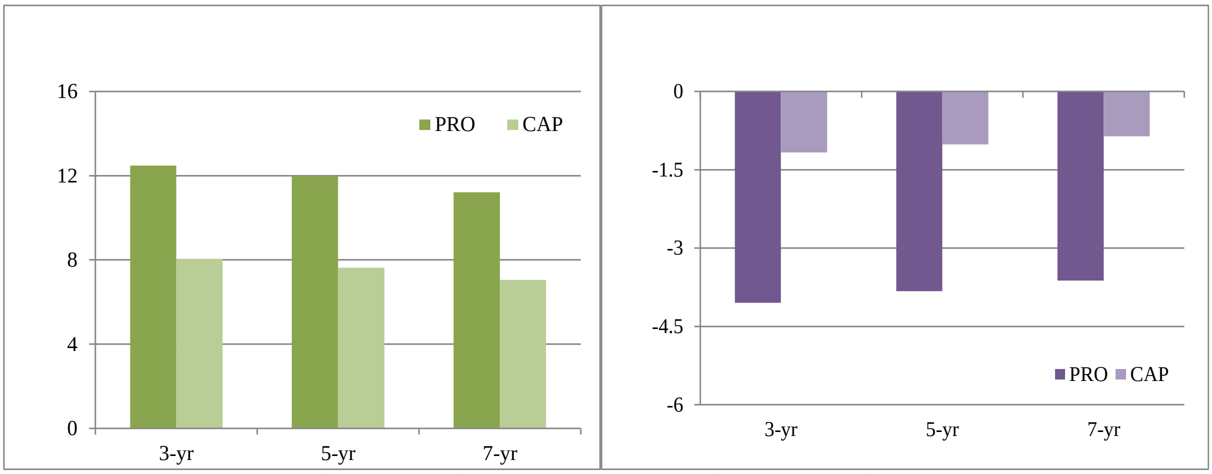

Figure 3.6: Total Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Electronic Equipment Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) [unit: billion TWD]

Source: Authors' calculation.

In contrast to these two sectors, which could successfully recover by the subsidies, the chemical sector (CHM) could not achieve any sustainable recovery (the panel on the far left of the third row of Figures 3.7 and 3.8). That is, CHM indeed could recover its output level owing to heavy subsidies only temporally in period 10, but its output level in the following periods would be below the BAU output level. This contrast is because CHM is heavily dependent on PET input, which is used more intensively for power generation owing to its nuclear power shutdown. This input shortage blocks sustainable recovery of CHM.[4]

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[4] Even when we assume a very high subsidy rate, we could not maintain the output level above the BAU level in and after period 10 because, as Figures 3.7 and 3.8 indicate, the output growth paths converge to the base run level consistently.

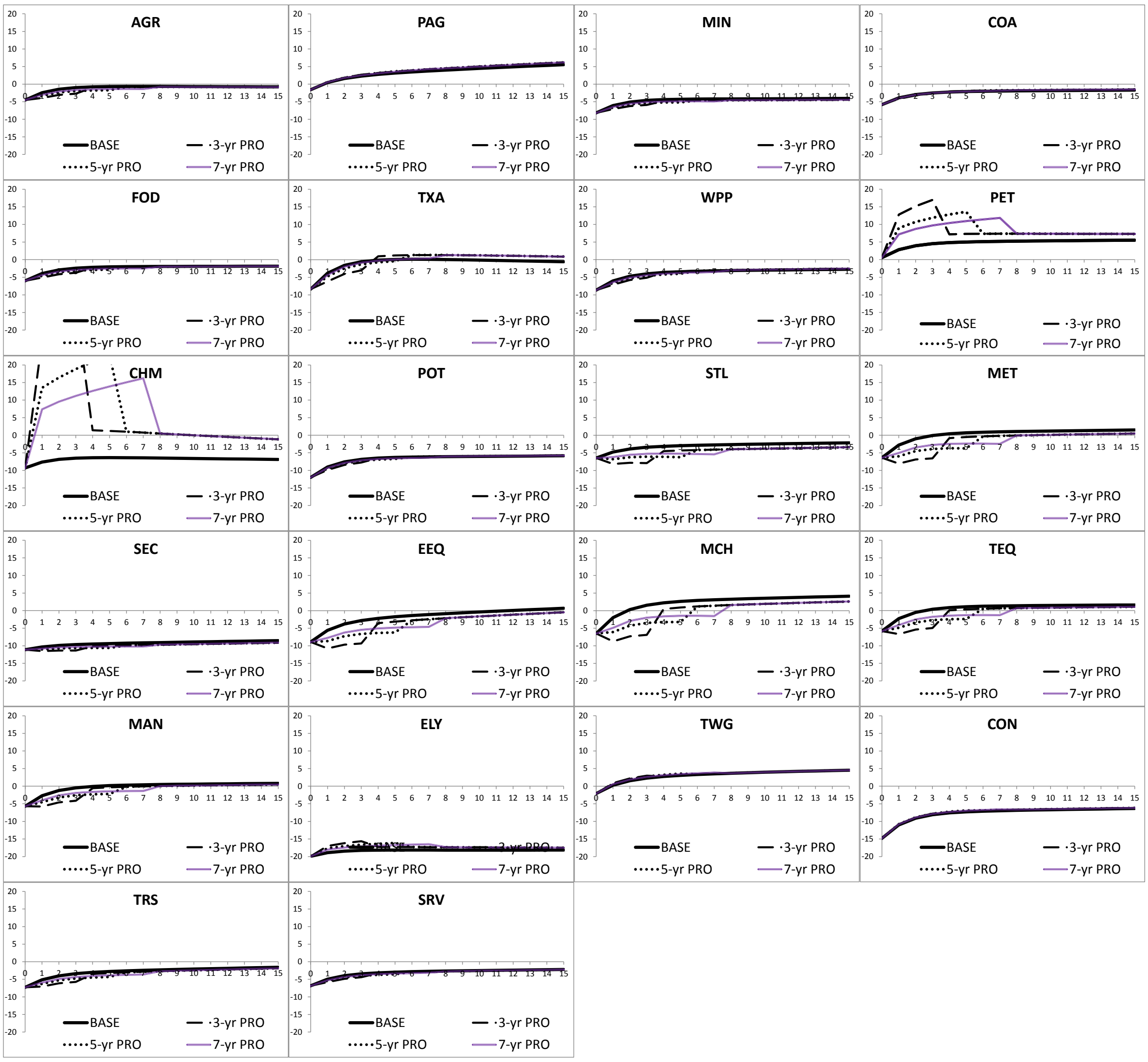

Figure 3.7: Sectoral Output with and without Production Subsidies for Chemical Sector [Unit: deviations from the BAU, %]

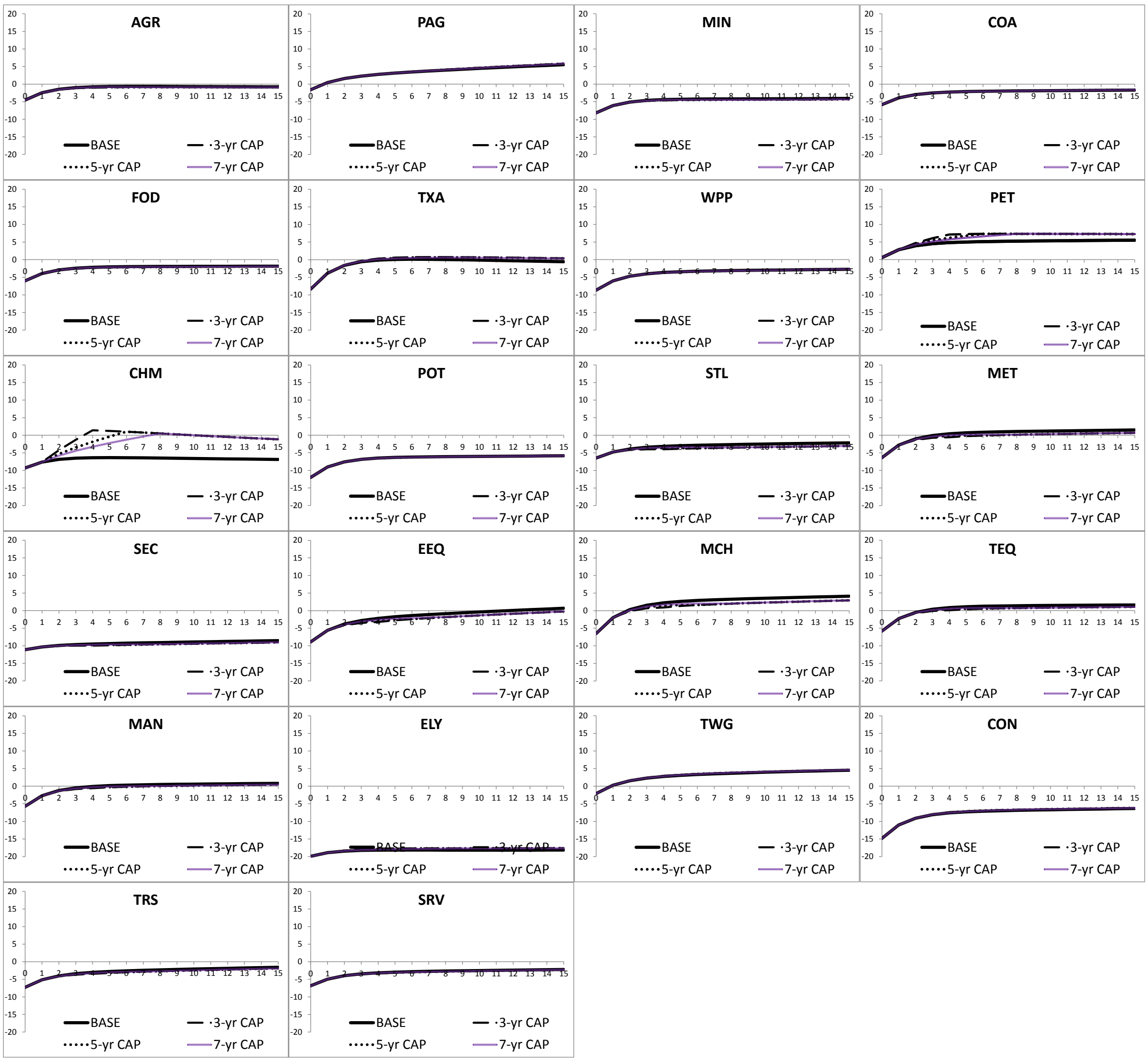

Figure 3.8: Sectoral Output with and without Capital-use Subsidies for Chemical Sector
[Unit: deviations from the BAU, %]

The electric power sector (ELY) would be hit so severely by the compound disaster that it could not achieve a recovery at all, even via very heavy subsidization of its output sales or capital usage (Figure 3.10).

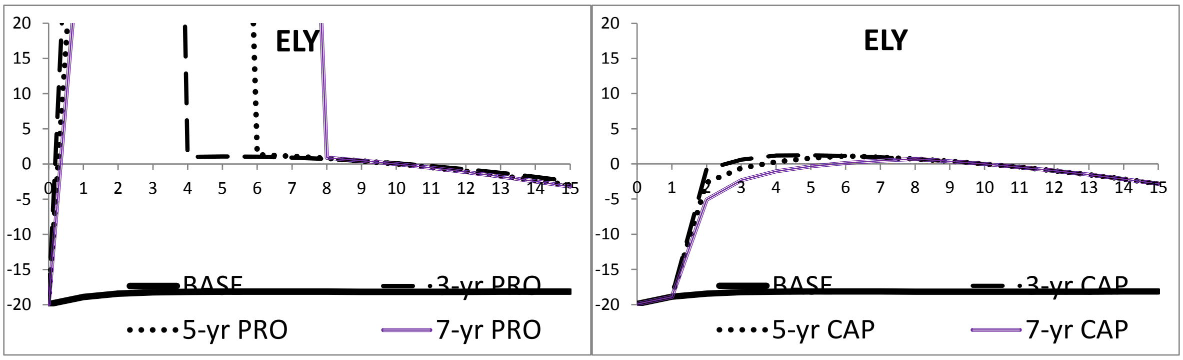

Figure 3.10: Output of Electric Power Sector with and without Production Subsidies (PRO) (Left Panel) and Capital-use Subsidies (CAP) (Right Panel)
[Unit: deviations from the BAU, %]

4. Concluding Remarks

In this paper, we simulated a compound disaster to hit northern Taiwan, where capital and major industries are located, in a dynamic CGE framework. We focused on the recovery process of these industries and examined the effectiveness and efficiency of recovery programs with production or capital-use subsidies. Among the four sectors examined, SEC could achieve a sustainable recovery in 10 years with subsidies which, however, need a very larger special budget in light of the Taiwan's annual budget. This indicates the full recovery of SEC would be too costly to pursue; we may have to be compromised and may have to pursue a more moderate recovery target. On the other hand, EEQ could recover with only a little help of subsidies.

Regarding the recovery program schemes, capital-use subsidies would cost less than production subsidies. The latter would need high subsidy rates that cause overshooting in the recovery process and, thus, are inefficient. When the recovery program is designed to support SEC for 2 years longer with a lower subsidy rate, we can save the fiscal costs by 7–10%. As subsidies cause distortions in resource allocation, efficiency losses would follow the recovery program. It is noteworthy that we would bear an additional 3% of social losses for the recovery of SEC. This is equivalent to an annual burden as high as 37,411 TWD per household or 3.4% of household income. This is solely a political issue of whether people are willing to bear such large costs for the recovery of their flagship industry.

While we could achieve a recovery of these two sectors, albeit sometimes at great cost, the energy-intensive sectors of CHM and ELY could not recover. The success or failure of their recovery would inevitably lead to the transformation of Taiwan's industrial structure after a disaster. As long as power supply is limited by a nuclear power shutdown, energy-intensive industries in the domestic economy could barely survive and would be replaced by other sectors that use less energy and/or could carry out offshoring of their production processes while maintaining their headquarters domestically. Such disaster-induced offshoring needs to be considered in a future analysis.

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References

Akune, Y., M. Okiyama, and S. Tokunaga. 2013. "The Evaluation on the Recovery Policy on Fishery Industry in the Great East Japan Earthquake: An approach of Dynamic CGE Model", RIETI Policy Discussion Paper Series 13-P-022. [in Japanese] (http://www.rieti.go.jp/jp/publications/pdp/13p022.pdf)

Armington, P. 1969. "A Theory of Demand for Products Distinguished by Place of Production", *International Monetary Fund Staff Papers*, 16: 159–178.

Board of Audit of Japan. 2013. *Audit Report for the Recovery Projects and their Implementations for the Great East Japan Earthquake*, the Government of Japan, Tokyo. [in Japanese] (http://report.jbaudit.go.jp/org/pdf/251031_zenbun_1.pdf)

Chang, Y., and D. Guan. 2005. "An Empirical Study on Total Factor Productivity and Economic Growth in Taiwan", *Socioeconomic Law and Institution Review*, 36: 111–154. (http://web.ntpu.edu.tw/~guan/papers/tfp.pdf) [in Chinese]

Chen, H. 2013. "Non-nuclear, Low-carbon, or Both? The Case of Taiwan", *Energy Economics* 39: 53–65.

Chow, G., and A. Lin. 2002. "Accounting for Economic Growth in Taiwan and Mainland China: A Comparative Analysis," *Journal of Comparative Economics*, 30(3): 507–530.

Davis, I. (Ed.) 2014. *Disaster Risk Management in Asia and the Pacific*. Routledge, London, UK.

Directorate-General of Budget, Accounting and Statistics, (DGBAS). 2007. Labor Force Statistics by County and Municipality, Taiwan. [in Chinese] (http://win.dgbas.gov.tw/dgbas04/bc4/timeser/shien_f.asp).

Directorate-General of Budget, Accounting and Statistics (DGBAS). 2011a. *2006 I/O Table of Taiwan*, Executive Yuan, Taiwan. (http://eng.stat.gov.tw/lp.asp?ctNode=1650&CtUnit=799&BaseDSD=7&MP=5)

Directorate-General of Budget, Accounting and Statistics, (DGBAS). 2011b. *Agriculture, Forestry, Fishery and Animal Husbandry Census*, Taiwan. (http://eng.stat.gov.tw/lp.asp?CtNode=1634&CtUnit=784&BaseDSD=7&mp=5)

Fukushige, M., and H. Yamawaki. 2015 "The Relationship between an Electricity Supply Ceiling and Economic Growth: An Application of Disequilibrium Modeling to Taiwan", *Journal of Asian Economics* 36, 14–23.

Hertel, T. (Ed.) 1997. *Global Trade Analysis*, Cambridge, New York.

Hosoe, N. 2014. "Japanese Manufacturing Facing Post-Fukushima Power Crisis: a Dynamic Computable General Equilibrium Analysis with Foreign Direct Investment", *Applied Economics* 46(17): 2010–2020.

Hsinchu Science Park. 2011. *The Special Edition for 30 Anniversary of Hsinchu Science Park*, Science Park Administration. [in Chinese] (http://www.sipa.gov.tw/file/20101216143851.pdf)

Huang, J.-H., and J. C. H. Min. 2002. "Earthquake Devastation and Recovery in Tourism: the Taiwan Case", *Tourism Management* 23: 145–154.

Huang, M., and N. Hosoe. 2014. "A General Equilibrium Assessment on a Compound Disaster in Northern Taiwan", GRIPS Discussion Paper 14-06. (http://www.grips.ac.jp/r-center/wp-content/uploads/14-06.pdf)

Kawata, Y. 2011. "Downfall of Tokyo due to Devastating Compound Disaster", *Journal of Disaster Research*, 6(2): 176–184.

Mai, C., Z. Yu, K. Sun, A. Lin, C. Wang, C. Chen, L. Shue, K. Ma, C. Chong, C. Du, Y. Du, C. Chou, and C. Hsu. 1999. *The Estimation of 921 Earthquake on Taiwan's Economy*, Chung-Hua Institution for Economic Research, Taipei, Taiwan. [in Chinese]

McEntire, D. 2006. *Disaster Response and Recovery*, Wiley, NY, USA.

Okiyama, M., S. Tokunaga, and Y. Akune. 2014 "Hisai-chiiki-keizai-eno Koka-teki-na Fukko-zaigen Seisaku-ni-kansuru Oyo-ippan-kinko-bunseki (Analysis of the Effective Source of Revenue to the Disaster-affected Region of the Great East Japan Earthquake: Utilizing the Two-regional CGE Model)", *Journal of Applied Regional Science 18*, 1–16. (In Japanese)

Prater, C., and J. Wu. 2002. "The Politics of Emergency Response and Recovery: Preliminary Observations on Taiwan's 921 Earthquake", *Australian Journal of Emergency Management*, 17: 48–59. (http://www.em.gov.au/documents/politics%20of%20emergency%20response%20and%20recovery.pdf)

Shieh, J. 2004. "Analysis of 921 Post-Earthquake Housing Reconstruction Policies", *International Conference in Commemoration of 5th Anniversary of the 1999 Chi-Chi Earthquake Proceedings*, Taipei, Taiwan: National Science Council.

Tsai, C., and C. Chen. 2011. "The Establishment of a Rapid Natural Disaster Risk Assessment Model for the Tourism Industry", *Tourism Management*, 32: 158–171.

Yamazaki, M., and S. Takeda. 2013. "An Assessment of a Nuclear Power Shutdown in Japan Using the Computable General Equilibrium Model", *Journal of Integrated Disaster Risk Management*, 3(1). (http://idrimjournal.com/index.php/idrim/article/viewFile/55/pdf_21)

Appendix Sensitivity Analysis

In CGE analysis, simulation results often depend on assumptions of key parameters. To examine the robustness of our results, sensitivity tests are conducted with respect to (1) the depreciation rate *dep*; (2) the rate of return of capital *ror*; (3) the population growth rate *pop*; (4) the elasticity parameter for investment allocation ζ; (5) the elasticity of substitution among energy sources σ^e and (6) Armington's (1969) elasticity of substitution/transformation σ_i/ψ_i.

We shifted these parameter values from those used in the main text (Table 2.2). The results generally show that our findings are qualitatively robust. Quantitatively, smaller fiscal and social costs would be generated by assuming a larger *dep* and ζ, which make investment and capital adjustment more flexible and with a larger *pop*, which makes capital less important. On the other hand, the impact of shifting *ror*, σ_i, ψ_i, and σ^e are found to be small.

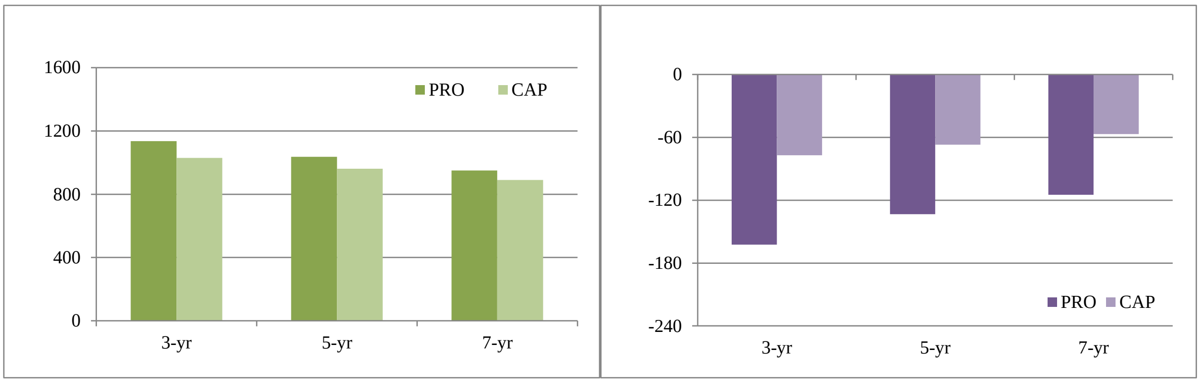

Figure A.1: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with *dep*=0.05
[unit: billion TWD]

Note: The total fiscal costs and social costs measured by the Hicksian equivalent variations in Periods 1–10 are discounted at a rate of 4%.

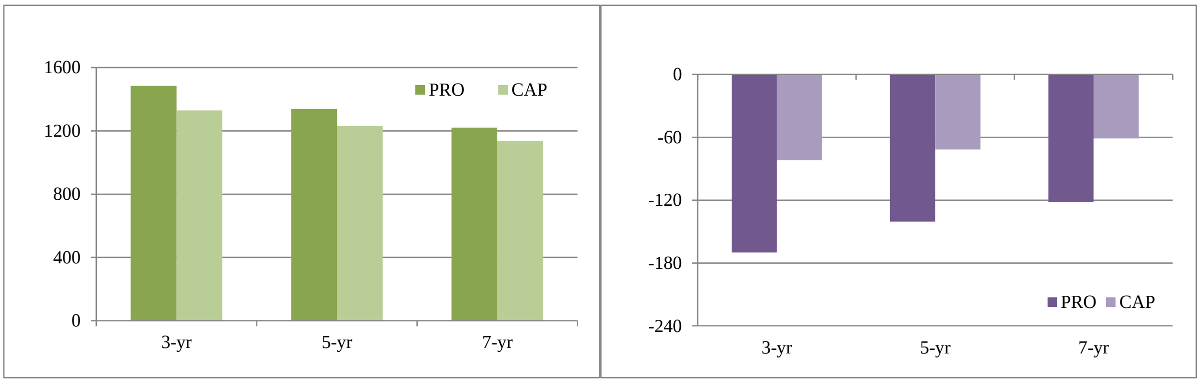

Figure A.2: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with *ror*=0.06
[unit: billion TWD]

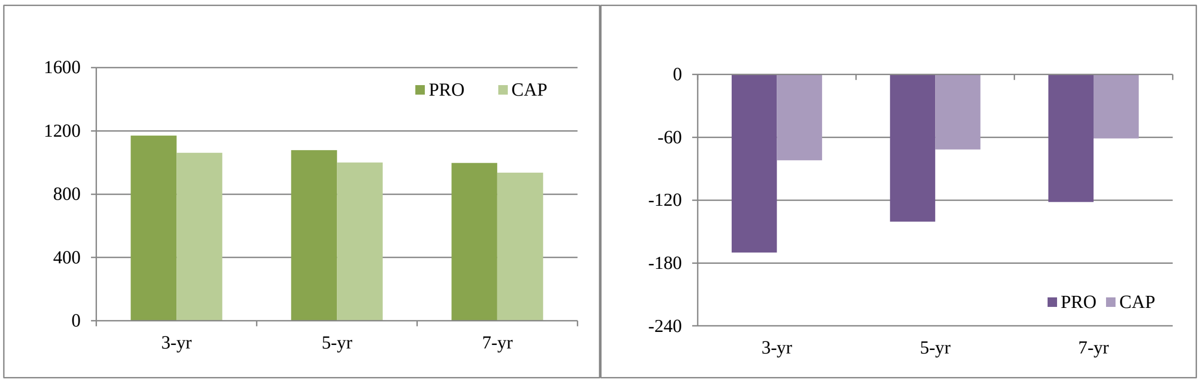

Figure A.3: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with *pop*=0.02
[unit: billion TWD]

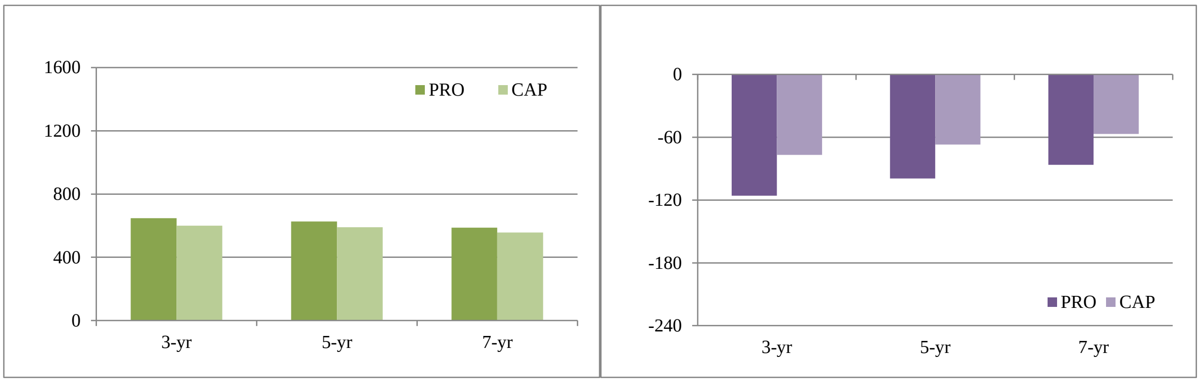

Figure A.4: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with $\zeta = 2$
[unit: billion TWD]

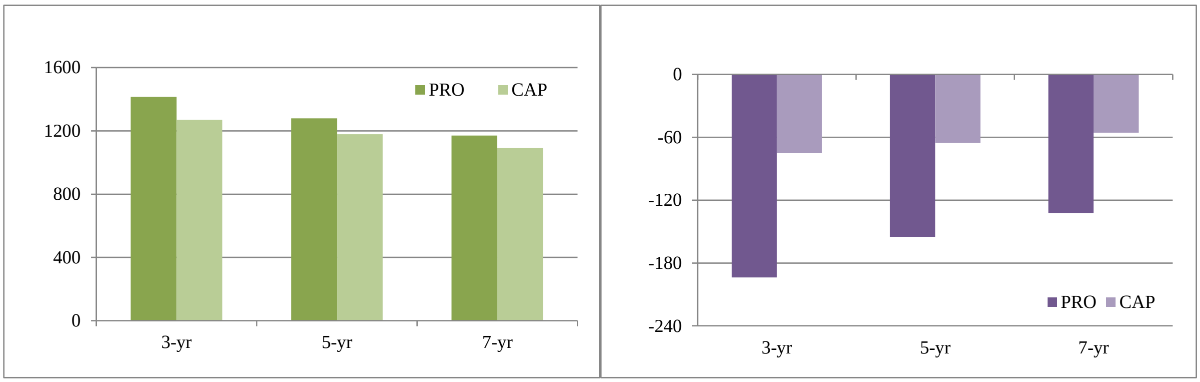

Figure A.5: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with $\sigma^e = 2$
[unit: billion TWD]

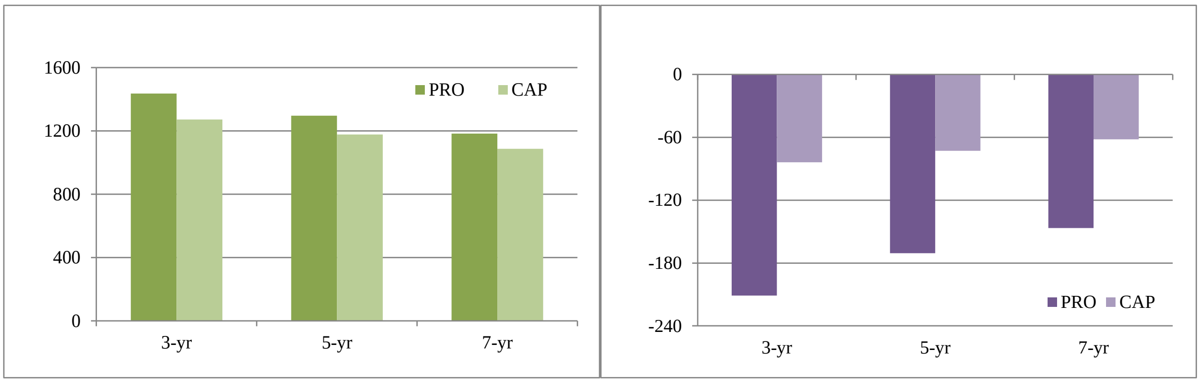

Figure A.6: Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for the Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with 30% smaller σ_i/ψ_i
[unit: billion TWD]

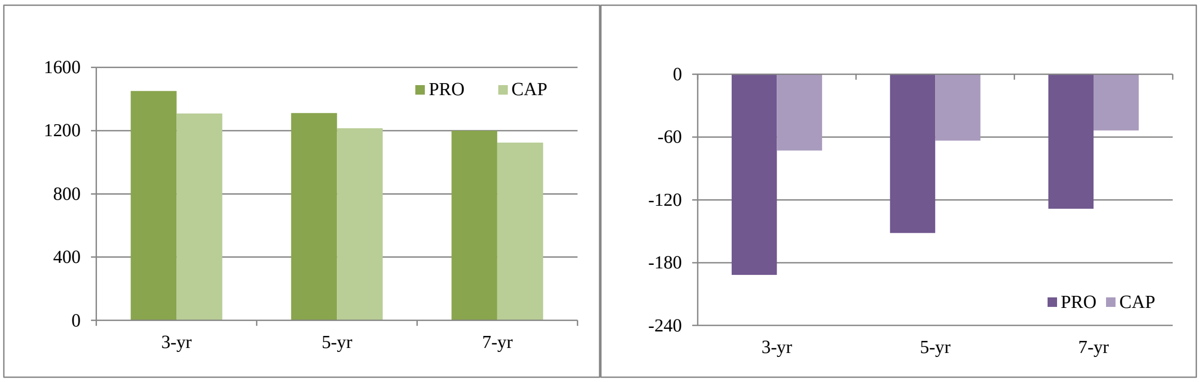

Figure A.7 Fiscal (Left Panel) and Social Costs (Right Panel) of Recovery Programs for Semiconductor Sector with Production Subsidies (PRO) and Capital-use Subsidies (CAP) with 30% larger σ_i/ψ_i
[unit: billion TWD]

Annex Details of the Model

Although the model we developed is a dynamic model, we do not show the time suffix t for simplicity unless needed.

Type of goods and factors, etc. in suffix	Symbol	Abbreviations
Sectors	i, j	AGR, PAG, MIN, COA, FOD, TXA, WPP, PET, CHM, CHM, POT, STL, MET, SEC, EEQ, MCH, TEQ, MAN, ELY, TWG, CON, TRS, SRV
Energy goods	ei, ej	PAG, PET, COA, ELY, TWG
Non-energy goods for the industries	ni, nj	$\{i\}\setminus\{ei\}$
Energy goods for households	$ei2$, $ej2$	PAG, PET, ELY, TWG
Non-energy goods for the household	$ni2$, $nj2$	$\{i\}\setminus\{ei2\}$
Non-electricity goods	ne	$\{i\}\setminus$ELY
Factor	h, k	CAP, LAB
Mobile factor	h_mob	LAB
Time period	t	0, 1, 2, …, 30

Endogenous variables

Y_j	Composite factor used by the j-th sector
$F_{h,j}$	The h-th factor input by the j-th sector
$X_{i,j}$	Intermediate input of the i-th good by the j-th sector
Z_j	Output of the j-th good
X_i^p	Household consumption of the i-th good
X_i^g	Government consumption
X_i^v	Input for composite investment good production

X_i^e	Energy composite used by the i-th sector
X^{pe}	Energy composite used by the household
E_i	Exports of the i-th good
M_i	Imports of the i-th good
Q_i	Armington's composite good
D_i	Domestic good
$p_{h,j}^f$	Price of $F_{h,j}$
p_j^y	Price of Y_j
p_i^e	Export price (in local currency)
p_i^m	Import price (in local currency)
p_i^d	Price of D_i
p_{ne}^{xe}	Price of X_{ne}^e
p^{xpe}	Price of X^{pe}
p_i^q	Price of Q_i
p_j^y	Price of Y_j
p_j^z	Price of Z_j
p^k	Price of the composite investment good, III
ε	Exchange rate
T^d	Direct tax revenue
T_j^z	Production tax revenue from the j-th sector
T_i^m	Import tariff revenue from the i-th good imports
$T_{h,j}^f$	Factor tax revenue from the uses of the h-th factor by the j-th sector
II_i	Sectoral investment in the i-th sector
III	Composite investment good
S^p	Private saving
KK_i	Capital stock in the i-th sector
CC	Composite consumption or felicity
$FF_{h,j}$	Factor endowment of the h-th factor in the j-th sector

Exogenous variables

τ_i^z	Production tax rate
τ_i^m	Import tariff rate
$\tau_{h,j}^f$	Factor tax rate for the h-th factor use by the j-th sector
S^f	Foreign savings (in US dollars)
p_i^{We}	World export price (in US dollars)
p_i^{Wm}	World import price (in US dollars)

Parameters

σ_i	Armington's elasticity of substitution between imports and domestic goods
σ^e	Elasticity of substitution among energy sources
ψ_i	Elasticity of transformation between exports and domestic goods
η_i	Substitution elasticity parameter (= $(\sigma_i - 1)/\sigma_i$)
ϕ_i	Transformation elasticity parameter (= $(\psi_i + 1)/\psi_i$)
χ	Substitution elasticity of energy goods (=$(\sigma^e - 1)/\sigma^e$)
pop	Population growth rate
ror	Rate of return of capital
dep	Depreciation rate
ς	Elasticity parameter for sectoral investment allocation

[Domestic production]

Composite factor production function (Cobb-Douglas)

$$Y_j = b_j \prod_h F_{h,j}{}^{\beta_{h,j}} \qquad \forall j$$

Factor demand function (Cobb-Douglas)

$$F_{h,j} = \frac{\beta_{h,j} p_j^y}{\left(1 + \tau_{h,j}^f\right) p_{h,j}^f} Y_j \qquad \forall h, j$$

Intermediate good demand function for non-electricity sectors

$$X_{ni,ne} = ax_{ni,ne} Z_{ne} \qquad \forall ni, ne$$

The energy composite good demand function for the non-electricity sectors

$$X_{ne}^{e} = ax_{ne}^{e} Z_{ne} \qquad \forall ne$$

Intermediate good demand function for the electricity sector (ELY)

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

The unit cost function for the non-electricity sectors

$$p_{ne}^{z} = ay_{ne} p_{ne}^{y} + \sum_{ni} ax_{ni,ne} p_{ne}^{q} + ax_{ne}^{e} p_{ne}^{xe} \qquad \forall ne$$

The unit cost function for the electricity sector (ELY)

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

[Household consumption]

Household demand of non-energy goods

$$X_{ni2}^{p} = \frac{\alpha_{ni2}}{p_{ni2}^{q}} \left(\sum\nolimits_{h,j} p_{h,j}^{f} FF_{h,j} - S^{p} - T^{d} \right) \qquad \forall ni2$$

Household demand of the energy composite good

$$X^{pe} = \frac{\alpha^{e}}{p^{xpe}} \left(\sum_{h,j} p_{h,j}^{f} FF_{h,j} - S - T^{d} \right)$$

[Felicity/Composite consumption good production function]

$$CC = a \left(\prod_{i} X_{i}^{p\,\alpha_{i}} \right) \left(X^{pe\,\alpha^{e}} \right)$$

[Energy Composite Aggregation]

The energy composite aggregation function for the non-electricity sectors

$$X_{ne}^{e} = o_{ne} \left(\sum_{ei} \kappa_{ei,ne} X_{ei,ne}{}^{\chi} \right)^{1/\chi} \qquad \forall ne$$

The energy good demand function for the non-electricity sectors

$$X_{ei,ne} = \left(\frac{{o_{ne}}^{\chi} \kappa_{ei,ne} p_{ne}^{xe}}{p_{ei}^{q}} \right)^{1/(1-\chi)} X_{ne}^{e} \quad \forall ei, ne$$

The energy composite aggregation function for the household

$$X^{pe} = o^{p} \left(\sum_{ei2} \kappa_{ei2}^{p} X_{ei2}^{p^{\chi}} \right)^{1/\chi}$$

The energy goods demand for the household

$$X_{ei2}^{p} = \left(\frac{o^{p^{\chi}} \kappa_{ei2}^{p} p^{xpe}}{p_{ei2}^{q}} \right)^{1/(1-\chi)} X^{pe} \quad \forall ei2$$

[Government behavior]

Factor tax revenue

$$T_{h,j}^{f} = \tau_{h,j}^{f} p_{h,j}^{f} F_{h,j} \quad \forall h, j$$

Lump-sum direct tax revenue

$$T^{d} = \sum\nolimits_{i} p_{i}^{q} X_{i}^{g} + S^{g} - \left(\sum\nolimits_{i} T_{i}^{m} + \sum\nolimits_{i} T_{i}^{z} + \sum\nolimits_{h,j} T_{h,j}^{f} \right)$$

Import tariff revenue

$$T_{i}^{m} = \tau_{i}^{m} p_{i}^{m} M_{i} \quad \forall i$$

Indirect tax revenue

$$T_{j}^{z} = \tau_{j}^{z} p_{j}^{z} Z_{j} \quad \forall j$$

[International Trade]

Export and import prices and the exchange rate

$$p_{i}^{e} = \varepsilon p_{i}^{We} \quad \forall i$$

$$p_i^m = \varepsilon p_i^{Wm} \qquad \forall i$$

Balance-of-payment constraint

$$\sum_i p_i^{We} E_i + S^f = \sum_i p_i^{Wm} M$$

Armington composite good production function

$$Q_i = \gamma_i (\delta m_i {M_i}^{\eta_i} + \delta d_i {D_i}^{\eta_i})^{1/\eta_i} \qquad \forall i$$

Import demand function

$$M_i = \left(\frac{{\gamma_i}^{\eta_i} \delta m_i p_i^q}{(1 + \tau_i^m) p_i^m} \right)^{1/(1-\eta_i)} Q_i \qquad \forall i$$

Domestic good demand function

$$D_i = \left(\frac{{\gamma_i}^{\eta_i} \delta d_i p_i^q}{p_i^d} \right)^{1/(1-\eta_i)} Q_i \qquad \forall i$$

Gross domestic output transformation function

$$Z_i = \theta_i \left(\xi e_i {E_i}^{\phi_i} + \xi d_i {D_i}^{\phi_i} \right)^{1/\phi_i} \qquad \forall i$$

Export supply function

$$E_i = \left(\frac{{\theta_i}^{\phi_i} \xi e_i (1 + \tau_i^z) p_i^z}{p_i^e} \right)^{1/(1-\phi_i)} Z_i \qquad \forall i$$

Domestic good supply function

$$D_i = \left(\frac{{\theta_i}^{\phi_i} \xi d_i (1 + \tau_i^z) p_i^z}{p_i^d} \right)^{1/(1-\phi_i)} Z_i \qquad \forall i$$

[Dynamic Equations]

Composite investment good production function

$$III = \iota \prod_i X_i^{v\lambda_i}$$

Sectoral investment allocation for the j-th sector

$$p^k II_j = \frac{{p^f_{CAP,j}}^{\zeta} F_{CAP,j}}{\sum_i {p^f_{CAP,i}}^{\zeta} F_{CAP,i}} (S^p + \varepsilon S^f) \quad \forall j$$

Capital accumulation

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

[Market-clearing condition]

Armington's composite good market-clearing condition

$$Q_i = X_i^p + X_i^g + X_i^v + \sum_j X_{i,j} \quad \forall i$$

Capital service market-clearing condition

$$F_{CAP,j} = rorKK_j \quad \forall j$$

Labor market-clearing condition

$$\sum_j F_{h\_mob,j} = \sum_j FF_{h\_mob,j} \quad \forall h\_mob$$

$$p^f_{h\_mob,j} = p^f_{h\_mob,i} \quad \forall h\_mob,i,j$$

Investment good market-clearing condition

$$\sum_j II_j = III$$