Will Greenhouse Gases Mitigation Policies Abroad affect the Domestic Economy? The Case of Taiwan

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Abstract

In this study we examine that when Taiwan carries out its national determined contribution (NDC) for the Paris agreement, will mitigation policies abroad affect Taiwan's economy, which participates actively in international trade activities and depends heavily on fossil fuel imports? To answer this question, we apply a global computable general equilibrium (CGE) model where Taiwan is explicitly represented and international trade is considered. We find that whether Taiwan will gain from foreign mitigation efforts depends on policy stringency. Under the current NDCs, when Taiwan accomplishes its NDC as part of a global policy, Taiwan's negative GDP impact is lowered compared with unilateral implementation because, under a global policy, producer prices for fossil fuels are suppressed, benefitting Taiwan. Nevertheless, with further emissions cut globally beyond the current NDCs, foreign mitigation efforts could hurt Taiwan, as capitalizing on lower fossil fuel prices becomes harder for Taiwan when cutting Taiwan's fossil fuel usage turns out indispensable, and as exports of Taiwan drop due to weaker foreign demand. We also evaluate the effect of U.S. withdrawal from the Paris Agreement, and find it has minimal impacts on Taiwan's economy compared with the global policy scenario, as changes in fossil fuel prices are small.

Keywords: Global economy-wide analysis; Energy-economic modeling; GHGs mitigation

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1. INTRODUCTION

Taiwan has proposed significant reductions in its greenhouse gas (GHG) emissions, which mostly come from burning fossil fuels. Specifically, CO_2 emissions from burning fossil fuels accounted for 89.2% of Taiwan's total GHG emissions in 2015 (The Environmental Protection Agency (EPA), 2017). Emissions mitigation policies may pose a challenge on Taiwan's economy because fossil fuels have been the dominant sources of its energy supply portfolio. Currently, in terms of the oil equivalent unit, Taiwan imports around 98% of its total energy supply (the sum of indigenous production and imports)[1], and 95.5% of which are fossil fuels, with the remaining 4.5% being the nuclear energy (Bureau of Energy (BOE), 2018).

In addition to energy imports, overall, international trade activities are crucial to Taiwan's economy. For instance, exports and imports account for 62% and 50% of Taiwan's GDP in 2015, respectively (National Development Council, 2016). Therefore, besides the domestic GHG reduction policies, similar policies abroad may also significantly affect Taiwan's economy through channels of international trade. As a result, even with a country-specific focus, using a modeling framework that takes into account the international trade is essential for analyzing the potential impact of a worldwide GHG mitigation effort on Taiwan's economy.

Nevertheless, so far relevant studies on Taiwan are simply based on a single-country modeling framework (Chen, 2013; Lin et al., 2012, Lin et al., 2009; Li, 2000). This framework, however, is ill-equipped for representing international trade, which constitutes a crucial part of Taiwan's economic activities. The limitation of the single-country setting makes it hard to consider the impact of foreign policies on domestic economy. To overcome this restriction and capture the trade effects, we develop and apply a global computable general equilibrium (CGE) model with energy use and emissions details where Taiwan is explicitly represented. With a global coverage and an explicit modeling for international trade, our model allows us to consider effects of foreign policies. In particular, the Paris Agreement, of which Taiwan is a part through its nationally determined contribution (NDC), entered into force in November 2016 (UNFCCC, 2016).

Under the Paris Agreement, most countries of the world will undertake climate policy simultaneously with efforts in Taiwan. Policies abroad may interact with measures taken in Taiwan through trade, affecting the cost and broader consequences for Taiwan. Therefore, our study will explore how different are the policy impacts on Taiwan if its NDC targets are enforced in the context of a global effort, versus if they are undertaken unilaterally? Since the federal government of the U.S. has announced its intention to withdraw from the agreement, we also consider the scenario where the U.S. only partially achieves its NDC through the state-level efforts, while other countries including Taiwan fulfill their NDC goals as planned. The rest of the paper is organized as follows: Section 2

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[1] This is equal to the sum of total primary energy supply, exports, international marine bunkers, international civil aviation, and stock changes. See Bureau of Energy (2018).

presents the model structure and data; Section 3 discusses the considered scenarios and analyzes simulation results; and Section 4 provides conclusions and future research directions.

2. MODEL STRUCTURE AND DATA

Our model, the Economic Projection and Policy Analysis (EPPA)-Taiwan, is a version of the MIT EPPA model developed jointly by the Institute of Nuclear Energy Research (INER) of Taiwan and the MIT Joint Program on the Science and Policy of Global Change (MIT JP). The motivation for the model's development is to study the implications of energy or carbon mitigation policies on Taiwan's economy. Taiwan has adopted an aggressive emissions reduction goal under its National Determined Contribution (NDC) in the Paris climate agreement, proposing a 50% cut from the business-as-usual level by 2030 (EPA, 2015). Thus, we use policy simulations achieving this goal in our evaluations.

EPPA-Taiwan is a multi-region and multi-sector CGE model of the world economy that uses the Global Trade Analysis Project database version 9 (GTAP 9) (Aguiar et al., 2016). The database classifies the world economy into 140 regions, 57 sectors, 5 primary factors, and provides data from three different years. We use the latest data in the database, which has the reference year of 2011, and aggregate the database into 19 regions (**Table 1**), 14 sectors (**Table 2**), and 4 primary factors (**Table 3**)—these settings are similar to EPPA6 (Chen et al., 2016), except that Taiwan is explicitly identified as another region. The complete mappings for regions, sectors, and primary factors from GTAP 9 are provided in **Appendix A**.

Table 1. Regions.

EPPA-Taiwan region	Symbol	EPPA-Taiwan region	Symbol
United States	USA	South Korea	KOR
Canada	CAN	Indonesia	IDZ
Mexico	MEX	China	CHN
Japan	JPN	India	IND
Australia, New Zealand & Oceania	ANZ	Brazil	BRA
The European Union+	EUR	Africa	AFR
Eastern Europe and Central Asia	ROE	Middle East	MES
Russia	RUS	Latin America	LAM
East Asia	ASI	Rest of Asia	REA
Taiwan	TWN		

Note:+ The European Union (EU-28) plus Norway, Switzerland, Iceland, and Liechtenstein.

Table 2. Sectoral Aggregation.

EPPA-Taiwan sector	Symbol	Subgroup	EPPA-Taiwan sector	Symbol	Subgroup
Crops	CROP	agri	Gas	GAS	enoe
Livestock	LIVE	agri	Electricity	ELEC	elec
Forestry	FORS	agri	Energy-Intensive Industries	EINT	eint
Food Products	FOOD	naenoe	Manufacturing	MAN	naenoe
Coal	COAL	enoe	Ownership of Dwellings	DWE	naenoe
Crude Oil	OIL	enoe	Services	SERV	naenoe
Refined Oil	ROIL	enoe	Transport	TRAN	naenoe

Table 3. Primary factors.

Primary factors	Symbol	Subgroup
Capital	CAP	mf
Labor	LAB	mf
Land	LND	sf
Natural resources	FIX	sf

In EPPA-Taiwan, there are three types of agents in each region: household, producers, and government. The household provides primary factors (labor, capital, and natural resources) to producers, receives income in return, and allocates income to consumption and savings. Producers convert primary factors and intermediate inputs into goods and services, then sell them domestically or abroad to other producers, households, or governments. The government collects taxes from household and producers to finance government consumption and transfers. These activities can be represented by a series of circular flow diagrams connecting to each other via international trade (**Figure 1**). The model is formulated in a series of mixed complementary problems (MCP) (Mathiesen, 1985; Rutherford, 1995; Ferris and Peng, 1997), and is written and solved using the modeling languages of GAMS and MPSGE (Rutherford, 1999).

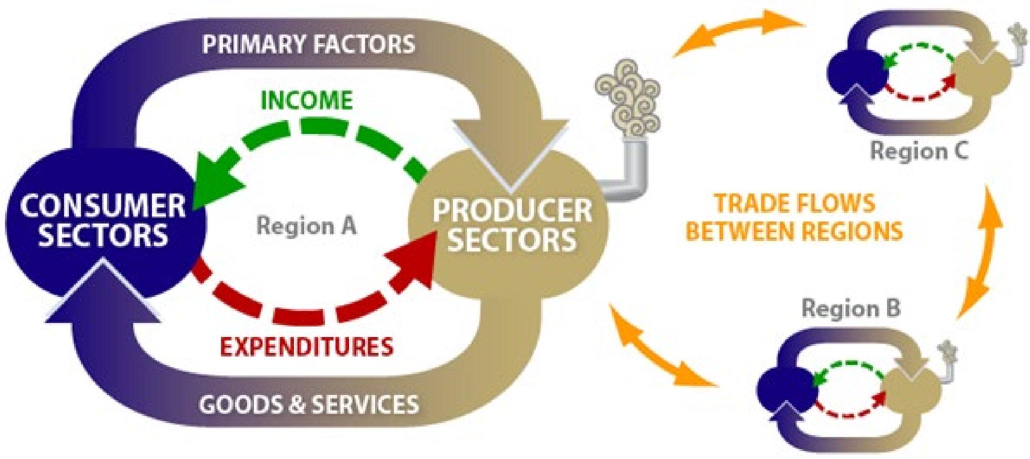

Figure 1. Schematic representation of EPPA-Taiwan.

To build a multi-region, multi-sector CGE model, a production nest must be specified for each production sector for each region, and an expenditure function must be specified for each representative regional household. Each sector uses primary inputs, and intermediate inputs (i.e., output of other sectors) to produce output. Each sector's output is used as an intermediate input or as final consumption.

To characterize production technology and consumer preferences, our model uses Constant Elasticity of Substitution (CES) functions and the special cases of it, including Leontief (elasticity of substitution of zero) and Cobb-Douglas (elasticity of substitution of one) functions. In addition, our model adopts a production structure that varies among sectors, providing greater flexibility in setting elasticities for individual inputs or groups of inputs, especially energy. In the model, each commodity can be imported and domestically produced, and they are aggregated together as an Armington good (Armington, 1969). Under this formulation, imported goods from a production sector and region are treated as imperfect substitutes for goods from the same sector produced domestically or in other regions.

The Armington assumption for aggregating domestically produced and imported goods allows a region to be both an importer and exporter of similar products, which reflects observed patterns, and the observation that most goods are differentiated (i.e., German goods produced by the Energy-Intensive Industry are substitutable for American, Japanese or Korean Energy-Intensive Industry goods, but they are not identical products). As a result, prices for similar sectors' goods from different regions can differ. When goods are perfect substitutes, there is a single global price, and a region cannot be both an exporter and importer in the same time period.

Per the household consumption, it includes energy, dwelling service, and other Armington goods, and they are aggregated by a nested CES function to form the expenditure function of the representative household. As in EPPA6 (Chen et al., 2016), the incentive for savings is taken into account in the expenditure function, and savings equal investment in the model. While this treatment may not be necessary in a static CGE, it provides the ground for developing a dynamic CGE for future studies. The elasticities of substitution for various nested CES functions used in our model are presented in **Appendix B**.

In a global CGE, besides interactions among sectors through inter-industry transactions, interactions among regions are considered via bilateral trade flows. As noted above, intermediate inputs and final consumption are Armington goods. We do not allow for a change in capital flows, and thus any change in the total value of exports must be balanced by an equal change in the total value of imports, i.e., we adopt the model closure where trade balance of each region remains unchanged. Each region may export part of its domestic outputs in exchange for imported commodities in a way such that any additional imports relative to the base year levels must be achieved by an increase in exports with similar market values. For most goods, the Armington assumption, which is widely used in modeling international trade, is adopted. The only exception in our model is crude oil, which is treated as a perfect substitute for other crude oil in global trade. Interested readers may refer to **Appendix B** and **Appendix C** for more details about the model structure and setting.

3. SIMULATIONS

To explore the implications on Taiwan's economy when it pursues its NDC to cut emissions, we calibrate the model so that it produces a business-as-usual (BAU) environment for the global economy in 2030—a strategy also known as "forward calibration." To do this, for each region, we calculate the total factor productivity level such that the projected BAU GDP in 2030 is consistent to the assumed BAU GDP growth rate and the given levels of labor, capital and autonomous energy efficiency improvement (AEEI). The growth rates of BAU GDP, labor, capital, and AEEI are drawn from Jacoby et al. (2017).

The policy scenarios we considered in this set of simulations include: 1) Taiwan pursues its NDC target unilaterally; 2) Taiwan and all countries in the rest of the world carry out their own NDC targets; and 3) Taiwan and most countries in the rest of the world carry out their NDCs as planned, except for the U.S., which only achieves half of its NDC's emissions reduction goal due to the U.S. withdrawal from the Paris Agreement. As mentioned in Section 2, Taiwan's NDC pledges to cut 50% of BAU GHG emissions by 2030. In both scenarios, we represent this target by cutting Taiwan's CO_2 emissions down to 50% of the BAU level. For each region, when a mitigation policy is in place, an economy-wide carbon tax is used as an instrument for cutting emissions. Since this assumes that the most efficient policy to achieve the NDC is in place, if alternatively, a country decides to cut emissions through other approaches, such as adjusting the energy consumption portfolio of the power sector (e.g., more gas and less coal) via administrative or legislative measures, the overall mitigation cost (e.g., reduction in GDP) could be higher.

For the second scenario where the rest of the world also pursues emissions mitigation, we draw the emissions reduction profiles from Jacoby et al. (2017) to represent NDCs of other EPPA regions. Specifically, for regions other than Taiwan, we draw from Jacoby et al. (2017) the projected emissions levels with regional NDCs in 2030 and the BAU emissions levels of the same year, and calculate the rate of emissions reduction relative to BAU in 2030 for each region. Subsequently, the reduction rate of each region is used as the target for CO_2 mitigation of that region considered in this simulation.[2]

Finally, for the third scenario, we consider the situation that even with the U.S. federal government withdrawing from the Paris Agreement, some mitigation efforts at the state level will still be carried out because some states, cities or businesses in the U.S. will continue to keep their commitments to fill part of the gaps left by the federal inaction. For example, New England and Mid-Atlantic states have founded the Regional Greenhouse Gas Initiative to regulate the power sector emissions (The Regional Greenhouse Gas Initiative (RGGI), 2018), and states including California have shown they can reduce their emissions by aggressive policies even in the absence of federal support (Urpelainen and Graaf, 2018). Of course, there are uncertainties regarding to what extent the NDC targets of the U.S. can be achieved. For instance, Larsen et al. (2018) found a 12% to 20% projected cut in GHG emissions by 2025 compared with the 2005 level, which is short of the Obama administration's 26% to 28% cut relative to the 2005 level presented in the NDC. To represent this scenario, we assume that the U.S. will achieve half of its NDC target.

As indicated in Section 1, international trade is crucial for Taiwan's economy. Therefore, we will study simulation results for Taiwan's domestic outputs and exports under different policy scenarios. In particular, we focus on the energy-intensive sector (EINT), manufacturing sector (MAN, with electrical and electronic manufacturers being the main players), and service sector (SERV). Based on the GTAP 9 database, these sectors together accounted for around 83% of Taiwan's total domestic output in the base year. The BAU results based on forward calibration for the year of 2030 show that, compared with other regions (especially developed countries), while Taiwan's EINT sector has relatively high levels of energy intensity (energy use per unit of output) and CO_2 intensity (carbon footprint per unit of output), those intensities are lower for Taiwan's MAN and SERV sectors. The projected regional energy and CO_2 intensities of these sectors for 2030 are provided in **Appendix D.**

Results from our model show that when Taiwan pursues its NDC, the negative impact on the EINT sector is higher than on the MAN and SERV sectors, regardless of whether other regions also pursue their NDCs. The sectoral output profile does not change much when concerted mitigation efforts exist at the global level (**Figure 2**). On the other hand, the exports of EINT products increase slightly under the global mitigation scenario (**Figure 3**), since the production cost of Taiwan's energy intensive sector becomes cheaper relative to the foreign production cost, due to the reduced fossil fuel prices.

Our simulation also reveals that compared with the scenario where Taiwan pursues its NDC unilaterally, prices of imported fossil fuels become much lower under the global mitigation scenario (**Figure 4**). In these figures we also present results for the scenario where the U.S. only achieves half of its NDC target. They show that under this scenario, compared with the case where all countries

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[2] Since most GHG emissions of Brazil are form land-use changes, which are not considered in our model, we draw Brazil's reduction rate of fossil CO_2 emissions from Jacoby et al. (2017) and use it as the reduction target of Brazil in our simulation.

carry out their NDCs as planned, while the impacts on Taiwan's sectoral output, exports, and fossil fuel prices are minimal, the negative impact on the energy intensive sector (EINT) is slightly higher since the reductions in fossil fuel prices are lessened, i.e., the fossil fuel prices will be increased as the U.S. (and therefore the world) consumes more fossil fuels due to the weakened mitigation efforts (**Figure 5**).

Next, we compare the impact on Taiwan's GDP under the three scenarios. We find that if all countries in the world can accomplish their NDC targets, the negative impact on Taiwan's GDP will be somewhat lower than the case where Taiwan carries out its NDC unilaterally, and when the U.S. fulfills only half of its target while other countries achieve their NDC goals, the negative impact on Taiwan's GDP is slightly increased compared with the case where globally all NDCs are implemented as planned (**Figure 6**).

We emphasize that the GDP impact is the outcome for the interaction of various factors.[3] For instance, the decreased value of total exports (Figure 3) resulted from the suppressed foreign demand when worldwide mitigation efforts exist will have negative impacts on Taiwan's economy, since it implies that for Taiwan, the value of total imports also has to decline, as our model closure suggests (see Section 2), and less imports eventually means the value of total consumption is diminished, a negative impact on GDP. On the other hand, the lower fossil fuel prices under the scenario with a global mitigation could benefit the economy (Figure 4), since it depends heavily on fossil fuel imports. Results in Figure 6 reveal that under the current NDCs of the Paris Agreement, for Taiwan, the benefit of lower fossil fuel prices outweighs the negative effects of diminished exports.

We find that results for Japan, another country that imports most of the fossil fuel supplies, are similar to those of Taiwan, i.e., the negative GDP impact of Japan is mitigated when all countries carry out their own NDCs as planned, as oppose to the negative GDP impact when Japan implements its NDC unilaterally (see **Figure E1** in **Appendix E**).[4] While a detailed cross-country comparison is beyond the scope of our study, we find that overall, the negative GDP impacts on Taiwan are higher than those of Japan, mainly because Taiwan's NDC, which requires cutting its BAU emissions by 50%, turns out to be much more stringent than Japan's, which is effectively a 22.9% cut relative to the BAU level.[5] Besides, compared with Japan, Taiwan depends more on coal and less on gas in its primary energy supply, and that may also contribute to the higher mitigation costs of Taiwan.[6]

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[3] We gratefully acknowledge the comment from one reviewer in improving the GDP impact analysis.

[4] We appreciate the suggestion of including the case of Japan for comparison purposes from a reviewer.

[5] While Japan pledges to cut 25% CO_2-e emission relative to the 2005 level, the projected BAU CO_2-e emission of Japan in 2030 is 2.8% lower than the 2005 level, and therefore Japan only needs to cut 22.9% of the BAU emission to meet its NDC.

[6] In the base year, coal, crude oil, and gas account for 41.0%, 40.3%, and 14.3% of Taiwan's total primary energy supply, while those shares for Japan are 26.5%, 40.4%, and 28.2% (Peters, 2016).

Finally, while we find that Taiwan could benefit from foreign mitigation efforts under the current NDCs, one question that follows is: can Taiwan still gain from the emissions cut abroad when mitigation efforts beyond the current NDCs are pursued worldwide?[7] To answer this question, we simulate two additional scenarios, where emissions cuts of all regions including Taiwan are increased by 20% and 40% relative to the current NDCs, respectively. We find that with further mitigation abroad, on the contrary, the negative GDP impact on Taiwan's economy becomes higher than that under the unilateral policy (**Figure 7**). This is because although prices for fossil fuels decline further as mitigation levels increase (**Figure 8**), cutting fossil fuel consumption of Taiwan to meet more stringent emissions cut means that it becomes harder for Taiwan to capitalize on the lower prices of fossil fuels. At the same time, the total exports of Taiwan decrease when all countries carry out their NDCs and when the worldwide mitigation efforts increase, both of which lower the GDP level of Taiwan (**Figure 9**).

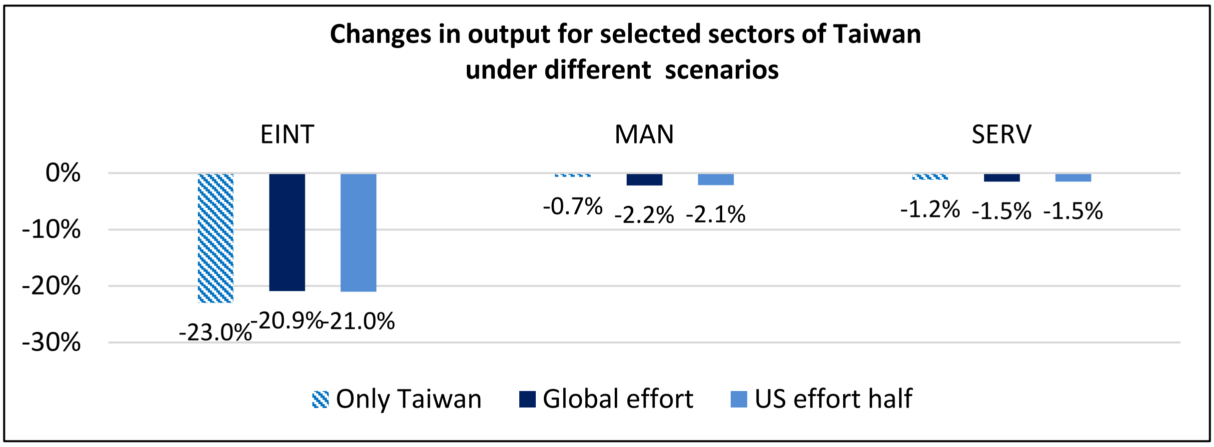

Figure 2. Changes in outputs for selected sectors of Taiwan under different scenarios.

[7] We appreciate the comment from a reviewer in raising this question.

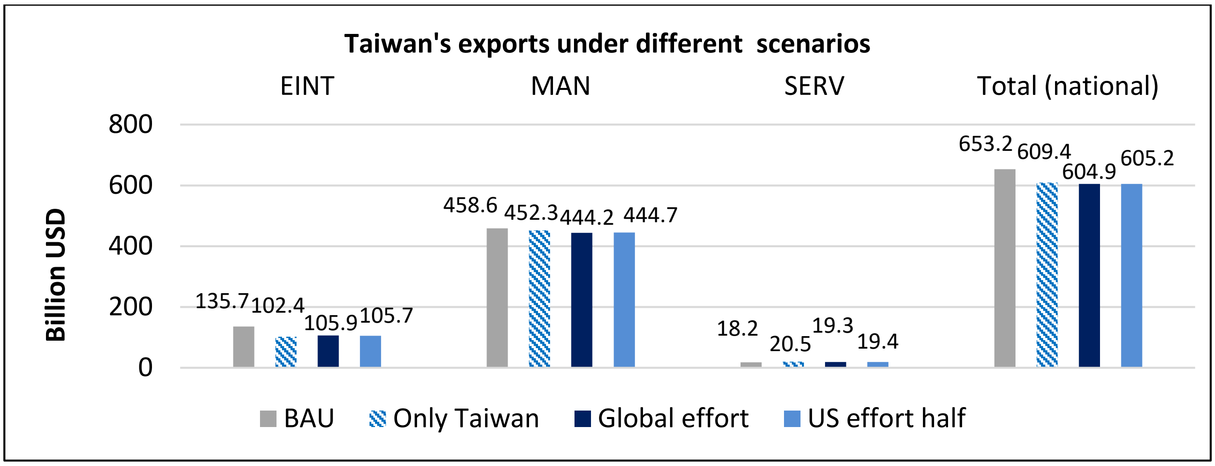

Figure 3. Exports of Taiwan under different scenarios.

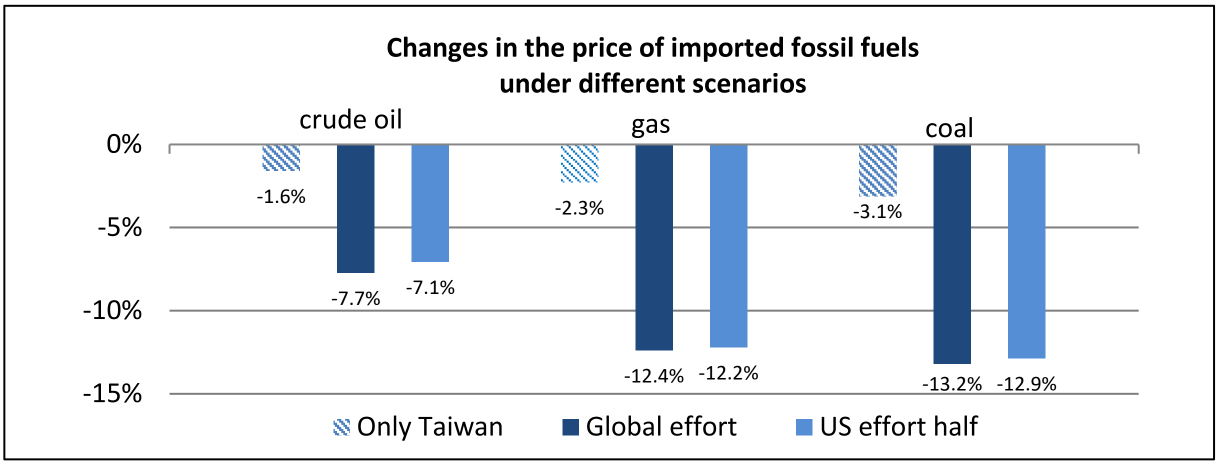

Figure 4. Changes in the prices of imported fossil fuels under different scenarios.

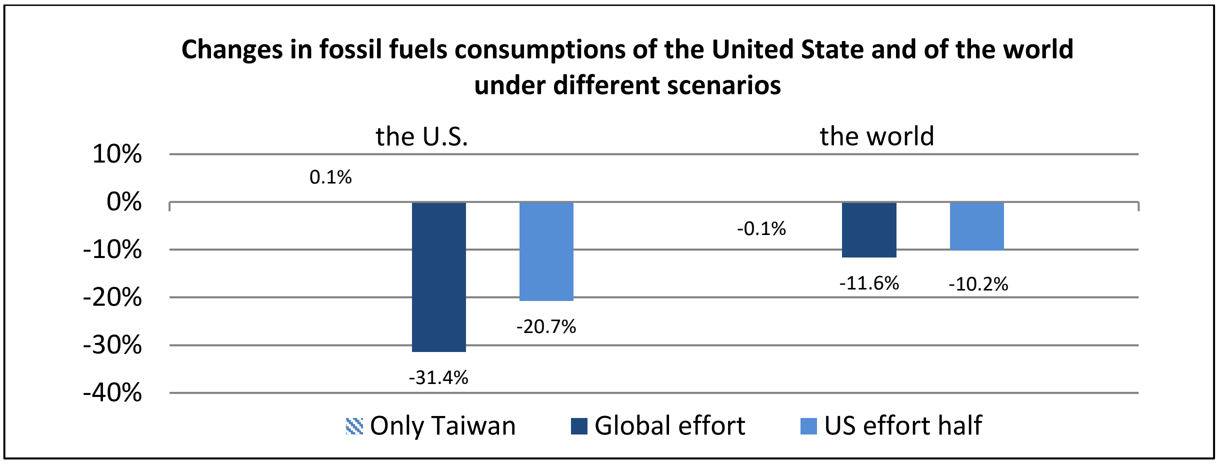

Figure 5. Changes in fossil fuels consumptions of the United State and of the world.

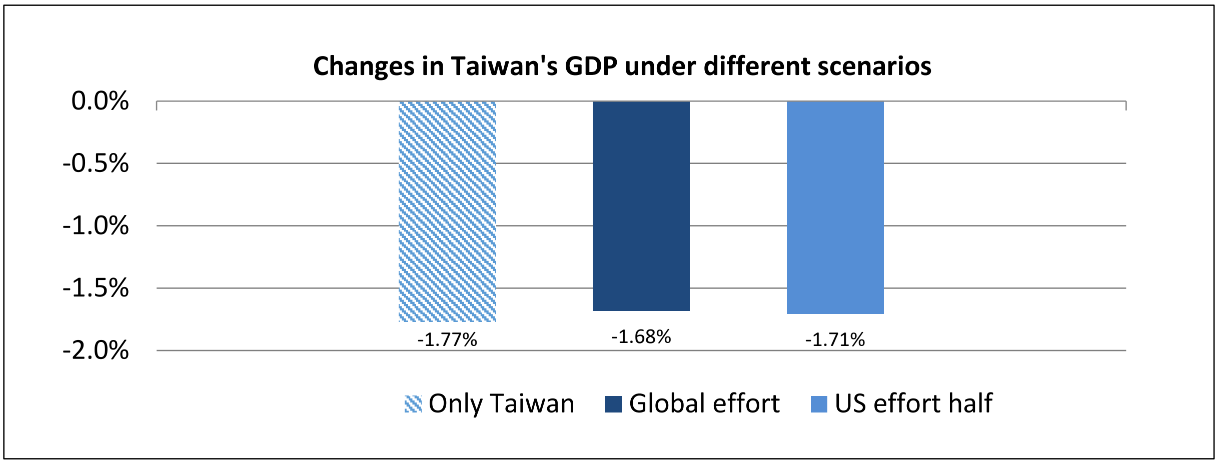

Figure 6. Changes in Taiwan's GDP under different scenarios.

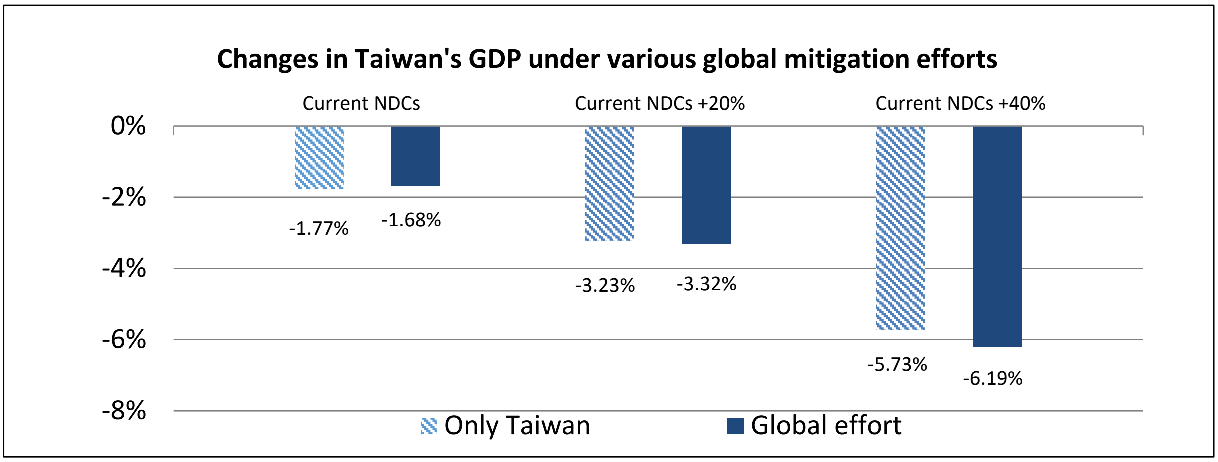

Figure 7. Changes in Taiwan's GDP under different global mitigation efforts.

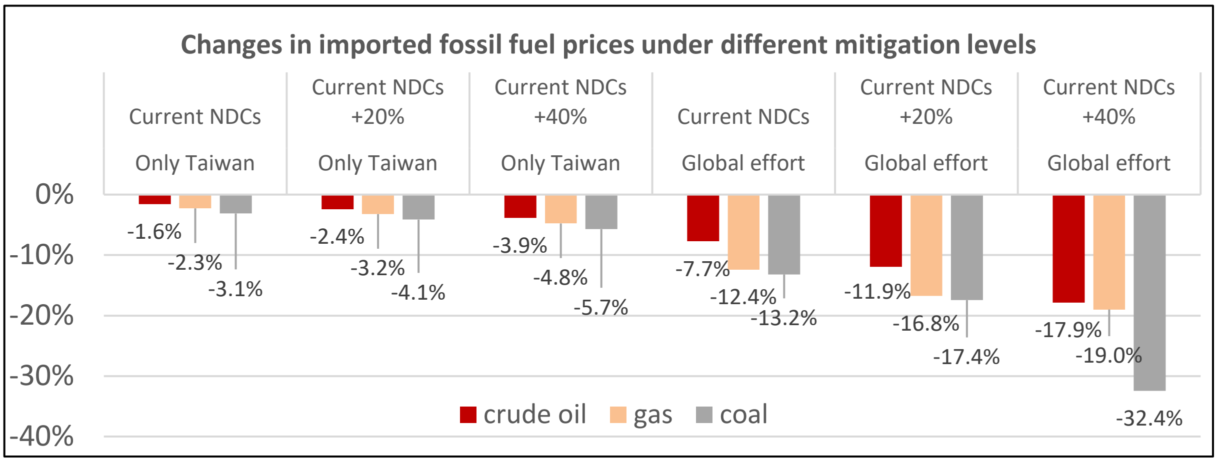

Figure 8. Changes in imported fossil fuel prices of Taiwan under different mitigation levels.

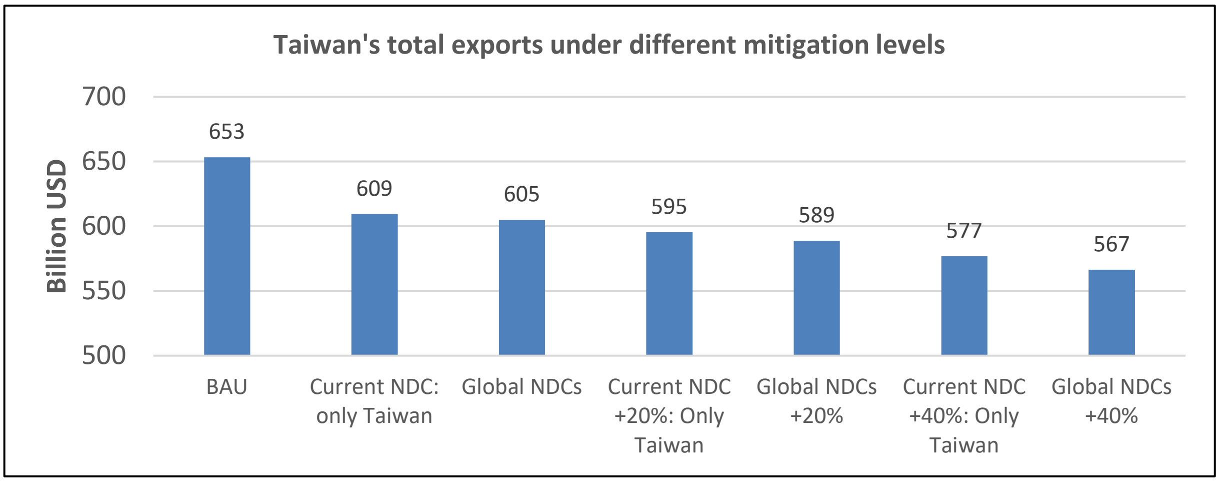

Figure 9. Taiwan's exports under different mitigation levels.

4. CONCLUSIONS

Global economy-wide equilibrium models have been used extensively by researchers in many countries to assess the effects of energy or climate policies, where sectoral and regional interactions need to be taken into account carefully. For Taiwan, which depends heavily on international trade and energy imports, relevant studies so far were conducted solely under a single-country modeling framework, which cannot capture effects such as impacts of climate mitigation policies abroad. To bridge this gap, we build a version of EPPA, a global energy-economic CGE model, where Taiwan is explicitly represented. The model allows us to explore the implications of pursuing Taiwan's emissions reduction target, as documented in its NDC, with and without a global mitigation effort.

We found that under the current NDCs of the Paris Agreement, a global policy benefits Taiwan, compared with a case where Taiwan acted alone. We traced this to the global policy significantly reducing prices for fossil fuels—crucial imports for Taiwan's economy. However, under a scenario with further emissions cut beyond the current NDCs globally, foreign mitigation efforts could hurt Taiwan, as capitalizing on lower prices for fossil fuels becomes harder for Taiwan when cutting Taiwan's consumption of fossil fuels is indispensable in meeting more stringent policies, and as exports of Taiwan drop due to weaker foreign demand. The finding suggests that for a small country that depends heavily on trade, it should consider the policies of other countries as well as its own, as policies abroad can affect the domestic economy.

Besides, we consider the scenario with the U.S. withdrawal from the Paris Agreement by assuming that U.S. only achieves half of its pledge through the state-level efforts, and find that while it has some negative impacts on Taiwan's economy via increased prices for fossil fuels, compared with the case where globally all NDCs are carried out as planned, these impacts are minimal. One implication of our findings is: if, however, more countries also follow the federal government of the U.S. and backtrack on their commitments in cutting emissions, it might become somewhat costlier for Taiwan to carry out its current NDC target, as prices for fossil fuels, which will remain crucial in Taiwan's energy supply portfolio even with the fulfilment of Taiwan's NDC, are likely to rise because of higher fossil fuel demand levels abroad due to weakened GHG mitigation efforts.

Our study demonstrates that even with a country-specific focus, for an economy such as Taiwan that relies heavily on imported fossil fuels and actively engages in international trade activities, using a model with global coverage can provide crucial insights for researchers and policy makers, as it can shed light on implications of the trade effects that are out of reach by studies based on a single-country framework.

Future extensions could be done in several different fronts so the model can answer questions beyond the current research scope. Those extensions may include 1) adopting the GTAP 9-Power data base that provides greater disaggregation of the electricity sector; 2) incorporating engineering data into the model to represent "backstop technologies" that may become economic under some energy or climate policies; and 3) developing a dynamic version of the model to better address issues about how changes in economic condition and policy stringency over time may affect the economy and emissions.

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APPENDIX A. Mappings of sectors, regions, and factors

Table A1. Mapping for regions from GTAP 9 to EPPA-Taiwan.

	GTAP 9 region	EPPA-Taiwan region		GTAP 9 region	EPPA-Taiwan region		GTAP 9 region	EPPA-Taiwan region
1	Albania	ROE	51	Kazakhstan	ROE	101	Ukraine	ROE
2	United Arab Emirates	MES	52	Kenya	AFR	102	Uruguay	LAM
3	Argentina	LAM	53	Kyrgyzstan	ROE	103	United States of America	USA
4	Armenia	ROE	54	Cambodia	REA	104	Venezuela	LAM
5	Australia	ANZ	55	Korea Republic of	KOR	105	Viet Nam	REA
6	Austria	EUR	56	Kuwait	MES	106	South Central Africa	AFR
7	Azerbaijan	ROE	57	Lao People's Democratic Republic	REA	107	Rest of Central America	LAM
8	Belgium	EUR	58	Sri Lanka	REA	108	Caribbean	LAM
9	Bangladesh	REA	59	Lithuania	EUR	109	Central Africa	AFR
10	Bulgaria	EUR	60	Luxembourg	EUR	110	Rest of East Asia	REA
11	Bahrain	MES	61	Latvia	EUR	111	Rest of Eastern Africa	AFR
12	Belarus	ROE	62	Morocco	AFR	112	Rest of Eastern Europe	ROE
13	Plurinational Republic of Bolivia	LAM	63	Madagascar	AFR	113	Rest of EFTA	EUR
14	Brazil	BRA	64	Mexico	MEX	114	Rest of Europe	ROE
15	Botswana	AFR	65	Malta	EUR	115	Rest of North America	LAM
16	Canada	CAN	66	Mongolia	REA	116	Rest of North Africa	AFR
17	Switzerland	EUR	67	Mozambique	AFR	117	Rest of Oceania	ANZ
18	Chile	LAM	68	Mauritius	AFR	118	Rest of South Asia	REA
19	China	CHN	69	Malawi	AFR	119	Rest of South African Customs Union	AFR
20	Cote d'Ivoire	AFR	70	Malaysia	ASI	120	Rest of Southeast Asia	REA
21	Cameroon	AFR	71	Namibia	AFR	121	Rest of South America	LAM
22	Colombia	LAM	72	Nigeria	AFR	122	Rest of Former Soviet Union	ROE
23	Costa Rica	LAM	73	Nicaragua	LAM	123	Rest of the World	ANZ
24	Cyprus	EUR	74	Netherlands	EUR	124	Rest of Western Africa	AFR
25	Czech Republic	EUR	75	Norway	EUR	125	Rest of Western Asia	MES
26	Germany	EUR	76	Nepal	REA	126	South Africa	AFR
27	Denmark	EUR	77	New Zealand	ANZ	127	Zambia	AFR
28	Ecuador	LAM	78	Oman	MES	128	Zimbabwe	AFR
29	Egypt	AFR	79	Pakistan	REA	129	Benin	AFR
30	Spain	EUR	80	Panama	LAM	130	Burkina Faso	AFR
31	Estonia	EUR	81	Peru	LAM	131	Brunei Darussalam	REA
32	Ethiopia	AFR	82	Philippines	ASI	132	Dominican Republic	LAM
33	Finland	EUR	83	Poland	EUR	133	Guinea	AFR
34	France	EUR	84	Portugal	EUR	134	Jamaica	LAM
35	United Kingdom	EUR	85	Paraguay	LAM	135	Jordan	MES
36	Georgia	ROE	86	Qatar	MES	136	Puerto Rico	LAM
37	Ghana	AFR	87	Romania	EUR	137	Rwanda	AFR
38	Greece	EUR	88	Russian Federation	RUS	138	Togo	AFR
39	Guatemala	LAM	89	Saudi Arabia	MES	139	Trinidad and Tobago	LAM
40	Hong Kong	CHN	90	Senegal	AFR	140	Taiwan	TWN
41	Honduras	LAM	91	Singapore	ASI			
42	Croatia	EUR	92	El Salvador	LAM			
43	Hungary	EUR	93	Slovakia	EUR			
44	Indonesia	IDZ	94	Slovenia	EUR			
45	India	IND	95	Sweden	EUR			
46	Ireland	EUR	96	Thailand	ASI			
47	Iran Islamic Republic of	MES	97	Tunisia	AFR			
48	Israel	MES	98	Turkey	ROE			
49	Italy	EUR	99	Tanzania United Republic of	AFR			
50	Japan	JPN	100	Uganda	AFR			

Table A2. Mapping for sectors from GTAP 9 to EPPA-Taiwan.

GTAP 9 sector	EPPA-Taiwan sector	GTAP 9 sector	EPPA-Taiwan sector
1 paddy rice	CROP	31 paper products - publishing	EINT
2 wheat	CROP	32 petroleum - coal products	ROIL
3 cereal grains nec	CROP	33 chemical - rubber - plastic products	EINT
4 vegetables - fruit - nuts	CROP	34 mineral products nec	EINT
5 oil seeds	CROP	35 ferrous metals	EINT
6 sugar cane - sugar beet	CROP	36 metals nec	EINT
7 plant-based fibers	CROP	37 metal products	EINT
8 crops nec	CROP	38 motor vehicles and parts	MAN / OTHR
9 bo horses	LIVE	39 transport equipment nec	MAN / OTHR
10 animal products nec	LIVE	40 electronic equipment	MAN / OTHR
11 raw milk	LIVE	41 machinery and equipment nec	MAN / OTHR
12 wool - silk-worm cocoons	LIVE	42 manufactures nec	MAN / OTHR
13 forestry	FORS	43 electricity	ELEC
14 fishing	LIVE	44 gas manufacture - distribution	GAS
15 coal	COAL	45 water	MAN / OTHR
16 oil	OIL	46 construction	MAN / OTHR
17 gas	GAS	47 trade	SERV
18 minerals nec	MAN / OTHR	48 transport nec	TRAN
19 bo meat products	FOOD	49 water transport	TRAN
20 meat products	FOOD	50 air transport	TRAN
21 vegetable oils and fats	FOOD	51 communication	SERV
22 dairy products	FOOD	52 financial services nec	SERV
23 processed rice	FOOD	53 insurance	SERV
24 sugar	FOOD	54 business services nec	SERV
25 food products nec	FOOD	55 recreational and other services	SERV
26 beverages and tobacco products	FOOD	56 public admin - and defence - education - health	SERV
27 textiles	MAN / OTHR	57 ownership of dwellings	DWE
28 wearing apparel	MAN / OTHR		
29 leather products	MAN / OTHR		
30 wood products	MAN / OTHR		

Table A3. Mapping for primary factors from GTAP 9 to EPPA-Taiwan.

	GTAP 9 primary factor	EPPA-Taiwan primary factor
1	Officials and Mangers legislators (ISCO-88 Major Groups 1-2)	LAB
2	Technicians technicians and associate professionals	LAB
3	Clerks	LAB
4	Service and market sales workers	LAB
5	Agricultural and unskilled workers (Major Groups 6-9)	LAB
6	Land,	LND
7	Capital,	CAP
8	Natural resources	FIX

APPENDIX B. The EPPA-Taiwan Model

B.1 Model Structure

EPPA-Taiwan adopts the production structure and elasticities of the static component of EPPA6 (Chen et al., 2016). The model utilizes the data aggregation routine documented in Lanz and Rutherford (2016) to produce the desired sectors and regions based on the GTAP 9 database (Aguiar et al., 2016). In EPPA-Taiwan, activities of different agents and their interactions can be described by: 1) zero-profit conditions; 2) market-clearing conditions; and 3) income-balance conditions. For the household and producer, the associated economic activities are utility and output, respectively. A typical zero-profit condition expressed in MCP format is:

$$MC - MB \geq 0; Q \geq 0\,; [MC - MB\,] \cdot Q = 0 \tag{1}$$

For instance, when a zero-profit condition is applied on a production activity, if the equilibrium output Q is positive, the marginal cost MC must equal the marginal benefit MB, and if MC is greater than MB in equilibrium, Q will be zero because the producer has no reason to produce. Note that MC less than MB is not an equilibrium state since in that case Q will increase until MC equals MB. Other activities such as investment, imports, exports, and commodity aggregation modeled using the Armington assumption (Armington, 1969) have their own zero-profit conditions.

For each market-clearing condition, the price level is determined based on market demand and supply. A typical market-clearing condition in MCP format is:

$$S \geq D; P \geq 0\,; [S - D\,] \cdot \mathrm{P} = 0 \tag{2}$$

The market-clearing condition states that for each market, if there is a positive equilibrium price P, then P must equalize supply S and demand D. If S is greater than D in equilibrium, then the commodity price is zero. Similarly, S less than D is not an equilibrium state because in that case, P will continue to increase until the market is cleared (S equals D).

The income-balance condition specifies the income of household that supports its spending levels (including savings). A typical income-balance condition in MCP format can be written as:

$$E \geq I; E \geq 0\,; [E - I\,] \cdot E = 0 \tag{3}$$

In CGE models, the expenditure E is equal to income I, hence equation (3) can be re-written as an equality of E and I. In EPPA-Taiwan, the price of utility for Taiwan is chosen as the numeraire of the model, so all other prices are measured relative to it.

B.2 Technology, Preferences, and International Trade

To provide an example of a CES function applied to represent a production activity, let us consider a technology that uses energy and non-energy inputs, and denote the rental prices of energy input Q_e and non-energy input Q_n by P_e and P_n, respectively. Following the calibrated share form for CES functions (Rutherford, 1998), the unit cost C for converting Q_e and Q_n into output Q can be formulated as:

$$C = \left[\alpha\left(\frac{P_e}{\bar{P}_e}\right)^{1-\sigma} + (1-\alpha)\left(\frac{P_n}{\bar{P}_n}\right)^{1-\sigma}\right]^{1/(1-\sigma)} \tag{4}$$

where α is the cost share of energy, $\bar{P}_e$ and $\bar{P}_n$ are the base year (pre-shock) levels of P_e and P_n, respectively, and σ is the elasticity of substitution between the energy and non-energy inputs defined as:

$$\sigma = \left[\frac{d\left(\frac{Q_e}{Q_n}\right)}{\left(\frac{Q_e}{Q_n}\right)}\right] / \left[\frac{d\left(\frac{P_n}{P_e}\right)}{\left(\frac{P_n}{P_e}\right)}\right] \tag{5}$$

Based on Condition (1) and Equation (4), if one denotes the equilibrium price of Q by P, which has a base year level of $\bar{P}$, the output of this technology is determined by the following MCP, which is simply the cost-benefit analysis for the production activity:

$$C \geq \frac{P}{\bar{P}}; Q \geq 0; \left(C - \frac{P}{\bar{P}}\right) \cdot Q = 0 \tag{6}$$

The production structure for a sector or the expenditure function for final consumption can be described by a diagram like that shown in **Figure B1.** In this case the diagram shows a cost function with two inputs, with prices P_e and P_n, that combine to produce a good with unit cost, C, and an elasticity of substitution between inputs, σ.

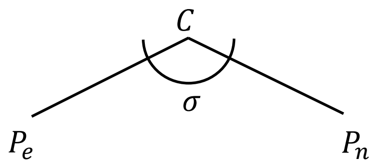

Figure B1. Nesting structure of the two-input CES cost function.

The two-input example above can be generalized to a N-input case ($N > 2$), however, a caveat is that all pairs of inputs are restricted to have identical elasticities of substitution. To overcome this restriction, nested CES functions are generally used in CES-based models. In a nested CES function, subsets of 2 or more of the N inputs ($N > 2$) can be grouped into a CES nest, and then these CES nests can be combined with a further CES function. Each nest can then be assigned a unique elasticity.

Per the applications of CES functions in our model, **Figure B2(a)** provides the Armington aggregations for imported goods from different regions, and for domestic and imported goods. PM, PT, and P are price indices for imports, international transportation service, and domestic production, respectively. Crude oil is modeled as an internationally homogenous good (i.e., crude oil from different regions are perfect substitutes). The Armington aggregation for the domestic and imported good is presented in **Figure B2(b)**, which also includes a carbon penalty with the price index PCO_2 if the relevant policy is in place.

Figure B3 presents, as an example, the nesting structure for the energy-intensive sector. It allows a separate elasticity of substitution for each of the seven nests. PA, P, PF, and PS are price indices for domestic, Armington goods, non-sector-specific primary factor, and sector-specific primary factor, respectively. Specifically, the notation $PA("coal", r)$ at the bottom nest in **Figure B3** represents the price index for coal as an Armington good in region r, i.e., coal is one of the inputs to the production activity of the energy-intensive sector in that region. **Figure B4**, on the other hand, provides the nesting structure for the expenditure function of the representative consumer (household), where PW is the price index for utility. The nesting of structures for the cost functions of other sectors or activities are presented in **Appendix C**.

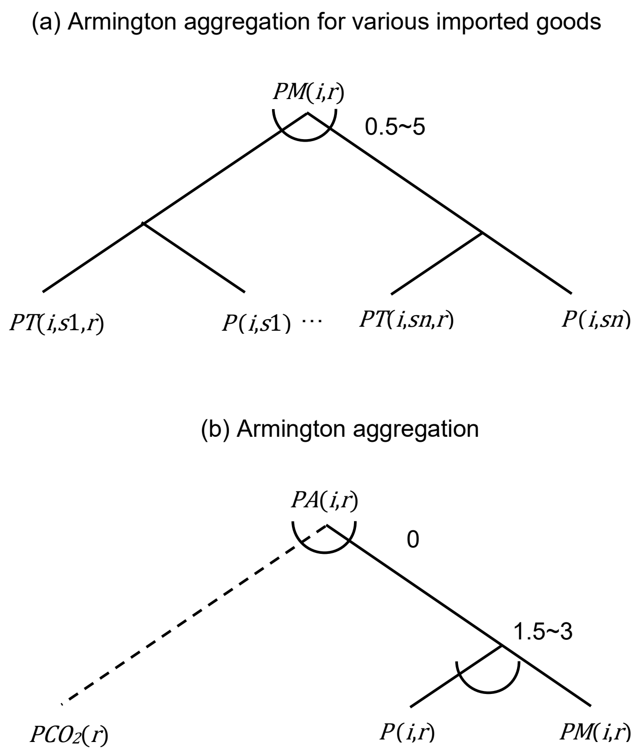

Figure B2. Nesting structure for the cost function of Armington goods.

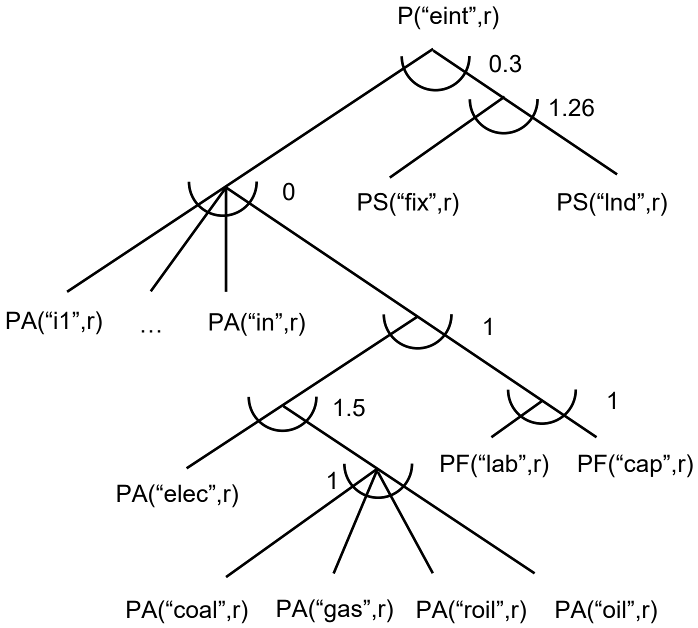

Figure B3. Nesting structure for the cost function of the energy-intensive sector**.**

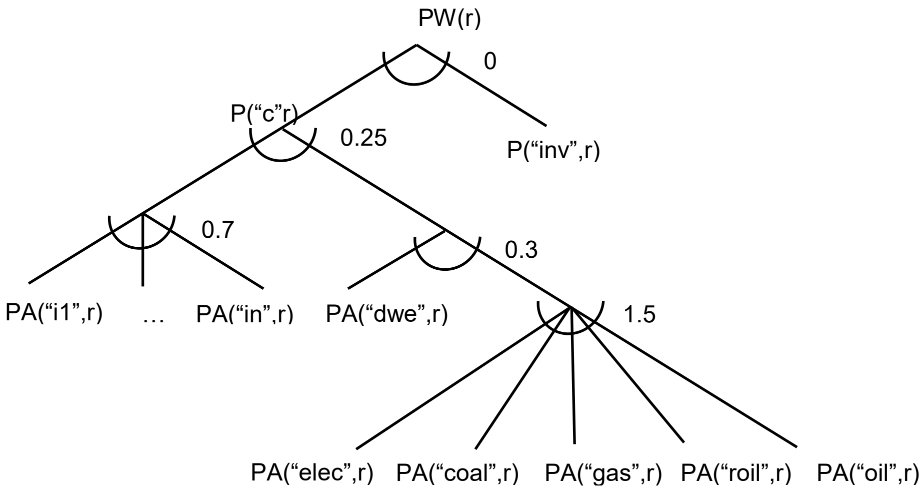

Figure B4. Nesting structure for the expenditure function of the household.

B.3 Social Accounting Matrix

A social accounting matrix (SAM) contains the base year input-output and supply-demand structures of the economy. It provides a consistent picture of production activities, market transactions, and income-expenditure flows between different agents in the economy. **Table A4** provides the structure for the SAM of each region in EPPA-Taiwan. It is worth noting that in our model, crude oil is treated as a homogeneous product, so there are corresponding market and activities for that homogeneous good (explained in detail later). Besides, land and natural resource are treated as sector-specific endowments.

The SAM of EPPA-Taiwan shown in **Table B1** is constructed based on the micro-consistent format of SAM presented in Rutherford (1999)—each row corresponds to a market-clearing condition (Condition 2 in Section 2.1), and columns characterize the zero-profit condition of an activity (Condition 1 in Section 2.1), except for the last column which represents the income-balance condition of the economy (Condition 3 in Section 2.1). Variables in blue/italic/bold denote output of each activity, supply of each market, or endowment of the representative agent (those in the last column); variables in red are input of each activity, demand of each market, or aggregate consumption of the representative agent (those in the last column).

The domestic production activities of region r, $Y(i,r)$, are presented in Column 1, where i represents the set for industrial sectors/goods, x denotes the set for sectors that produce globally homogeneous goods (which only includes crude oil), and i^* is all other sectors/goods, i.e., $i^* = i - x$. In the current setting, since crude oil is a homogeneous product globally, there is a single world market price for crude oil. $vom(i^*,r)$ and $vom(x,r)$ denote the values of base year outputs by production activities of $Y(i^*,r)$ and $Y(x,r)$ respectively. The inputs of domestic production include: $vfm(sf,i,r)$ (land and natural resource inputs), $vfm(mf,i,r)$ (labor and capital inputs), and $voam(j,i,r)$ (energy and non-energy inputs of Armington goods, which are the aggregations for the values of domestic produced product $vdfm(j,i,r)$ and imports $vifm(j,i,r)$). $rto(g,r)$ and $rtf(f,g,r)$ are taxes on output and primary input, respectively. The index g includes i (industrial sectors), C (final consumption of the representative consumer), G (government consumption), and INV (investment).

Columns 2–4 are for activities of total household consumption $Y(C,r)$, the government activity $Y(G,r)$, and capital formation $Y(INV,r)$. The base year value of $Y(C,r)$, which is $vom(C,r)$, includes the Armington good $voam(i,C,r)$ and the associated taxes or subsidies under the rate of $rto(C,r)$. $voam(i,C,r)$ is the sum of domestic produced commodities $vdfm(i,C,r)$, imported commodities $vifm(i,C,r)$, and the associated tax payments under the tax rates of $rtfi(i,C,r)$ (for firm's import tax rates) and $rtfd(i,C,r)$ (for firm's domestic tax rates). Relevant notations and explanations for the values of output and inputs of $Y(G,r)$ and $Y(INV,r)$ are analogous to those of $Y(C,r)$.

Columns 5–7 are activities for international transportation service $YT(j)$, trade flow $M(i^*,r)$, and the Armington aggregation $A(i,r)$. The value of $YT(j)$ is $vtw(j)$ with j being the transportation sector, while the regional input of $vtw(j)$ is denoted by $vst(j,r)$. The value of M is denoted by $vxmd(i^*,s,r)$, which is the value of trade flow of commodity i^* from region s to region r. $vxmd(i^*,s,r)$ includes $vim(i^*,r)$, the import value of sector i^* for region r, the transportation margin $vtwr(j,i^*,s,r)$, and the export tax or subsidy imposed by region s based on the tax or subsidy rate $rtxs(i^*,s,r)$, and the tariff imposed by region r based on the rate of $rtms(i^*,s,r)$. The base year value for the Armington output is $voama(i,r)$, which is the CES aggregation of the domestic component $vdfma(i,r)$, and the imported component $vifma(i,r)$. $vdfma(i,r)$ and $vifma(i,r)$ are the sum of $vdfm(i,g,r)$ and $vifma(i,g,r)$, respectively.

Columns 8–9 are activities for the trade flow of homogeneous good x, which is crude oil in our model. Since we treat crude oil as a homogeneous good in EPPA, a country will never be an exporter and importer of crude oil at the same time. The activities of $HOMX(x,r)$ and $HOMM(x,r)$ are net export and net import, respectively, of x in region r. For example, in a region with a net export of crude oil, there is no value for the column $HOMM(x,r)$. The base year value of export is $homx(x,r)$, which is export tax- or subsidy-included, as shown in Column 9. The base year value of import is $vhomm(x,r)$, which is constituted of $homm(x)$, the pre-tariff import value that also excludes transport margin; the transport margin $homt(x,r)$; the tariff based on the rate of $tmhom(x,r)$; and the tax or subsidy rate $txhom(x,r)$.

Columns 10 and 11 are activities for the welfare (utility) function $W(r)$ and the income balance condition of the representative household RA. The welfare W has the base year value of $vum(r)$, and it is derived from consumption and saving, which have the base year values of $vom(C,r)$ and $vom(INV,r)$, respectively. The total household income comes from returns to labor, capital, land, and natural resources, with the base year values being denoted by $evom(f,r)$ ($f =$ labor, capital, land, and natural resources). The base year current account balance value is $vb(r)$. Specifically, when there is a current account surplus, $vb(r)$ will be negative, which can be interpreted as the foreign saving owned by the domestic representative household. In case of a current account deficit, $vb(r)$ will be positive, which means the domestic consumption exceeds the domestic income. Lastly, when CO_2 reduction policies are in place, the penalty will be imposed on the consumption of burning fossil fuels, which include coal, refined oil, and gas. In our model, the government is treated as a passive entity, which collects taxes from household and producers to finance government consumption and transfers. The remaining tax revenues, including those derived from a carbon tax when an emissions mitigation policy exists, are recycled back to the representative household in a lump-sum fashion. When the adjustment of net export/import for homogeneous goods is done, there will be changes in relevant tax revenues and transportation margins, which are reflected in $homadj(x,r)$ and $trnadj(j,x,r)$, and both terms are put in the income-balance condition to make sure the accounting is correct.

Table B1. The Social Accounting Matrix of EPPA-Taiwan.

SAM/MCM for EPPA-Taiwan

			Columns in this matrix correspond to Activities and their corresponding Zero-profit Conditions										Income-Balance Conditions
			Domestic Production Activity	Consumer Activity	Goverment Activity	Investment Activity (Capital)	International Transportation	Import Activity	Armington Goods	Homogeneous good export	Homogeneous good import	Utility	Representative consumer
			Y(i,r)	Y(C,r)	Y(G,r)	Y(INV,r)	YT(j)	M(i*,r)	A(i,r)	HOMX(x,r)	[HOMM(x,r)]	W(r)	RA(r)
Rows in this matrix correspond toMarket-clearing conditions	Domestic Production	P(i*,r)	*+vom(i*,r)*				vst(i*,r)	vxmd(i*,s,r)	vdfma(i*,r)				
		PH(x,r)	*+vom(x,r)*				vst(x,r)		vdfma(x,r) [vifma(x,r)]	vhomx(x,r)	*[+vhomm(x,r)]*		*+homadj(x,r)*
	HH consump	P(C,r)		*+vom(C,r)*								vom(C,r)	
	Gov. consump.	P(G)r			*+vom(G,r)*								vom(G,r)
	Loanable Funds	P(INV,r)				*+vom(INV,r)*						vom(INV,r)	
	Primary Factors	PS(sf,i,r)	vfm(sf,i,r)										*+vfm(sf,i,r)*
		PF(mf,r)	vfm(mf,i,r)										*+evom(mf,r)*
	Intl. Transp.	PT(j)					*+vtw(j)*	vtwr (j,i*,s,r)			[homt(j,x,r)]		*+trnadj(j,x,r)*
	Imports	PM(i,r)						*+vim(i*,r)*	vifma(i*,r)				
	Armington Good	PA(i,r)	voam(j,i,r)	voam(i,C,r)	voam(i,G,r)	voam(i,INV,r)			*+voama(i,r)*				
	CO_2-penalty	PCO_2(r)	CO_2(j,i,r)	CO_2(i,C,r)	CO_2(i,G,r)	CO_2(i,INV,r)							*+CO2lim(r)*
	Homogeneous good	PWH(x)								*+homx(x,r)*	[homm(x,r)]		
	Total HH consump.	PW(r)										*+vum(r)*	vum(r)
	Resources for Tax payment	TAX(i,g,r)	rto(i,r), rtf(f,i,r)	rto(C,r)	rto(G,r)	rto(INV,r)		rtms(i*,s,r), rtxs(i*,s,r)	rtfda(i,r), rtfia(i,r)	txhom(x,r)	[tmhom(x,r)]		*tax revenue(r)*
	Current Account	P(C,TWN)											*+vb(r)*

Note: i* denotes sector set i excluding item x, x denotes crude oil which is an homogeneous good in the EPPA-Taiwan.

B.4 Elasticities of Substitution, Emissions, and Energy Use

The elasticities of substitution of EPPA-Taiwan are drawn from those in EPPA6, which are based on literature review (**Table B2**). The energy use data (in terms of energy units), included in the GTAP 9 database, are from the International Energy Agency (IEA) (McDougall and Lee, 2006). The reference year CO_2 emissions of our model are derived from the fossil fuel consumption levels in GTAP 9 through emission factors for each type of fossil fuel. The economic data in SAM drawn from GTAP 9 are expenditure in terms of a monetary unit. Based on the energy use data (in energy units) provided in GTAP 9, we are able to link to base year energy consumption and production (in terms of exajoule (EJ) or terawatt-hour (TWh)) to the corresponding expenditure level (US dollar), and therefore keep track of the evolution of both consumption and production under a counterfactual simulation.

Table B2. Substitution elasticities used in EPPA-Taiwan.

	Notation	Value
Between domestic and imported goods	sdm	1.0–3.0
Between imported goods	smm	0.5–5.0
Between energy and non-energy (labor-capital bundle) inputs	e_kl	0.1–1.0
Between electricity and fossil energy bundle for the aggregated energy	noe_el	1.5
Between labor and capital	l_k	1
Between fossil energy inputs for the fossil energy bundle	esube	1
Between natural resource and other inputs	esup	0.3–0.5
Between natural resources and land	Esubva	0.2~1.67
Final consumption	enoe_el; eed; d_elas; delas	0.25~1.5

Sources: For EPPA-Taiwan, see Cossa (2004).

APPENDIX C. Nesting structures of other sectors

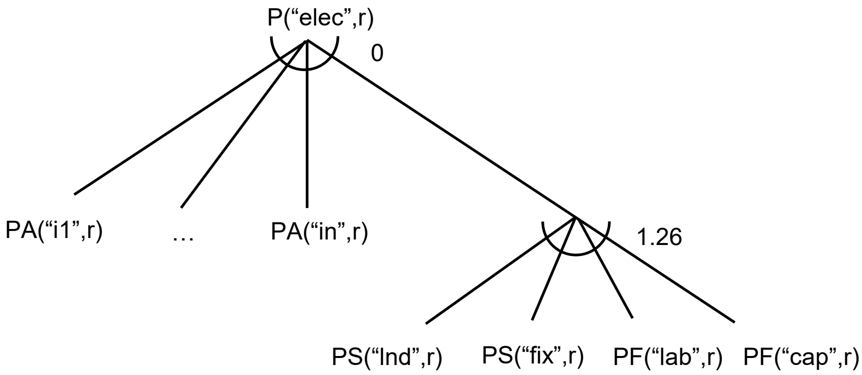

Figure C1. Nesting structure of electricity sector.

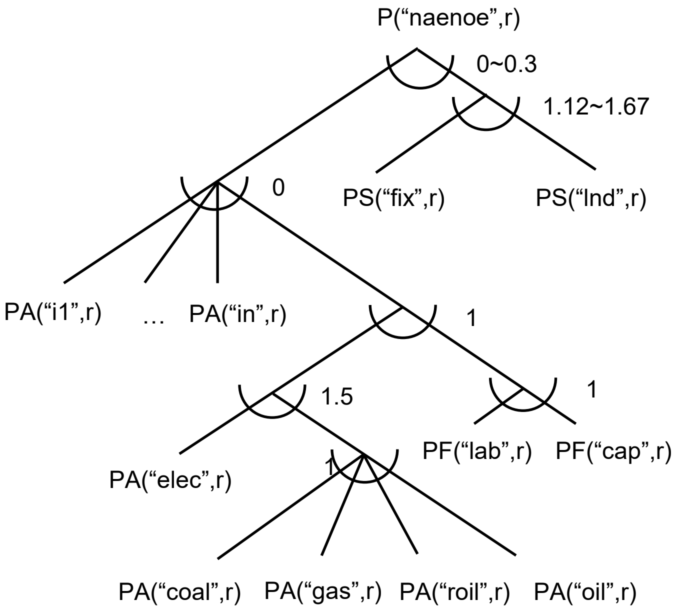

Figure C2. Nesting structure of dwelling, food, other, service, and transportation sector.

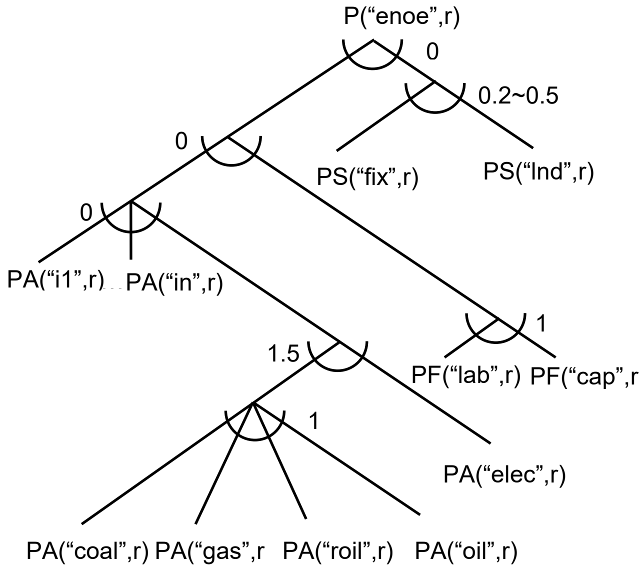

Figure C3. Nesting structure of oil, gas, refined oil and coal sector.

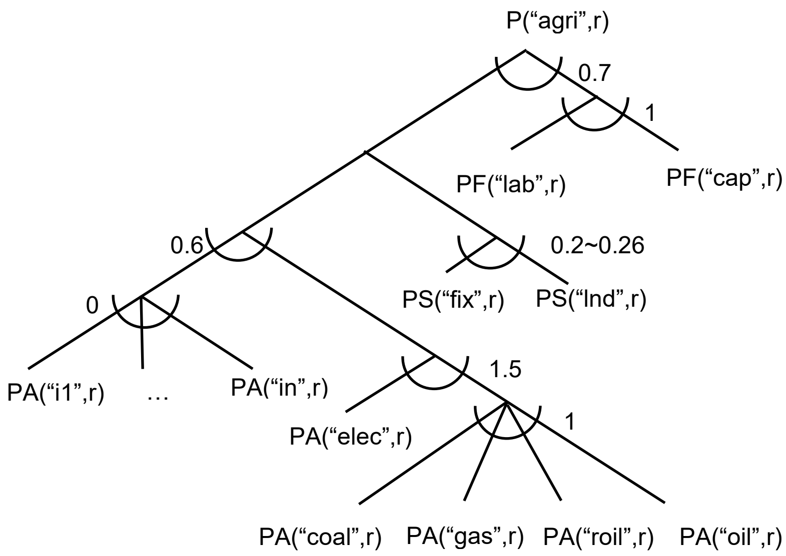

Figure C4. Nesting structure of crop, live, and forest sector.

APPENDIX D. Projected energy and CO_2 intensities by region in 2030

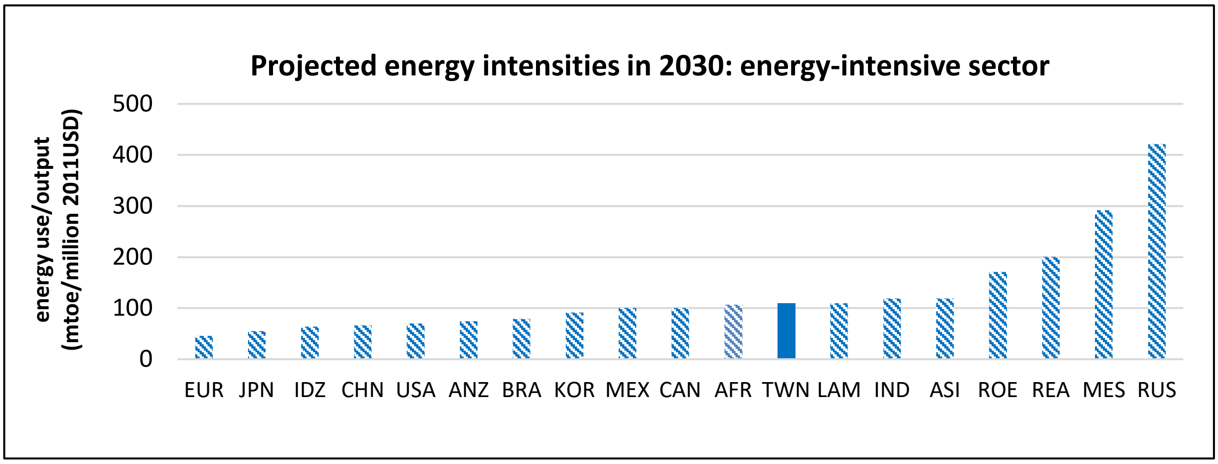

Figure D1. Projected energy intensities of the energy-intensive sector in 2030.

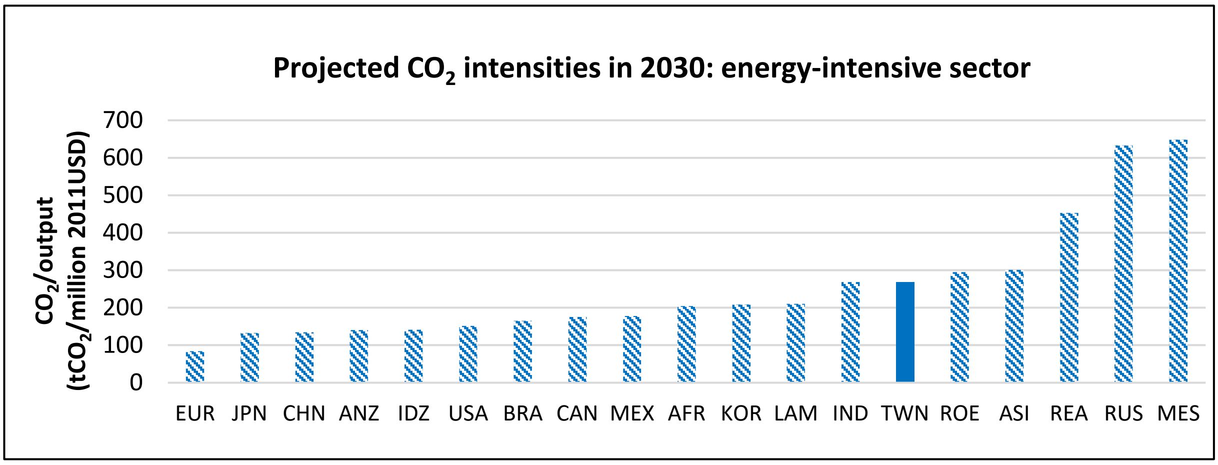

Figure D2. Projected CO2 intensities of the energy-intensive sector in 2030.

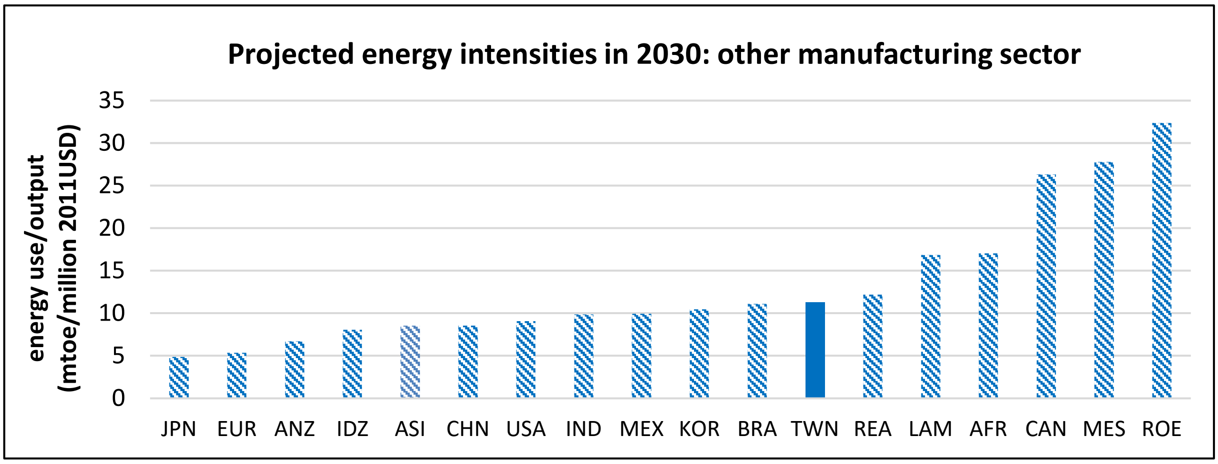

Figure D3. Projected energy intensities of the manufacturing sector in 2030.

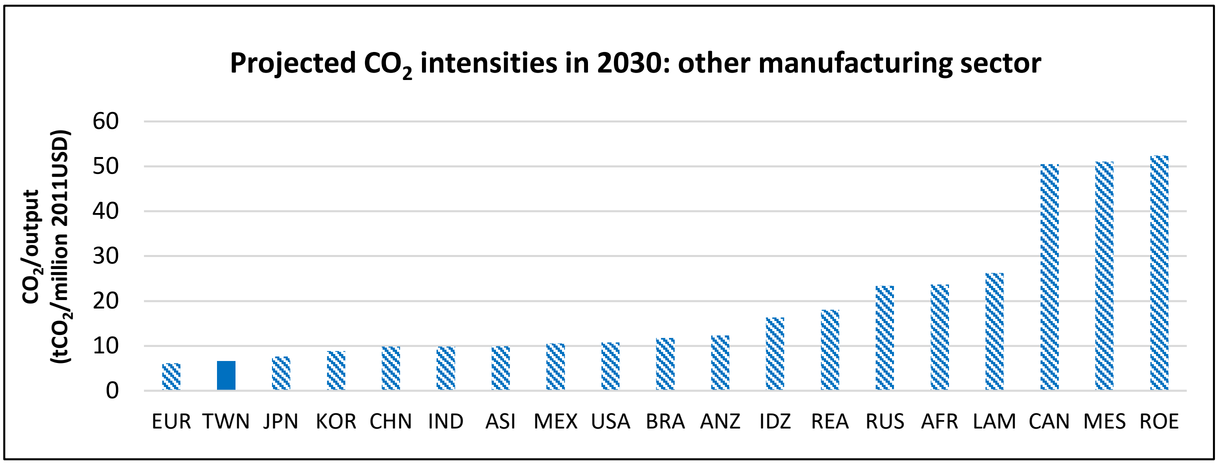

Figure D4. Projected CO2 intensities of the manufacturing sector in 2030.

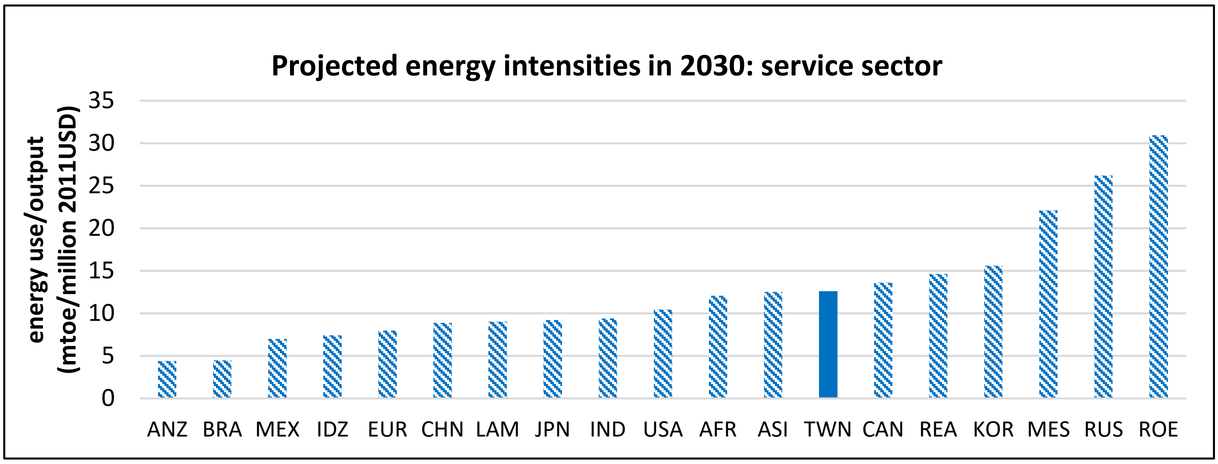

Figure D5. Projected energy intensities of the service sector in 2030.

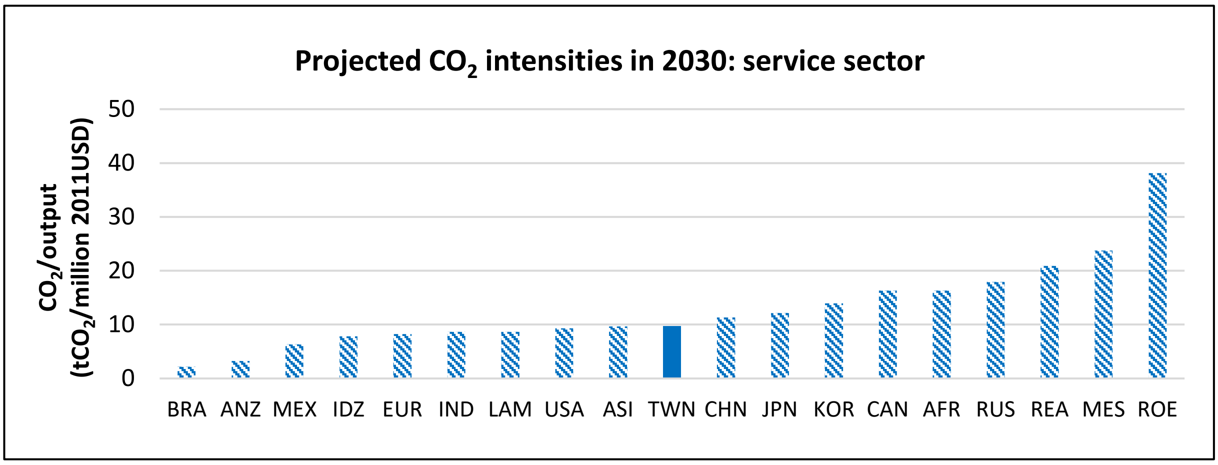

Figure D6. Projected CO2 intensities of the service sector in 2030.

APPENDIX E. Japan's GDP impact under different policy scenarios

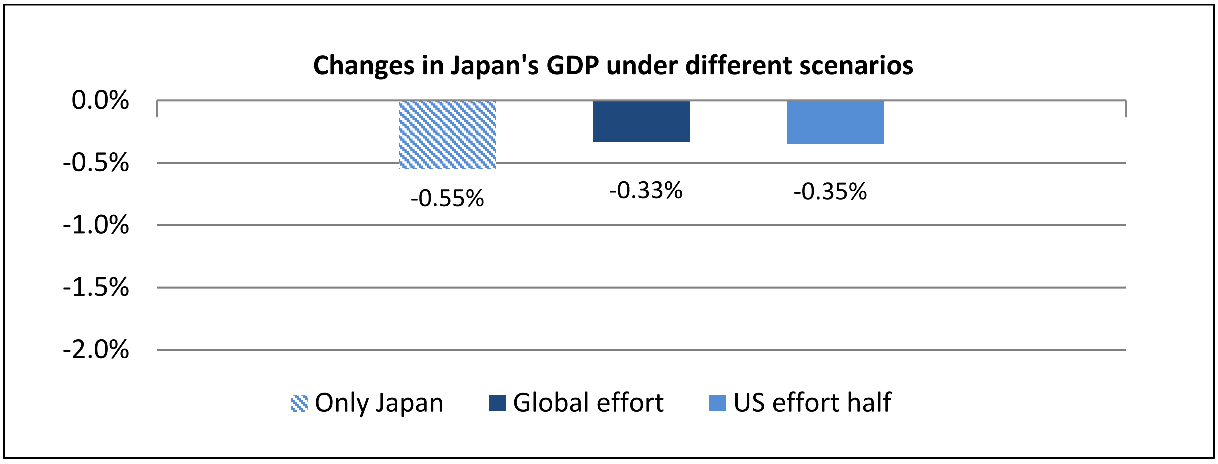

Figure E1. Changes in Japan's GDP under different scenarios.