The Impacts of Regionally Fragmented Climate Policies on Trade Flows and CO_2 Emissions in Northeast Asia: A Recursive Dynamic CGE Analysis

Jintae Kim [a] · **Jong-ho Hong** [b*]

[a] Graduate School of Environmental Studies, Seoul National University

[b] Graduate School of Environmental Studies, Seoul National University

*Corresponding author: hongjongho@snu.ac.kr

Email: kimjintae9011@snu.ac.kr

Abstract: As Northeast Asia (NEA) accounts for over 38% of global GHGs and serves as the core of global manufacturing, its transition to Net-Zero is poised to trigger profound structural shifts in global trade. This study employs GUIDE-GLOBAL-CGE, a 17-region recursive dynamic Computable General Equilibrium model, to analyze the macroeconomic impacts of asymmetric climate policies across six NEA nations (South Korea, China, Japan, Russia, Mongolia, and North Korea) toward 2050. To address existing methodological limitations, this study introduces an independently reconstructed Social Accounting Matrix (SAM) for North Korea and rigorously calibrates energy substitution elasticities using empirical meta-data to reflect realistic transition frictions. Simulation results demonstrate that an isolated national approach to Net-Zero induces severe asymmetric shocks: export-driven economies (South Korea and Japan) suffer significant Terms of Trade (TOT) deterioration due to high domestic abatement costs, while unconstrained nations (North Korea) inadvertently transform into pollution havens via trade-induced carbon leakage. Conversely, the establishment of an Integrated Carbon Market (ICM) substantially optimizes aggregate compliance costs. Crucially, market integration mitigates severe economic disruptions: heavily industrialized nations can alleviate their transitional burdens via imported allowances, while resource-abundant exporters (Russia and Mongolia) replace declining physical fossil fuel exports with valuable carbon credits. The resulting carbon trade surpluses drive a substantial influx of advanced machinery imports, financing their structural industrial modernization. Taken together, our findings highlight that for NEA, transitioning from fragmented policies to a fully inclusive ICM is not merely an environmental obligation, but an essential strategy for regional economic cooperation.

Keywords: Computable General Equilibrium (CGE), Northeast Asia, Integrated Carbon Market (ICM), Regional Cooperation, Trade and Environment, Carbon Neutrality, Carbon Leakage

1. Introduction

The global community is currently at a critical crossroads, facing an urgent need to transition toward a low-carbon economy to mitigate the impacts of climate change. Within this global landscape, Northeast Asia (NEA)—comprising South Korea, China, Japan, Mongolia, North Korea, and the Russian Federation—stands as a pivotal region. Accounting for approximately 25% of global GDP (World Bank, 2024) and 38% of global greenhouse gas (GHG) emissions (EDGAR, 2025), the region's climate trajectory is not merely a local concern but a primary determinant of the world's environmental future. The economic structure of NEA is uniquely characterized by a high share of manufacturing, a heavy reliance on energy imports, and a significant concentration of energy-intensive industries, such as steel, electronics, and transport equipment. Consequently, the decarbonization efforts of these nations are expected to trigger significant structural shifts in global trade flows and energy markets.

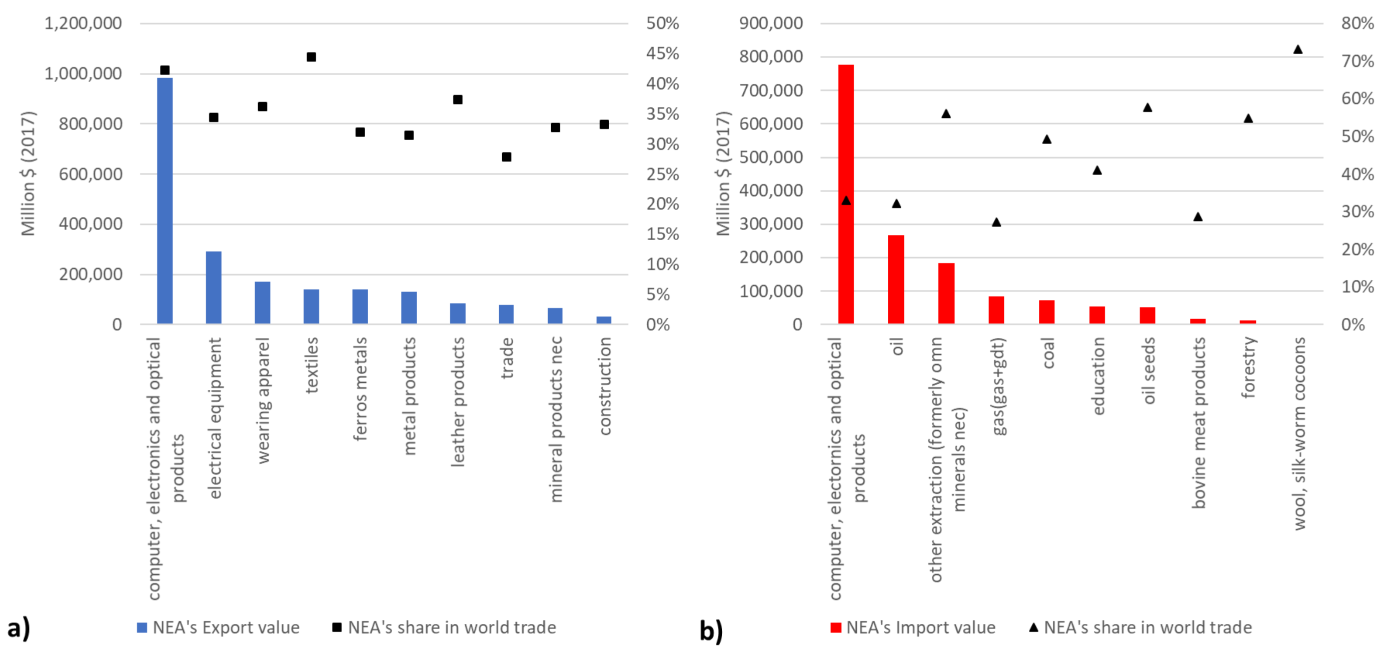

Figure 1. NEA's Top 10 Exports and Imports - Panel (a) Export value and share, Panel (b) Import value and share

As illustrated by the regional trade structure in Figure 1, derived from the 2017 GTAP 11 database, the region's macroeconomic engine is fundamentally defined by a "processing trade" model. Northeast Asia relies on the mass importation of primary fossil fuels (crude oil, natural gas, and coal) to power its export-driven manufacturing base, which is heavily concentrated in electronics, apparel, and energy-intensive intermediate goods such as iron and steel. Furthermore, the exceptionally high volume of trade in electronic components and metal products highlights the deeply intertwined, intra-regional supply chains operating within NEA.

However, coordinating a unified climate response to address these structural vulnerabilities is profoundly complicated by the region's unique geopolitical landscape. Northeast Asia is home to major global political, economic, and military powers—such as China, Japan, Russia, and South Korea—yet it simultaneously encompasses Mongolia, a landlocked, resource-dependent developing nation, and North Korea, an economy strictly isolated from the global market. Unlike the European Union, where deep institutional and political integration facilitates the implementation of harmonized environmental frameworks, Northeast Asia is characterized by starkly contrasting political systems and a historically low level of formal economic integration (Aggarwal & Koo, 2005). Because of this inherent geopolitical and structural fragmentation, ambitious and uncoordinated carbon pricing policies are likely to inflict severe asymmetric shocks across the region—drastically inflating the costs of essential energy imports while simultaneously deteriorating the international competitiveness of its core manufacturing exports.

This study seeks to address critical gaps in the existing literature by making two primary innovative contributions. First, from a methodological perspective, we provide a comprehensive reconstruction of a Social Accounting Matrix (SAM) for North Korea, enabling its full integration into a global recursive dynamic CGE framework. Second, while previous energy-economic analyses have primarily focused on long-term projections for the industrialized core (e.g., China, Japan, and South Korea), this research explicitly incorporates the often-overlooked economies of Mongolia and North Korea into the regional equation. By utilizing the GUIDE-GLOBAL-CGE model to disaggregate the world into 17 specific regions—evaluating the direct interactions between the 6 distinct NEA nations and 11 global regions—this study uniquely captures the intricate spillover effects, trade interactions, and carbon leakage dynamics across the entire global supply chain toward the 2050 carbon neutrality targets.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 provides an overview of the GUIDE-GLOBAL-CGE model, followed by a detailed explanation of its mathematical structure in Section 4. Section 5 describes the base-year data and the macroeconomic calibration procedures. Section 6 presents the scenario designs and the analysis of simulation results. Finally, Section 7 offers conclusions and policy implications, and Section 8 discusses the limitations of this study and avenues for future research.

2. Literature Review

The global transition toward carbon neutrality is increasingly challenged by asymmetric climate policies, which raise significant concerns regarding carbon leakage and diminished industrial competitiveness. In response to these challenges of policy fragmentation, the concept of a "Climate Club" and the implementation of Carbon Border Adjustments (CBAs) have emerged as prominent theoretical and policy frameworks. As proposed by Nordhaus (2015), a Climate Club involves a coalition of nations that agree on a common carbon price and apply trade penalties to non-members to deter free-riding. Complementing this strategic framework, the work of Böhringer, Balistreri, and Rutherford (2012) has provided foundational economic evidence on how border taxes can mitigate carbon leakage and protect the competitiveness of domestic industries under asymmetric climate regulations.

To quantitatively assess the economic efficiency of such cooperative mechanisms, Computable General Equilibrium (CGE) models have long served as the primary analytical workhorse. The lineage of utilizing CGE frameworks to evaluate international emissions trading dates back to the formative years of the Kyoto Protocol in the early 2000s. Seminal multi-model evaluations, such as the Energy Modeling Forum (EMF) 16 study (Weyant & Hill, 1999) and the comprehensive assessments by Böhringer (2002), firmly established the foundational premise that cross-border carbon market integration significantly reduces aggregate macroeconomic compliance costs by equalizing marginal abatement costs. Building upon this, Böhringer and Rutherford (2002) highlighted the profound impact of carbon abatement policies on international spillovers. By decomposing the welfare effects, they demonstrated that unilateral abatement heavily distorts international prices, severely penalizing fossil fuel exporters while providing secondary terms of trade benefits to fuel-importing nations. Crucially, their analysis revealed that international emissions trading considerably mitigates the magnitude of these adverse trade spillovers compared to unilateral carbon taxation, providing a robust argument for integrated carbon markets beyond mere domestic efficiency.

Applying these cooperative frameworks and theoretical insights to the specific context of Northeast Asia, however, presents unique regional challenges. Von Hippel et al. (2011) provided an early and comprehensive overview of the energy situation in NEA, highlighting the starkly different energy profiles across the six nations and the strategic importance of regional cooperation to ensure long-term stability. Furthermore, as highlighted by Matsumoto and Andriosopoulos (2016), climate mitigation scenarios in the 21st century pose complex challenges to the energy security of East Asian nations, where the pursuit of emission targets must be balanced against the stability and diversity of energy supplies. The formation of unified cooperative mechanisms in NEA is inherently complicated by geopolitical complexities and disparate industrial priorities, suggesting that a "one-size-fits-all" approach may be difficult to implement. This complexity is further exacerbated by the diverse developmental and political realities of the region: Mongolia must balance its Net-Zero ambitions with its needs as a burgeoning developing economy, Russia's current mitigation targets face scrutiny regarding their practical efficacy, and North Korea remains largely isolated from sustained international climate cooperation.

To quantify the economic and environmental implications of these regional dynamics, previous literature has extensively utilized Computable General Equilibrium (CGE) models to evaluate the efficiency of regional cooperation. For instance, Zhang et al. (2016) found that regional market integration could significantly mitigate GDP losses for Japan and South Korea. Building on this, Li and Zhang (2018) emphasized that since the China-Japan-Korea (CJK) economies are heavily manufacturing-oriented, regional cooperation serves as a powerful signal of climate commitment and a cost-effective mechanism for pollution control. They specifically highlighted the institutional challenges of linking heterogeneous carbon markets, noting that disparities in emission targets and regulatory stringency could lead to market distortions. Similarly, Ma et al. (2019) utilized the GTAP-E-DYN model to assess national reduction targets among the CJK core, while Effendi and Resosudarmo (2025) examined the socio-economic and environmental implications of decarbonization strategies in East Asia, suggesting that a policy mix of carbon taxes and technological retrofitting is essential to mitigate output contraction.

While these studies have provided foundational insights into the benefits of regional market integration, they exhibit critical limitations. Previous analyses have been largely confined to the heavily industrialized CJK core, neglecting the interconnected roles of resource-abundant or politically isolated neighboring states. This study integrates several core international and environmental economic theories—namely, the Pollution Haven Hypothesis, carbon leakage, Marginal Abatement Cost (MAC) equalization, and Terms of Trade (TOT) theory—into a cohesive general equilibrium framework. Within this framework, North Korea is theoretically positioned as a potential pollution haven, providing a critical testbed to evaluate how fragmented policies distort regional trade and emissions. By utilizing the GUIDE-GLOBAL-CGE model to analyze the long-term impacts of regionally fragmented climate policies toward 2050, this study captures the comprehensive spillover effects and trade-induced carbon leakage dynamics that previous CJK-centric models could not observe.

3. Overview of the GUIDE-GLOBAL-CGE model

3.1 The GUIDE Project

The GUIDE-GLOBAL-CGE model is a core analytical module of the broader GUIDE (GHGs and air pollutants Unified Information DEsign system) project (Jang et al., 2024), an integrated modeling framework developed in South Korea. The GUIDE project was initiated to address the critical, yet often under-researched, transboundary environmental challenges specific to Northeast Asia. While the region experiences significant cross-border environmental impacts—such as the heavy influx of air pollutants from rapidly growing neighboring economies—most existing integrated environmental-economic analyses have predominantly focused on the United States and the European Union, or at a highly aggregated global level (Diaz and Moore, 2017).

Addressing these regional challenges requires a comprehensive framework capable of evaluating both major emitters (e.g., China) and geographically adjacent nations with high uncertainty and limited data availability (e.g., North Korea and Mongolia). Employing a conventional bottom-up energy system modeling approach is methodologically infeasible due to the severe absence of detailed power and energy system statistics for Mongolia and North Korea. To overcome these critical data limitations, this study strategically employs a top-down, multi-regional Computable General Equilibrium (CGE) framework that explicitly captures broader economic systems and international trade dynamics. This approach enables a robust projection of future energy transitions and macroeconomic impacts induced by climate policies across all six Northeast Asian nations.

Within this integrated system, the GUIDE-GLOBAL-CGE model plays a central role in quantifying the macroeconomic and sectoral impacts of long-term decarbonization policies. The core theoretical structure of the model is built upon the widely recognized PEP-w-t recursive dynamic framework (Lemelin et al., 2013). However, this standard framework has undergone extensive modifications and expansions to explicitly incorporate detailed energy sectors, backstop technologies, and emissions modules, enabling a rigorous assessment of the economic effects of various climate policies. By capturing how market-clearing relative prices adjust to balance supply and demand under new environmental and technological constraints, the model is particularly well-suited for counterfactual analyses and answering "what-if" questions, providing comprehensive system-wide assessments. It translates multiple long-term decarbonization scenarios into tangible economic outcomes, such as variations in GDP, shifts in bilateral trade dynamics, relative price changes, and changes in sectoral production.

3.2 Model Dynamics, Computational Approach, and Time Horizon

From a computational perspective, the model is implemented in the General Algebraic Modeling System (GAMS). While many existing CGE studies rely on the MPSGE (Mathematical Programming System for General Equilibrium) subsystem and the Mixed Complementarity Problem (MCP) solver, the GUIDE-GLOBAL-CGE model is formulated directly as a system of simultaneous equations and solved using the Constrained Nonlinear System (CNS) solver. This explicit equational approach allows for a more intuitive interpretation of the underlying economic mechanisms, providing greater transparency and flexibility. This is particularly advantageous when integrating complex, non-linear energy and environmental modules into the standard CGE framework.

The model is calibrated to a base year of 2019, utilizing the most recent macroeconomic and energy datasets (GTAP 11) available prior to the structural disruptions caused by the global pandemic. From this base year, the model simulates economic and environmental outcomes on an annual basis up to the target year of 2050. To project the growth trajectory of the global economy, the model incorporates the latest GDP and population projections from the Shared Socioeconomic Pathways (SSP) database provided by the International Institute for Applied Systems Analysis (IIASA). Specifically, the SSP2 ("Middle of the Road") scenario is selected as the baseline growth pathway, utilizing the most recently updated global population and human capital projections (KC et al., 2024a; KC et al., 2024b). These global projections have been reaggregated and downscaled to align with the 17-region aggregation of the GUIDE-GLOBAL-CGE model, ensuring that the long-term macroeconomic drivers are consistent with the model's regional and structural definitions.

3.3 Regional Aggregation

To accurately capture the localized impacts of regionally fragmented climate policies, the GUIDE-GLOBAL-CGE model adopts a highly disaggregated regional structure. As emphasized in the introduction, the strategic interplay among Northeast Asian nations is central to this study. Therefore, we explicitly isolate the six core NEA nations—South Korea, China, Japan, Russia, Mongolia, and North Korea—from broader regional aggregates. For the rest of the world, the model follows the MESSAGE model's R11 classification (Fricko et al., 2017; Krey et al., 2020), aggregating non-NEA countries into broader regions based on geographical, cultural, and economic proximity.

In total, the global economy is divided into 17 distinct regions, allowing the model to simulate detailed bilateral trade flows, capital movements, and the spillover effects of asymmetric carbon constraints. Two important assumptions regarding the NEA regional definitions should be noted:

1. **Scope of Russia**: While the conventional geographical and political definition of Northeast Asia typically includes only the Russian Far East, this study incorporates the entirety of the Russian Federation (RUS) as a single entity within the NEA framework due to macroeconomic linkages and data structures.
2. **Definition of North Korea**: In the GTAP 11 database, the "Rest of East Asia" (xea) region comprises both North Korea and Macau. For the purposes of this analysis, we assume xea exclusively represents North Korea (PRK). The specific data balancing and reconciliation procedures applied to accurately reflect the North Korean economy will be elaborated upon in Section 4.

It is important to acknowledge that aggregating the rest of the world into 11 broader macro-regions may introduce a degree of regional aggregation bias. As demonstrated by Kunimitsu (2024), spatial aggregation in global CGE models can sometimes obscure localized economic impacts and distort the assessment of climate change and trade policies. While we recognize the presence of this inherent aggregation bias within our global classification, the primary analytical focus of this study remains strictly on the detailed macroeconomic dynamics, bilateral trade shifts, and policy spillovers among the six specific Northeast Asian nations. The broader regional aggregates are utilized primarily to close the global trade system and capture macro-level exogenous trends.

The mapping of the 17 model regions based on the original GTAP database is detailed in Table 1.

Table 1 Regional Aggregation in the GUIDE-GLOBAL-CGE Model

Region Code	Description	Corresponding GTAP 11 Regions
KOR	South Korea	kor
CHN	China	chn, hkg
JPN	Japan	jpn
RUS	Russia	rus
MNG	Mongolia	mng
PRK	North Korea	xea
NAM	North America	can, usa, pri
LAM	Latin America and the Caribbean	mex, arg, bol, bra, chl, col, ecu, pry, per, ury, ven, xsm, cri, gtm, hnd, nic, pan, slv, xca, dom, hti, jam, tto, xcb
WEU	Western Europe	xna, aut, bel, cyp, dnk, fin, fra, deu, grc, irl, ita, lux, mlt, nld, prt, esp, swe, gbr, che, nor, xef, tur
EEU	Central and Eastern Europe	bgr, hrv, cze, est, hun, lva, ltu, pol, rou, svk, svn, alb, srb, xer
RFS	Rest of Former Soviet Union	blr, ukr, xee, kaz, kgz, tjk, uzb, xsu, arm, aze, geo
MEA	Middle East and North Africa	bhr, irn, irq, isr, jor, kwt, lbn, omn, pse, qat, sau, syr, are, xws, dza, egypt, mar, tun, xnf, sdn
AFR	Sub-Saharan Africa	ben, bfa, cmr, civ, gha, gin, mli, ner, nga, sen, tgo, xwf, caf, tcd, cog, cod, gnq, gab, xac, com, eth, ken, mdg, mwi, mus, moz, rwa, tza, uga,

		zmb, zwe, xec, bwa, swz, nam, zaf, xsc, xtw
MEK	Mekong Region	khm, lao, vnm
SAS	South Asia	afg, bgd, ind, npl, pak, lka, xsa
SEA	Southeast Asia and Taiwan	xoc, twn, brn, idn, mys, phl, sgp, tha, xse
ANZ	Australia and New Zealand	aus, nzl

3.4 Sectoral Aggrefation

The sectoral aggregation in the GUIDE-GLOBAL-CGE model is designed to reflect the energy-intensive nature of the NEA economy. Notably, due to data limitations, all service-related activities have been aggregated into a single service sector (SER). Overall, the model identifies 20 main commodities, with a particular emphasis on fossil fuels (Coal, Oil, Gas), energy-intensive manufacturing, and transportation.

Crucially, to analyze decarbonization strategies, the electricity commodity (ELEC) is modeled as a composite good produced by combining the outputs of a transmission and distribution (TnD) network and eight distinct power generation industries. Furthermore, the model introduces Backstop (BS) industries for Chemicals, Non-metallic minerals, Iron and steel, and explicitly for road, water, and air transport sectors, allowing for the assessment of low-carbon transitions in hard-to-abate sectors.

The overall sectoral aggregation was determined by referencing the Flow Definition provided in the *World Energy Balances Database Documentation 2024 edition* (IEA, 2024). The complete sectoral mapping is presented in Table 2.

Table 2 Sectoral Aggregation in the GUIDE-GLOBAL-CGE

Commodity Code	Industry Code	Description	Corresponding GTAP 11 Sectors
AGRICULT	AGRICULT	Agricultural, forest, and fishery goods	pdr, wht, gro, v_f, osd, c_b, pfb, ocr, ctl, oap, rmk, wol, frs, fsh
COAL	COAL	Coal	coa

OIL	OIL	Crude petroleum	oil
GAS	GAS	Natural gas, Gas distribution	gas, gdt
MINING	MINING	Mined and quarried goods	oxt
FOODPRO	FOODPRO	Food, beverages, and tobacco products	cmt, omt, vol, mil, pcr, sgr, ofd, b_t
TEXTILES	TEXTILES	Textile and leather products	tex, wap, lea
WOODPRO	WOODPRO	Wood products	lum
PAPERPRO	PAPERPRO	Paper products	ppp
PETROLCOAL	PETROLCOAL	Petroleum and coal products	p_c
CHEMICAL	CHEMICAL	Chemical products	chm, bph, rpp
	BS_CHEM	Backstop Chemical products	-
NONMET	NONMET	Non-metallic mineral products	nmm
	BS_NONMET	Backstop Non-metallic mineral products	-
IRONSTL	IRONSTL	Primary iron and steel products	i_s
	BS_IRON	Backstop Iron and steel products	
NONFERR	NONFERR	Non-ferrous metal products	nfm
MACHINE	MACHINE	Fabricated metal products, Electronic/electrical equip., Machinery	fmp, ele, eeq, ome
TRANSEQ	TRANSEQ	Motor vehicles, Other transport equipment	mvh, otn
OTHERIND	OTHERIND	Other manufactured products	omf
ELEC	TnD	Transmission and Distribution	TnD
	eNuclear	Nuclear generation	NuclearBL
	eCoal	Coal generation	CoalBL
	eGas	Gas generation	GasBL, GasP
	eOil	Oil generation	OilBL, OilP
	eWind	Wind generation	WindBL
	eSolar	Solar generation	SolarP
	eHydro	Hydro generation	HydroBL, HydroP
	eOther	Other generation	OtherBL
CONSTRUC	CONSTRUC	Construction	cns
LTRP	LTRP	Land transport service (road, rail)	otp
	BS_LTRP	Backstop Land transport service	-
WTRP	WTRP	Water transport service	wtp
	BS_WTRP	Backstop Water transport service	-
ATRP	ATRP	Air transport service	atp

	BS_ATRP	Backstop Air transport service	-
SER	SER	Services	trd, afs, whs, cmn, ofi, ins, rsa, obs, ros, dwe, osg, edu, hht, wtr

3.5 Economic Agents, Primary Factors, and Macro Closures

Consistent with the standard PEP-w-t architecture, the GUIDE-GLOBAL-CGE model identifies explicit economic agents—households, governments, and investors—within each region. Households receive factor incomes, pay taxes, and determine consumption and savings, while the government manages carbon pricing revenues and transfers.

The model identifies capital, labor, land, and natural resources as primary factors. Capital is assumed to be sector-specific and immobile, following a putty-clay approach, and the model maintains a unified capital stock per. Labor is aggregated into a single homogeneous category to ensure computational stability for smaller economies like North Korea and Mongolia. International trade follows the Armington assumption of imperfect substitutability. Macroeconomic closures are savings-driven, with exchange rates being endogenous for all regions except the reference region, North America (NAM), which serves as the global numeraire.

3.6 Emission Module

Focusing strictly on combustion-related CO_2 based on 2006 IPCC GL, the model maintains a direct link between energy use and climate policy.

4. Mathematical Structure of the GUDIE-GLOBAL-CGE Model

4.1 Production Structure

Figure 2 shows the multi-level nested production structure of the GUIDE-GLOBAL-CGE model, which is designed to effectively capture substitution dynamics under climate policy shocks. For the majority of sectors—including agriculture, services, and general manufacturing—we adopt a KLE (Capital-Labor-Energy) nesting approach. As illustrated in the figure, at the highest level of this hierarchy, sectoral output is produced by combining a KLE composite and non-energy intermediate inputs in fixed proportions according to a Leontief specification.

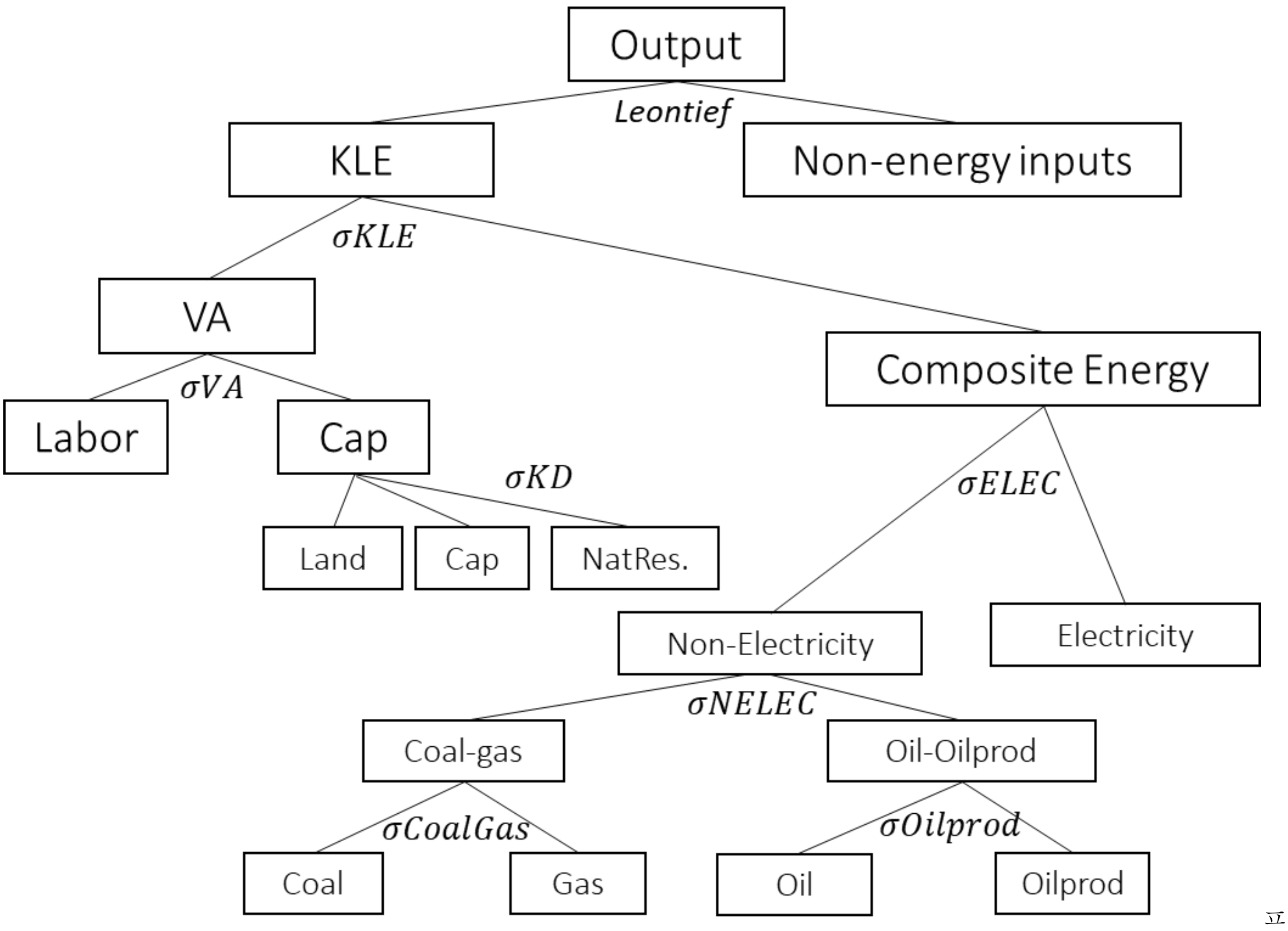

Figure 2. Production Structure of the GUIDE-GLOBAL-CGE Model

At the intermediate level, the KLE composite is disaggregated into a Value-Added (VA) bundle and an Energy composite using a Constant Elasticity of Substitution (CES) function. As extensively reviewed by Burniaux and Truong (2002) in their development of the GTAP-E framework, various energy-economic models employ distinct nesting hierarchies to capture the substitution dynamics between energy bundles and capital or primary factor composites. In this study, the specific substitution structure between the primary factor (value-added) composite and the energy composite is adopted from the GEM-E3 model (Capros et al., 2013). The substitution elasticity at this juncture is particularly critical, as it dictates the economy's potential to decouple energy consumption from overall production.

Moving down to the bottom levels, the production nests are further detailed through additional CES functions. The VA nest separates Labor from a Capital composite, which is subsequently divided into specific endowment factors: Capital, Land, and Natural Resources. Concurrently, the Energy nest isolates Electricity from a Non-Electricity bundle. To simulate detailed fuel switching capabilities, the non-electricity bundle is sequentially disaggregated into Coal versus Gas, and Crude Oil (OIL) versus Petroleum and Coal Products (PETROLCOAL). Notably, crude oil is explicitly included in this lower-level CES energy composite structure; although the vast majority of crude oil is sold directly to the petroleum refining sector as an intermediate feedstock, a specific portion is also purchased and consumed directly by various manufacturing sectors. Including the OIL commodity in the energy nest ensures that these direct industrial physical flows and substitutions are accurately captured in the model.

It is important to note certain sectoral exceptions to this general structure. For the energy supply sectors (Coal, Oil, Gas) and specific energy-intensive industries, the energy-value-added substitution mechanism is excluded. Due to technical rigidities in these sectors, energy enters directly as standard intermediate inputs at the top Leontief level. Consequently, decarbonization in these specific industries is driven primarily by technology switching—such as the adoption of backstop technologies—rather than through simple factor substitution. A comprehensive summary of the specific substitution elasticities applied across each of these hierarchical energy and factor nests is provided in Appendix B.

4.2 Aggregated Power Sector

Figure 3 illustrates the production and allocation structure of the aggregated power sector in the model. Drawing inspiration from the C-PLAN model developed by Winchester and White (2022), the GUIDE-GLOBAL-CGE model adopts an integrated "bottom-up" representation of the electricity sector within its macroeconomic framework.

At the core of this structure, the final electricity commodity is modeled as a composite good produced by combining a Transmission and Distribution (TnD) network service with an aggregated power generation bundle (Elec1) using a Constant Elasticity of Substitution (CES) function. The fundamental rationale behind this design choice is to treat electricity as a homogeneous good. From the perspective of end-users (both households and industries), electricity is consumed as a unified commodity, without the consumers distinguishing or prioritizing the specific power generation source (e.g., whether the power comes from a coal plant or a wind farm).

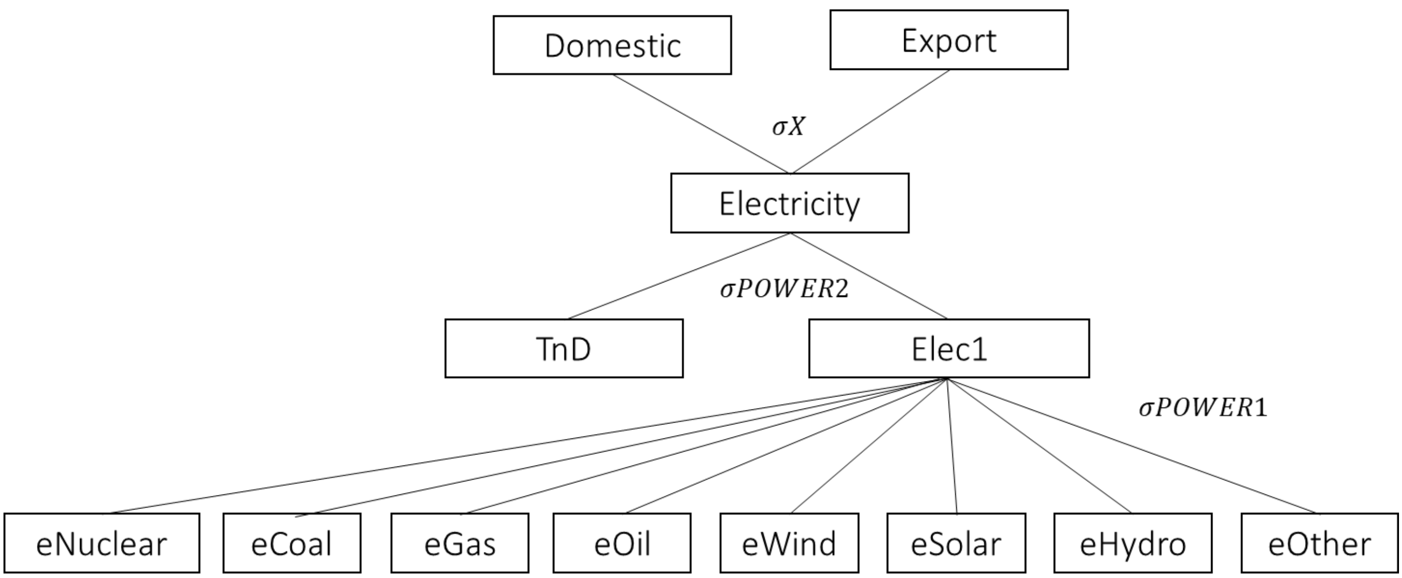

Figure 3. Structure of the Aggregated Power Sector

The aggregated power generation composite (Elec1) itself is formed by combining the outputs of eight distinct power generation technologies—Nuclear, Coal, Gas, Oil, Wind, Solar, Hydro, and Other—through a lower-level CES function. This critical nesting allows the model to simulate the substitution dynamics among different power sources. When climate policies such as carbon pricing are introduced, the relative generation costs of fossil-based power plants increase, which endogenously prompts a systemic shift toward renewable energy sources within the Elec1 composite to minimize the overall cost of electricity production.

At the lower level, outputs from eight distinct power generation technologies p are aggregated into a single unified power generation bundle ($QPOWER_{z,t}$) via a CES function, reflecting electricity as a homogeneous good:

$$QPOWER_{z,t} = B_{X4,z}\left[\sum_{p}\beta_{X4,p,z}\cdot XS_{p,ELEC,z,t}^{-\rho_{X4,z}}\right]^{-\frac{1}{\rho_{X4,z}}}$$

where:

- QPOWER_{z, t} is the composite power generation bundle in region z at time t.
- $XS_{p,ELEC,z,t}$ is the intermediate electricity output supplied by specific generation technology p (e.g., Coal, Nuclear, Solar).
- $B_{X4,z}$ and $\beta_{X4,p,z}$ are the shift (scale) parameter and the baseline distribution share of each power source, respectively.
- $\rho_{X4,z}$ is the substitution parameter, which is mathematically derived from the elasticity of substitution ($\sigma_{X4,z}$).

The optimal dispatch is derived from cost minimization, shifting generation away from fossil fuels as carbon pricing alters relative costs:

$$XS_{p,ELEC,z,t} = QPOWER_{z,t}B_{X4,z}^{1-\sigma_{X4,z}}\left[\frac{\beta_{X4,p,z}\cdot PPOWER_{z,t}}{P2_{p,ELEC,z,t}}\right]^{\sigma_{X4,z}}$$

where $PPOWER_{z,t}$ represents the composite price of the aggregated generation bundle, and $P2_{p,ELEC,z,t}$ is the specific production cost of technology p, which surges for fossil-based plants under carbon constraints.

The choice of the substitution elasticity among power generation technologies ($\sigma_{POWER1,z}$) is crucial for determining the power sector's responsiveness to carbon pricing. While Winchester and White (2022) assume an infinite elasticity (implying perfect substitution) and the OECD-LINKAGE model employs a value of 5 (de Bruin, Dellink, & Agrawala, 2009), this study adopts a regionally differentiated approach to reflect varying degrees of grid flexibility. Specifically, we assign an elasticity of 5 to the highly industrialized CJK core (China, Japan, and South Korea), consistent with the OECD-LINKAGE assumption. Conversely, a lower elasticity of 3 is applied to Russia, Mongolia, and North Korea, reflecting their relatively rigid power infrastructure and institutional constraints.

At the top level, the generation bundle must be transmitted to consumers. This combination with Transmission and Distribution (TnD) services follows a strict Leontief (fixed-proportion) specification:

$$XS_{TnD,ELEC,z,t} = TnDShare_z \cdot XS\_I_{ELEC,z,t}$$

$$XS\_I_{ELEC,z,t} = XS_{TnD,ELEC,z,t} + QPOWER_{z,t}$$

where $XS\_I_{ELEC,z,t}$ is the total production of the final electricity commodity, $XS_{TnD,ELEC,z,t}$ is the demand for transmission and distribution services, and $TnDShare_z$ is the fixed input-output coefficient. This ensures that any expansion in electricity demand fundamentally requires a proportional expansion of transmission infrastructure.

Finally, at the top level of the structure, the total supplied electricity is allocated between the Domestic market and Exports via a Constant Elasticity of Transformation (CET) function. This ensures that the flow of the electricity commodity remains consistent with the standard Armington trade assumptions utilized throughout the model.

4.3 Emission Intensity, Carbon Pricing, and Revenue Recycling

To capture the endogenous response of greenhouse gas emissions to climate policies, the GUIDE-GLOBAL-CGE model incorporates a price-based emission intensity reduction mechanism. This approach draws upon the methodologies established in the Victoria University Regional Model (VURM) (Adams, Dixon, & Horridge, 2015) and the Global Trade and Environment Model (GTEM).

Rather than explicitly modeling highly disaggregated, micro-level abatement technologies across all sectors, this mechanism employs a stylized approach by assuming an exogenous Marginal Abatement Cost (MAC) curve. Under this framework, the emission intensity of production—defined as the volume of emissions per unit of economic activity—is modeled as a decreasing function of the carbon price. As the carbon price rises, industries are incentivized to enhance their energy efficiency, causing their emission intensity to decline asymptotically toward a predefined minimum threshold. This stylized specification effectively captures the aggregate, price-induced energy efficiency improvements and incremental abatement efforts that occur continuously across the economy without necessitating the explicit modeling of every potential technological retrofit.

Consistent with the assumptions made in the broader production structure (Section 3.1), this emission intensity reduction mechanism is applied to all general industries—including agriculture, services, and manufacturing. However, it is explicitly excluded from the primary energy supply sectors, namely Coal, Oil, and Gas. For these specific energy-producing sectors, decarbonization is assumed to be driven strictly by absolute output reductions or macro-level technology switching, rather than marginal improvements in their own production efficiency.

When a regional carbon price ($\tau_{z,t}$) is introduced, it inflates the effective purchaser's price (PE) of fossil fuels:

$$PE_{ene,j,z,t} = P_{ene,z,t} \cdot \left(1 + \tau_{z,t} \cdot \theta_{ene,j,z,t}\right)$$

where:

- $PE_{ene,j,z,t}$ is the effective, tax-inclusive price of fossil fuel ene consumed by industry j.
- $P_{ene,z,t}$ is the base market commodity price of the fossil fuel.
- $\tau_{z,t}$ is the specific regional carbon tax rate or ETS permit price.
- $\theta_{ene,j,z,t}$ is the endogenous CO_2 emission intensity factor (emissions per unit of energy).

The model employs an endogenous Marginal Abatement Cost (MAC) framework, where the optimal target emission intensity (θ^*) is an exponentially decreasing function of the carbon price:

$$\theta^*_{ene,j,z,t} = \theta^{base}_{ene,j,z} \cdot exp\left[\alpha - \alpha\left(1 + \tau_{z,t}\right)^{\gamma}\right]$$

where $\theta^{base}_{ene,j,z}$ is the base-year emission intensity, and α (set to 0.15) and γ (set to 1.5) are structural parameters governing the abatement responsiveness and the curvature of the MAC.

To reflect capital turnover and adjustment frictions, the actual emission factor follows a lagged partial adjustment mechanism:

$$\theta_{ene,j,z,t} = \theta_{ene,j,z,t-1} + \delta \cdot \left(\theta^*_{ene,j,z,t} - \theta_{ene,j,z,t-1}\right)$$

where δ represents the speed-of-adjustment parameter. This dynamic specification, constrained by a minimum floor ($\theta^{min}_{ene,j,z} = 0.01 * \theta^{base}_{ene,j,z}$), prevents unrealistic instantaneous decarbonization. Furthermore, fossil-based power generation faces a linear regulatory phase-out post-2040.

To ensure rigorous carbon accounting, this endogenous MAC mechanism is applied strictly and exclusively to conventional sectors lacking explicit backstop alternatives (e.g., agriculture, services). For sectors with modeled Backstop technologies or within the power sector, decarbonization is driven purely through structural CES fuel-switching or physical technology adoption, preventing double-counting.

The total domestic carbon tax revenue ($TCTAX_{z,t}$) is explicitly tracked:

$$TCTAX_{z,t} = \sum_{ene} \sum_{j} P_{ene,z,t} \cdot \tau_{z,t} \cdot \theta_{ene,j,z,t} \cdot DE_{ene,j,z,t}$$

where $\mathrm{DE}_{\mathrm{ene,j,z,t}}$ is the volume of intermediate energy demand.

In ICM scenarios, net trading revenue is added to determine the total macroeconomic rebate ($\mathrm{REBATE}_{\mathrm{z,t}}$):

$$\mathrm{REBATE}_{\mathrm{z,t}} = \mathrm{TCTAX}_{\mathrm{z,t}} + \left(\overline{\mathrm{CAP}}_{\mathrm{z,t}} - \mathrm{E}_{\mathrm{z,t}}\right) \cdot \mathrm{P}_{\mathrm{t}}^{\mathrm{global}}$$

where:

- $\mathrm{REBATE}_{\mathrm{z,t}}$ is the total macroeconomic rebate generated from climate policies.
- $\mathrm{TCTAX}_{\mathrm{z,t}}$ is the revenue collected from domestic carbon taxation.
- $\overline{\mathrm{CAP}}_{\mathrm{z,t}}$ is the exogenously allocated emission quota (allowance) for region z.
- $\mathrm{E}_{\mathrm{z,t}}$ is the actual total carbon emissions produced by region z.
- $\mathrm{P}_{\mathrm{t}}^{\mathrm{global}}$ is the uniform global (or regional integrated) carbon price established in the cross-border emissions trading market.

This financial stream is recycled as a lump-sum transfer directly into household income ($\mathrm{YH}_{\mathrm{z,t}}$), driving the import-substitution dynamics observed in resource-abundant nations. By re-injecting both the domestic tax and the international trading surplus into the local economy, the model mathematically captures the precise mechanisms of capital revitalization in permit-exporting nations.

4.4 Backstop Technologies and Direct Air Capture

To simulate deep decarbonization pathways and achieve stringent Net-Zero targets, the GUIDE-GLOBAL-CGE model explicitly incorporates both sector-specific "backstop" technologies and an overarching Negative Emission Technology (NET) via Direct Air Capture (DAC).

Specifically, backstop industries are introduced for Chemicals, Non-metallic minerals, Iron and steel, Land transport, Water transport, and Air transport. Following a logic similar to the aggregated power sector, these advanced technology industries supply the exact same, perfectly homogeneous commodities as their conventional counterparts. This design allows end-users to transition seamlessly from conventional to low-carbon alternatives based solely on relative price changes induced by carbon constraints.

To provide a realistic representation of sectoral decarbonization, these backstop industries are parameterized based on representative advanced technologies. For instance, in the primary iron and steel sector, the backstop technology represents Hydrogen Direct Reduction Iron coupled with Electric Arc Furnaces (H2-DRI-EAF). For chemicals, it assumes the adoption of green hydrogen-based synthesis (e-chemicals) and biomass feedstocks. The non-metallic minerals backstop, primarily representing the cement industry, incorporates Carbon Capture and Storage (CCS)-integrated kilns.

Figure 4 illustrates the specific production structure applied to these backstop industries.

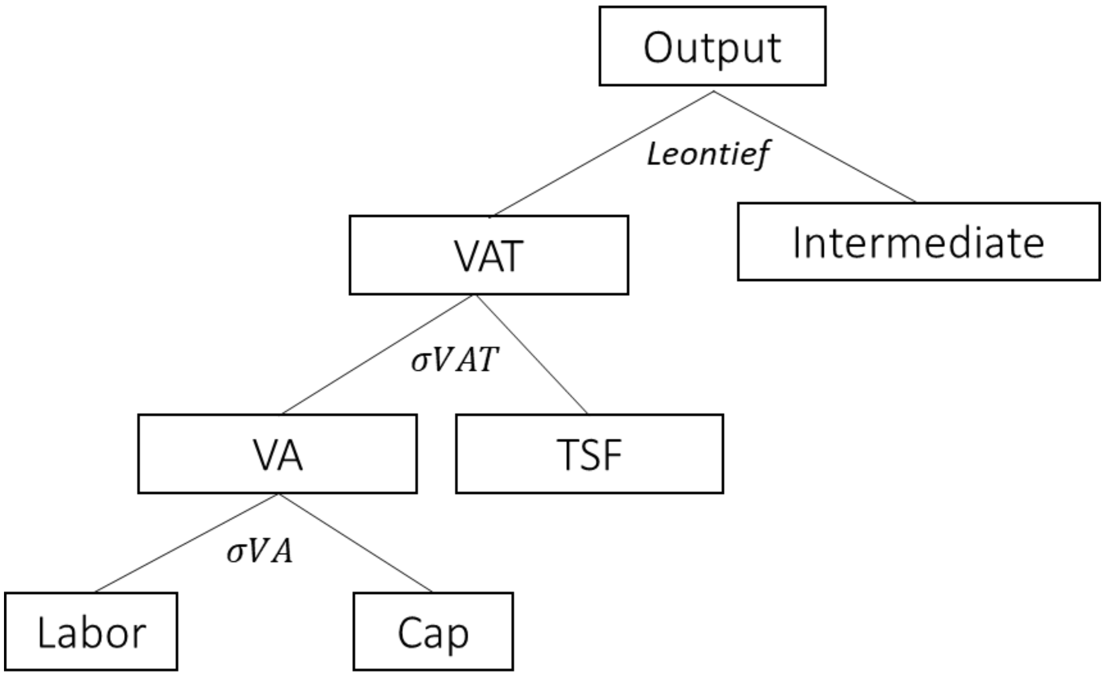

Figure 4. Production Structure of Backstop Technologies

At the intermediate level of the backstop structure, the Value-Added and Technology-Specific

Factor (VAT) composite is formed by a Constant Elasticity of Substitution (CES) function. The inclusion of the Technology-Specific Factor (TSF) acts as an implicit capacity constraint that limits the rapid expansion rate of the backstop technology, thereby preventing unrealistic "bang-bang" corner solutions.

$$Q_{c,z,t} = B_{c,z}\left[\beta_{Conv,z} \cdot XS_{Conv,z,t}^{-\rho_c} + \beta_{BS,z} \cdot XS_{BS,z,t}^{-\rho_c}\right]^{-\frac{1}{\rho_c}}$$

where $Q_{c,z,t}$ is the total composite demand for commodity c, XS_{Conv} and XS_{BS} denote the physical supply from conventional and backstop technologies respectively, and ρ_c is the substitution parameter.

To prevent instantaneous "bang-bang" solutions, we introduce a Technology-Specific Factor (TSF) representing limited specialized capacity. TSF is combined with Value-Added via CES, and its rental price (P_{TSF}) is absorbed in the composite price:

$$P_{VAT,BS,z,t} \cdot VAT_{BS,z,t} = P_{VA,BS,z,t} \cdot VA_{BS,z,t} + P_{TSF,BS,z,t} \cdot TSFD_{BS,z,t}$$

where P_{VAT} is the price of the value-added-technology composite, P_{VA} is the standard price of labor and capital, VA is standard value-added, P_{TSF} is the marginal rental price of the specific technology, and $TSFD$ is the demanded volume of the specific technological capacity.

The supply of TSF ($TSFS$) expands endogenously based on a market profitability signal ($Signal$):

$$Signal_{BS,z,t} = max\left(0, \frac{P_{Conv,z,t-1}}{P_{BS,z,t-1}} - 1\right)$$

$$TSFS_{BS,z,t} = TSFS_{BS,z,t-1} \cdot \Omega\left(P_{TSF,t-1}\right) \cdot \left[1 + min\left(0.3, \alpha_{BS} \cdot Signal_{BS,z,t}\right)\right]$$

where Ω is a rent-adjustment multiplier (ranging smoothly from 0.95 to 1.05 based on P_{TSF}) that scales baseline capacity, and the profitability $Signal$ provides an additional rapid-expansion boost capped at 30% per year.

Regarding the expansion of these advanced technologies, previous literature has explored various capacity-building mechanisms. For example, to overcome the modeling limitations identified by Morris et al. (2014), the MIT EPPA6 model (Chen et al., 2015) introduced a dynamic function where the supply of technology-specific factors (initially designed for nuclear generation) increases endogenously in tandem with production growth. While the TSF supply mechanism in the GUIDE-GLOBAL-CGE model explicitly reacts to the cost competitiveness of backstop technologies via the profitability signal, its underlying growth trajectory retains a strong exogenous character to conservatively bound the maximum annual expansion rate and prevent unrealistic market takeovers.

Efficiency improvements (B_VAT_t) exogenously grow for backstops, while conventional technologies face an annual technological deterioration (e.g., 2% decay).

In addition to sectoral backstops, the model features an endogenous, price-triggered Direct Air Capture (DAC) module. While DAC can theoretically offset residual emissions to achieve Net-Zero, it is highly energy-intensive and costly. The model captures this critical trade-off by explicitly linking DAC operation to carbon prices, macroeconomic electricity demand, and government fiscal burdens.

First, the activation of DAC is endogenously governed by a regional carbon price trigger ($P_{z,t}^{carbon}$). The binary parameter $SwitchDAC_{z,t}$ is activated ($SwitchDAC_{z,t} = 1$) only when the carbon price exceeds the threshold of \$500 per tCO_2 ($\overline{P}^{trigger}$), reflecting the high commercialization cost of atmospheric carbon removal. If the carbon price remains below this threshold, the parameter remains inactive ($SwitchDAC_{z,t} = 0$).

Once activated, the volume of carbon captured via DAC ($Q_{z,t}^{DAC}$) expands annually following an endogenous exponential growth rate ($\lambda_{z,t}$), up to a predefined regional maximum potential ($Q_{MAX,z}^{DAC}$), which is bounded by geographic and geological storage constraints (assumed to be 30% of base-year emissions for most regions, and 50% for WEU and JPN). The net total emission allowance available in the economy ($PermitTotal_{z,t}$) is physically expanded by the volume of captured carbon:

$$PermitTotal_{z,t} = \sum_{j} Permit_{j,z,t} - Q_{z,t}^{DAC} \cdot SwitchDAC_{z,t}$$

Crucially, the operation of DAC inflicts a severe macroeconomic penalty. The model explicitly calculates the intermediate electricity required to run the DAC facilities, assuming an energy intensity (θ_{elec}) of 2.5 MWh per ton of CO_2. This parameter represents a conservative assumption based on current technological levels, reflecting recent engineering assessments (Li & Yao, 2024). This substantial electricity demand ($D_{DAC,z,t}^{elec}$) is added to the regional commodity market clearance equation, creating an upward pressure on electricity prices:

$$D_{DAC,z,t}^{elec} = \theta_{elec} \cdot Q_{z,t}^{DAC}$$

Furthermore, because DAC generates a public good (negative emissions) without producing a marketable physical commodity, its operational cost must be financed. In this model, the expenditure is assumed to be borne by the government. The total cost of DAC—derived from the electricity price ($P_{z,t}^{elec}$) and the technology coefficient—is directly subtracted from the net government revenue ($YG_{z,t}$):

$$YG_{z,t} = TaxRevenue_{z,t} - \left(P_{z,t}^{elec} \cdot D_{DAC,z,t}^{elec}\right)$$

By integrating these dynamics, the GUIDE-GLOBAL-CGE model ensures that while DAC provides a mathematical pathway to Net-Zero, it realistically crowds out other economic activities by monopolizing electricity resources and straining government budgets.

5. Base-Year Data and Macroeconomic Calibration

5.1 GTAP 11 Database, Baseline Updating, and BAU Projections

The core economic dataset utilized for calibrating the GUIDE-GLOBAL-CGE model is the Global Trade Analysis Project (GTAP) 11 database (Aguiar et al., 2022). Although the latest available reference year for the standard GTAP 11 database is 2017, we purposefully anchored our model to the reference year of 2019 to capture the most recent macroeconomic conditions immediately prior to the distortions caused by the COVID-19 pandemic.

To bridge this temporal gap, we employed the standard GTAP Version 7 model (Corong et al., 2017) to project the 2017 database forward to 2019. This updating process involved applying iterative technological shocks to align the simulated regional GDPs with the actual nominal GDP growth rates observed between 2017 and 2019. Notably, for the xea region (which combines North Korea and Macau), the GDP volume was explicitly targeted and adjusted to match the North Korean GDP estimates provided by the United Nations Statistics Division. The resulting 2019-updated GTAP-SAM, reflecting these targeted macroeconomic growth trajectories, serves as the primary input matrix for the GUIDE-GLOBAL-CGE model.

As summarized in Table 3, to achieve the targeted nominal GDP growth rates (vgdp) from 2017 to 2019 across all 17 regions, we iteratively applied shocks to the regional Total Factor Productivity (avareg) to successfully reproduce the updated base-year economy.

Table 3 Macroeconomic Targets for 2019 Base year Updating

Region Code	GTAP 11 DB GDP (2017) Million USD	WB, UN GDP (2019) Million USD	% vgdp Change (Target)
KOR	1,623,899	1,651,423	1.69
CHN	12,651,702	14,643,043	15.74
JPN	4,930,838	5,117,994	3.80
RUS	1,574,201	1,693,115	7.55
MNG	11,481	14,206	23.74
PRK	67,806	16,331	-75.91
NAM	21,232,294	23,240,315	9.46

LAM	5,704,330	5,365,456	-5.94
WEU	18,080,553	18,828,981	4.14
EEU	1,595,888	1,787,657	12.02
RFS	528,128	614,149	16.29
MEA	3,404,539	3,514,288	3.22
AFR	1,579,326	1,793,077	13.53
MEK	263,025	380,195	44.55
SAS	3,426,937	3,658,217	6.75
SEA	3,185,470	3,425,524	7.54
ANZ	1,533,666	1,607,763	4.83

Furthermore, while the GTAP database provides an exhaustive global economic framework, simulating complex energy transitions requires an alignment between economic values and physical energy flows. Therefore, following standard CGE modeling practices, we recalibrate the energy-related substitution elasticities and emission factors using the physical energy balances documented in the IEA World Energy Balances. This ensures that the baseline carbon emissions strictly correspond to the structural energy consumption of each region in 2019.

To establish the long-term Business-as-Usual (BAU) baseline extending to 2050, the model calibrates regional economic growth based on future demographic and macroeconomic projections. We utilize the Shared Socioeconomic Pathways (SSP2) "Middle of the Road" scenario provided by the International Institute for Applied Systems Analysis (IIASA), imposing exogenous population and GDP growth rates. Within our dynamic CGE framework, these targeted GDP growth paths are endogenously achieved by adjusting the Total Factor Productivity (TFP) parameter for each region.

However, a critical adjustment was necessary for North Korea's baseline projection. The default IIASA SSP2 projections (KC et al., 2024a; KC et al., 2024b) simulate an exceptionally rapid economic expansion for North Korea, presumably driven by a theoretical "catch-up" growth model often applied to low-income developing nations. Given the geopolitical realities and historical stagnation of the North Korean economy, applying such aggressive growth rates would severely overestimate its future economic scale and, consequently, its baseline carbon emissions. To ensure a realistic trajectory, we overrode the SSP2 GDP projections for North Korea. Instead, we calculated its historical Compound Annual Growth Rate (CAGR) over a 30-year period (1990-2020) and applied a highly conservative, steady annual growth rate of approximately 0.25% to formulate its BAU scenario.

5.2 Reconstruction of the North Korean Social Accounting Matrix (SAM)

One of the most significant methodological challenges and contributions of this study is the explicit representation of the North Korean economy. In the standard GTAP 11 database, North Korea is not represented as an independent region but is rather aggregated alongside Macau into a residual region denoted as "Rest of East Asia" (xea).

Directly utilizing the unadjusted xea dataset to proxy North Korea would yield highly distorted simulation results. Because the xea region encompasses Macau—a high-income, service-oriented economy heavily reliant on international tourism and gambling—the aggregated data portrays a macroeconomic structure that is fundamentally incompatible with North Korea’s highly isolated, industry- and agriculture-centric planned economy.

To resolve this critical discrepancy, we developed a rigorous SAM balancing procedure to extract and reconstruct an independent Social Accounting Matrix for North Korea (PRK) from the original xea data. This procedure involved utilizing reliable external macroeconomic estimates to establish accurate calibration targets. Specifically, the value-added components and the overarching industrial structure of North Korea were calibrated utilizing detailed data published by the Bank of Korea (BOK, 2025). Concurrently, the bilateral trade volumes and the specific import structures were strictly adjusted based on North Korean trade statistics provided by the Korea Trade-Investment Promotion Agency (KOTRA, 2025). To execute this recalibration, we utilized the GEMPACK-based SAM balancing utility (SAMBAL) developed by Horridge (2008), adjusting the underlying input-output coefficients and trade matrices to precisely match these two distinct sets of external targets.

Figure 5 illustrates the profound structural corrections achieved through this SAM balancing process.

As shown in Figure 5(a), the original GTAP xea data ("Original GTAP (xea)") exhibited an exceptionally large service sector, reflecting Macau's economic influence. After the balancing procedure ("Reconstructed (PRK)"), the value-added structure drastically shifted, accurately reflecting North Korea's heavy reliance on agriculture and traditional manufacturing industries, while significantly compressing the service sector.

Furthermore, Figure 5(b) highlights the correction in international trade patterns. The original xea data suggested a highly open economy engaging in substantial trade with North America (NAM) and a vast array of other global regions (Rest of World, RoW). Post-balancing, the total volume of international trade was drastically reduced to reflect North Korea's economic isolation. More importantly, the composition of trade partners was accurately recalibrated to reflect geopolitical realities, with the vast majority of North Korea's remaining international trade being deeply concentrated with China (CHN), effectively eliminating the disproportionate shares of NAM and RoW.

This targeted SAM reconstruction allows the GUIDE-GLOBAL-CGE model to accurately depict the genuine economic isolation and specific industrial vulnerabilities of North Korea, thereby enabling a truly comprehensive analysis of climate policy spillovers across the entire Northeast Asian region.

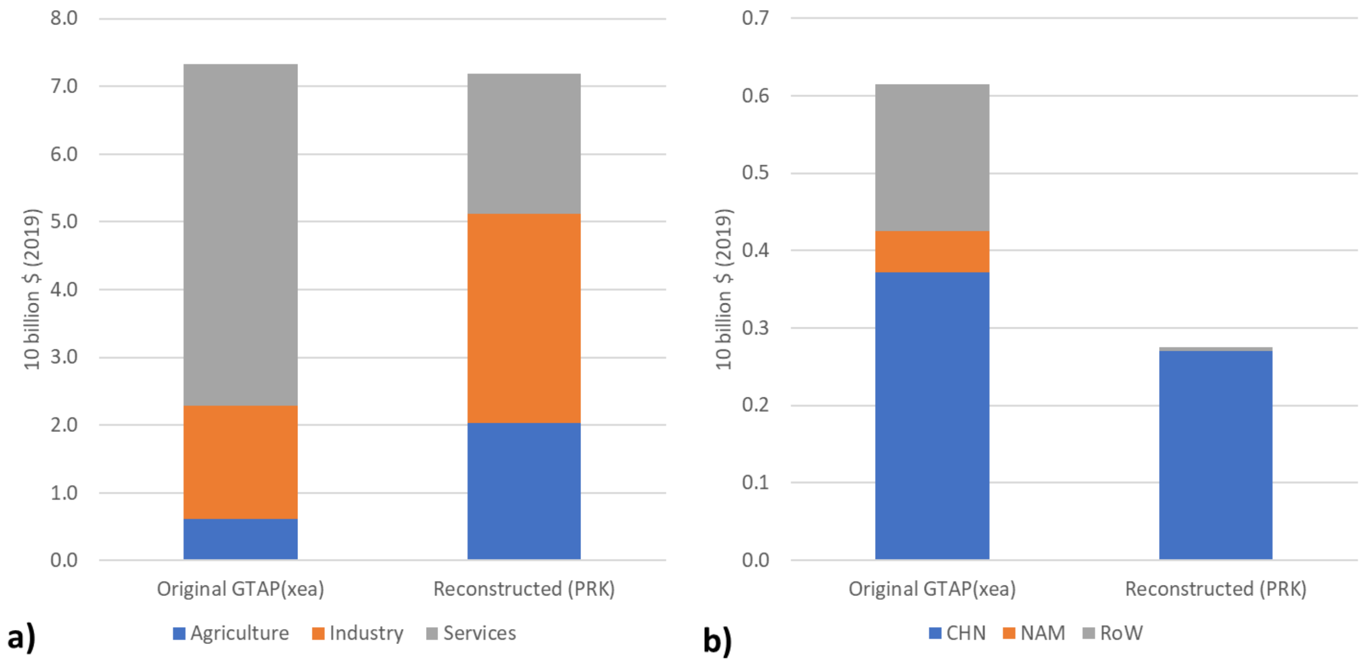

Figure 5. Structural Adjustments of the North Korean Economy via SAM Balancing: (a) Value Added by Sector, and (b) Trade Volume by Partner

5.3 Own Price Elasticity Calibration

In energy-oriented CGE models, the choice of substitution elasticities significantly dictates the model's behavioral response to carbon pricing, making robust empirical calibration essential. Drawing upon the validation framework proposed by Beckman, Hertel, and Tyner (2011), this study undertook a rigorous recalibration of the substitution elasticities specifically for key energy markets—coal, petroleum and coal products, natural gas, and electricity—across Northeast Asia. We first conducted a comprehensive literature review to collect existing econometric estimates of demand price elasticities for these energy commodities. Subsequently, a meta-analysis and regression analysis were applied to derive representative target price elasticities tailored to the distinct economic contexts of the six NEA nations.

This methodological challenge is particularly evident when comparing our approach to standard energy-extended frameworks such as the GTAP-E model (Burniaux and Truong, 2002). In GTAP-E, energy responsiveness is primarily evaluated using *General Equilibrium (GE) elasticities*, which are *ex-post* measurements obtained by introducing an output tax shock to an energy commodity and observing the simulated change in its equilibrium output. This GE elasticity inherently combines both the pure input substitution effect and the macroeconomic expansion/contraction (output) effect after the entire general equilibrium system has cleared. However, as highlighted by He et al. (2011), directly inserting econometrically estimated demand elasticities into a CGE model without differentiating these mechanisms is methodologically flawed. There is an inherent structural discrepancy between isolated econometric estimates, the theoretical elasticities implied by a CGE model's deep nesting structure, and the actual *ex-post* elasticities realized after a model simulation.

To bridge this gap and ensure structural consistency, we implemented an advanced iterative calibration procedure. Because the GUIDE-GLOBAL-CGE model employs a complex KLE hierarchy for specific industries (while excluding it for energy supply sectors) and incorporates domestic-import (Armington) and export-domestic substitution dynamics, we first analytically calculated the theoretical average price elasticity for each region based on its specific structural shares. Then, guided by the relative contribution of each parameter to the overall demand response, we iteratively modified the Armington substitution elasticities, the inter-energy substitution elasticities, and the energy-value-added substitution elasticities. This systematic recalibration was repeated until the model's theoretical, system-wide price response accurately converged on the empirically estimated targets for the six NEA countries.

A detailed description of the final elasticity values and the calibration algorithm is provided in Appendix B. The profound impact of this procedure is visually summarized in Figure 6, which contrasts the theoretical own-price elasticities of the four primary energy commodities (Coal, Gas, Petroleum & Coal Products, and Electricity) across all 17 regions before and after the calibration. As illustrated, relying solely on the default substitution parameters from the pre-calibrated elasticities (Before Calibration) yields theoretical energy price elasticities that are highly elastic, with absolute values frequently exceeding 1.0—and in extreme cases, surpassing 10.0 for natural gas. However, following the application of our targeted iterative calibration method (After Calibration), these parameters are systematically adjusted. Consequently, the theoretical elasticities successfully converge to reflect the structurally inelastic nature (absolute values falling between 0 and 1.0) of actual energy demand markets across the vast majority of regions and commodities. This critical structural correction prevents unrealistic, frictionless fuel switching and ensures a more reliable, empirically grounded simulation of climate policy impacts.

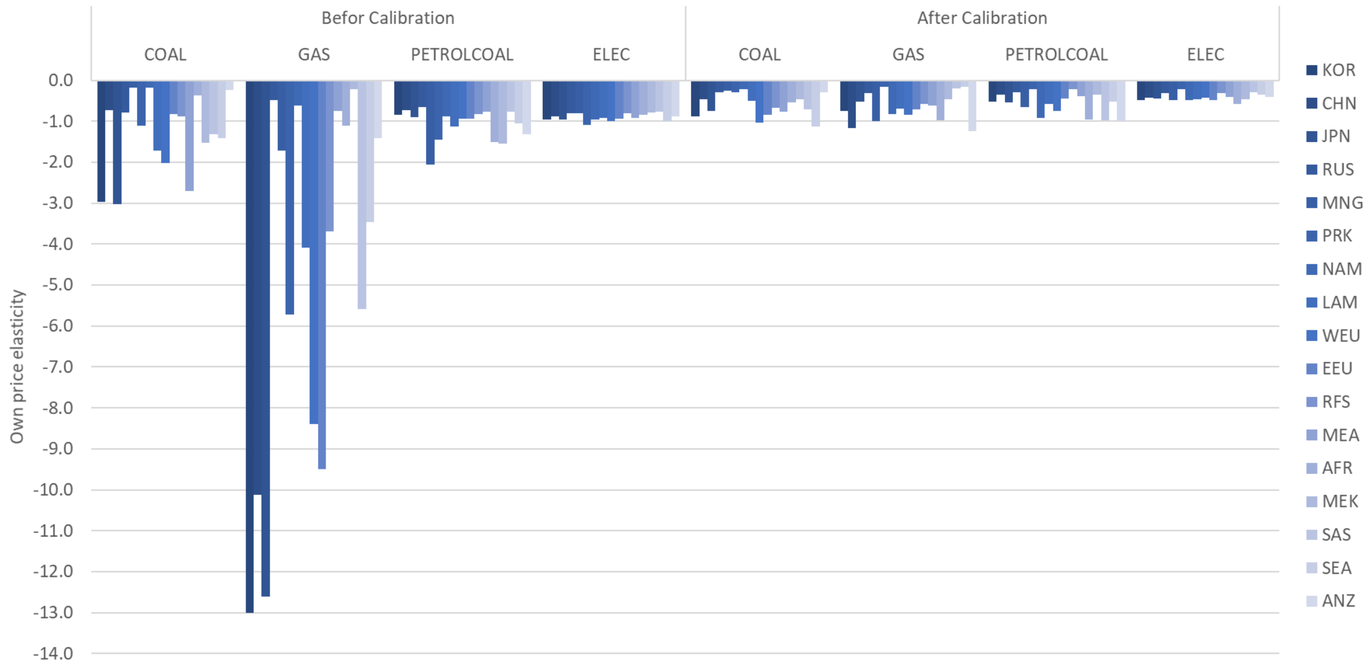

Figure 6. Comparison of Theoretical Own-Price Elasticities Before and After Calibration

6. Scenarios and Simulation Results

6.1 Scenario Design

To evaluate the economic and environmental impacts of regionally fragmented climate policies in Northeast Asia, we design a suite of six counterfactual scenarios. These scenarios are designed to contrast isolated national decarbonization efforts against various configurations of regional cooperation and integrated carbon markets through the target year of 2050. It should be noted that across all Net-Zero compliance scenarios (with the exception of non-compliant regions in Fragmented_NZ), the overarching global emissions cap is calibrated to reach approximately 28% of the 2019 baseline level by 2050. This specific target is highly consistent with the median residual CO2 emissions (approximately 27%) projected for the 2°C global warming mitigation pathways (Category C3) detailed in the IPCC Sixth Assessment Report (IPCC, 2022). As the IPCC explicitly indicates, reaching absolute zero gross CO2 emissions from the energy and industrial sectors is practically infeasible due to hard-to-abate sectors (e.g., heavy industry and aviation). Therefore, this modeled constraint specifically covers energy-sector CO2 emissions and accounts for technological carbon removal via CCS and DAC, while the residual 28% of gross emissions is assumed to be fully neutralized by natural carbon dioxide removal (CDR), such as the Land Use, Land-Use Change, and Forestry (LULUCF) sector, to achieve absolute global Net-Zero.

The predefined scenarios are:

1. **BAU (Business-as-Usual)**: A baseline trajectory where no additional climate policies are enacted beyond those already in place as of 2019. Economic growth follows the new IIASA SSP2 (KC et al., 2024a; KC et al., 2024b) without explicit emission constraints. It is important to note that this study deliberately defines the BAU as a "no-additional-policy" baseline rather than a "Current Policies Scenario (CPS)". This methodological choice is made for two primary reasons. First, quantifying and harmonizing the highly fragmented and heterogeneous current climate policies across 17 distinct regions—especially for opaque or

isolated economies like North Korea and Mongolia—introduces excessive uncertainty and modeling complexity. Second, by establishing a pure macroeconomic growth baseline, the model can cleanly isolate and evaluate the "total abatement effort" and the pure economic shock required to achieve the Net-Zero targets, free from the noise of varying intermediate policy baselines.

2. **Global_NZ (Global Net-Zero)**: An idealized benchmark scenario assuming a perfectly cooperative global mechanism where a unified global carbon market ensures harmonized marginal abatement costs across all 17 regions. In this scenario, the total global emissions cap is strictly constrained to match the aggregate sum of the individual emission targets defined in the Isolated_NZ scenario. Furthermore, the regional emission trading balances (i.e., the net flow of carbon allowances) are calculated based on the difference between a region's actual optimized emissions under the unified market and its initial allowance quota. This initial quota is determined by the region's committed abatement efforts, measured as the difference between its projected BAU emissions and its specific Isolated_NZ target. This explicit allocation rule is theoretically crucial. Without such a predefined constraint, the model could yield multiple equilibrium states, as the macroeconomic outcomes would vary significantly depending on arbitrary assumptions regarding the distribution of carbon pricing revenues and international trading rents. Therefore, anchoring the initial allocation to these established baselines ensures a determinate and policy-consistent benchmark to isolate the pure efficiency gains of market integration.
3. **Isolated_NZ (Isolated Net-Zero)**: A highly fragmented scenario where each NEA nation, along with other global regions, pursues its stated 2050/2060 Net-Zero targets independently. In this scenario, there is no cross-border emissions trading (no carbon market integration), forcing each country to rely solely on domestic abatement options A comprehensive summary of the specific emission constraints applied to all 17 regions across the key milestone years (2019, 2030, 2035, 2040, 2045, and 2050) is provided in Appendix

C.

4. **Fragmented_NZ (Fragmented Net-Zero with Non-Compliance Spillover)**: A scenario designed to examine the extreme impacts of asymmetric climate ambition and geopolitical fragmentation. While nations like Russia and Mongolia have officially declared Net-Zero targets (e.g., Russia by 2060), their heavy reliance on fossil fuel exports, energy security priorities, and geopolitical complexities raise uncertainties regarding strict policy compliance. In contrast to the Isolated_NZ scenario, this counterfactual assumes a "worst-case" regional divergence where the resource-abundant but geopolitically distinct NEA nations (North Korea, Russia, and Mongolia) fail to implement their reduction constraints or prioritize immediate economic growth, effectively reverting to BAU trajectories. Meanwhile, the heavily industrialized "CJK core" and all other global regions strictly maintain their emission targets. This configuration allows us to explicitly isolate and analyze the worst-case spillover effects, such as carbon leakage and competitiveness shifts, within the Northeast Asian trade network.
5. **NEAICM_All_NZ (Northeast Asia Integrated Carbon Market - All Net-Zero)**: A comprehensive regional cooperation scenario representing a "Climate Club" across all six NEA nations (South Korea, China, Japan, Russia, Mongolia, and North Korea). An integrated regional emissions trading system is established, allowing for the free flow of carbon credits and equalizing the carbon price within the region. Consistent with the global market framework, the initial emission allowance (quota) for participating NEA nations is strictly allocated based on its domestic target defined in the Isolated_NZ scenario. This ensures that the carbon trade balances and financial transfers are driven purely by differences in marginal abatement costs rather than arbitrary quota allocations.
6. **NEAICM_CJK_NZ (Northeast Asia Integrated Carbon Market - CJK Net-Zero)**: A restricted cooperation scenario where the integrated carbon market is exclusively formed among the heavily industrialized "CJK core" (China, Japan, and South Korea). Crucially,

unlike the stress-test in the Frag_NZ scenario, the non-participating NEA nations (Russia, Mongolia, and North Korea) do not abandon their climate goals; instead, they strictly adhere to their independent domestic reduction constraints as defined in the Isolated_NZ scenario. The carbon trading mechanism among the participating CJK nations operates under the assumption that initial allowances are fixed to their respective Isolated_NZ emission targets. This precise configuration allows us to cleanly isolate the marginal economic benefits of expanding the carbon market from a CJK-only framework to a full pan-NEA framework (Scenario 5).

6.2 The GDP Loss of Achieving Net-Zero

The transition to a Net-Zero economy intrinsically necessitates a departure from the unconstrained, fossil-fueled growth trajectories of the past. To establish a foundational understanding of this macroeconomic burden, we first compare the policy-constrained scenarios against the no-policy BAU baseline. This comparison isolates the pure economic shock generated by the forced adoption of low-carbon technologies and the penalization of carbon-intensive industries. Figure 7 presents the CO_2 emission projections for the global and Northeast Asian regions across the various scenarios.

Panel (a) of Figure 7 illustrates the global CO_2 emissions trajectory indexed to the 2019 baseline. Under the BAU scenario, global emissions grow continuously without constraint. By methodological design, the Global_NZ and Isolated_NZ scenarios follow the exact same global emission reduction trajectory, reaching the targeted 28% level by 2050. The Frag_NZ scenario, however, demonstrates a marginally higher global trajectory, reflecting the unconstrained baseline emissions of the non-compliant regions that effectively offset parts of the global mitigation effort.

Panel (b) focuses specifically on the aggregate emissions of the six Northeast Asian nations.

The regional BAU trajectory exhibits an initial rise followed by a distinctive downward bend in the later periods (post-2035). This inflection is primarily driven by the structural peaking and subsequent decline of China's baseline emissions, a reflection of its maturing industrial structure and slowing population growth. Furthermore, a comparative analysis of the compliance scenarios reveals a critical regional dynamic: the aggregate emission reductions within Northeast Asia are significantly deeper under the Global_NZ scenario compared to the Isolated_NZ scenario. This disparity indicates that when integrated into a global carbon market, Northeast Asia functions as a net supplier of abatement. In other words, the region undertakes additional, cost-effective domestic emission cuts beyond its own targets in order to export valuable carbon allowances to higher-cost regions globally.

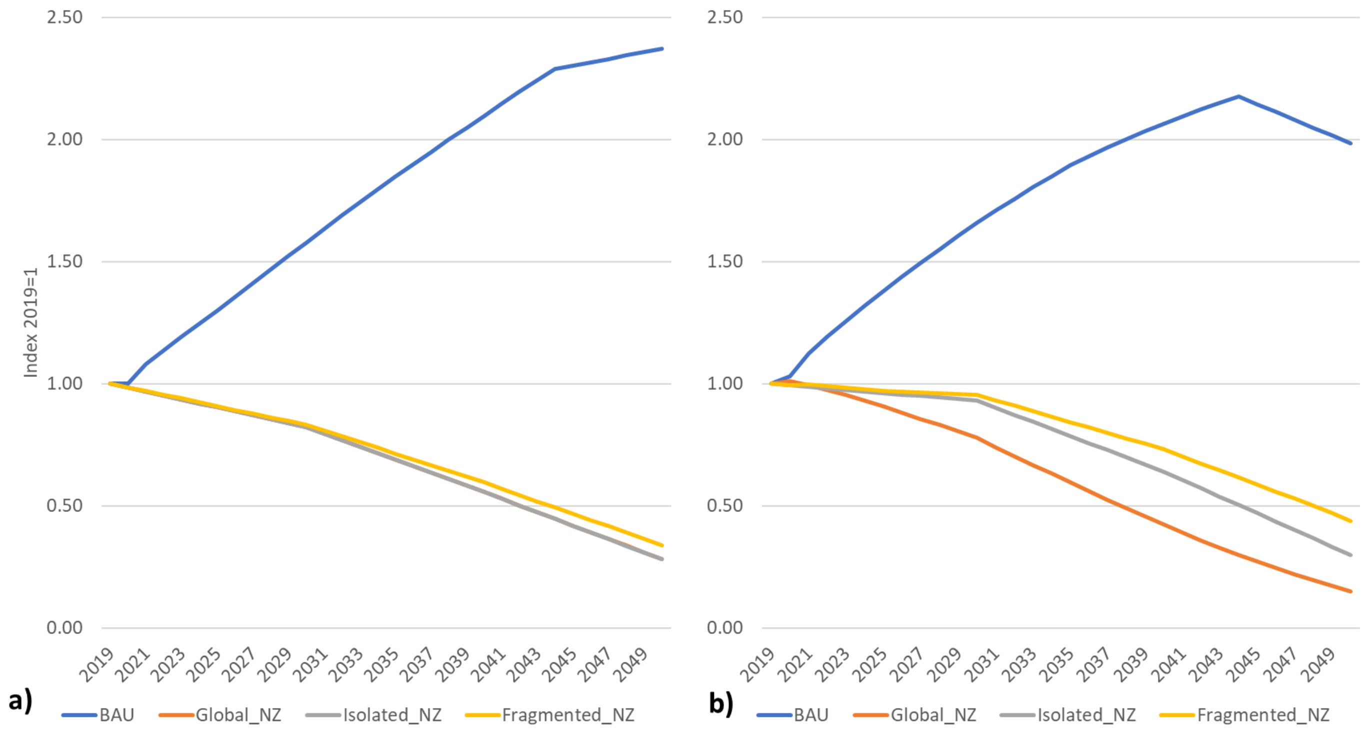

Figure 7. (a) Global and (b) Northeast Asian CO_2 Emission Trajectories (Index 2019=1)]

Table 4. Real GDP Changes (% relative to BAU) for the 6 NEA Nations

Scenario	Year	KOR	CHN	JPN	RUS	MNG	PRK
Global_NZ	2030	-4.6%	-6.5%	-5.2%	-2.5%	-20.7%	0.2%
	2040	-9.3%	-12.0%	-10.4%	-5.4%	-36.8%	1.7%

	2050	-9.2%	-11.3%	-10.9%	-7.1%	-46.4%	8.6%
Isolated_NZ	2030	-4.6%	-6.7%	-5.2%	-2.1%	-19.6%	0.5%
	2040	-9.2%	-12.6%	-10.3%	-3.8%	-32.4%	2.3%
	2050	-9.3%	-11.8%	-10.9%	-4.5%	-39.0%	10.0%
Fragmented_NZ	2030	-4.6%	-6.7%	-5.2%	-1.9%	-19.7%	0.7%
	2040	-9.2%	-12.6%	-10.3%	-3.3%	-32.6%	2.8%
	2050	-9.3%	-11.8%	-11.0%	-3.6%	-38.7%	10.4%
NEAICM_ALL_NZ	2030	-4.8%	-6.7%	-5.2%	-1.0%	-16.5%	0.2%
	2040	-10.0%	-12.5%	-10.4%	2.6%	-22.4%	1.3%
	2050	-10.4%	-11.8%	-11.2%	17.2%	-20.0%	6.5%
NEAICM_CJK_NZ	2030	-4.8%	-6.7%	-5.2%	-2.1%	-19.8%	0.5%
	2040	-10.0%	-12.5%	-10.4%	-3.7%	-32.8%	2.3%
	2050	-10.4%	-11.7%	-11.1%	-4.4%	-39.3%	10.0%

A detailed breakdown of the macroeconomic impacts across the six NEA nations is presented in Table 4. The simulation results can be systematically interpreted across three distinct dimensions: temporal evolution, regional divergence, and scenario-specific mechanisms.

Regarding the temporal evolution, the economic burden intensifies progressively from 2030 to 2050 across virtually all regions and scenarios. For example, South Korea's GDP loss in the Isolated_NZ scenario doubles from -4.6% in 2030 to -9.3% in 2050. This non-linear escalation reflects the depletion of "low-hanging fruit" in early mitigation efforts. As nations push toward absolute Net-Zero by 2050, they are forced to adopt increasingly expensive backstop technologies and energy-intensive Direct Air Capture (DAC), which compounds the downward pressure on capital accumulation and real GDP over time.

When examining regional divergence, the structural characteristics of each economy fundamentally dictate its vulnerability to climate policies, revealing extreme disparities within the region. Mongolia, functioning as a highly vulnerable exporter, suffers the most severe economic contraction across all frameworks, experiencing a substantial 39.0% drop in Scenario 3 by 2050. This decline is primarily driven by the structural collapse in regional demand for coal—Mongolia's dominant export commodity—leading to a substantial loss of export revenue and domestic investment. Meanwhile, the heavily industrialized CJK core (South Korea, China, and Japan) experiences consistent, manageable, yet significant GDP losses ranging from -9.3% to -11.8% by 2050 in Scenario 3. This reflects the significant capital reallocation required to transition their vast energy-intensive manufacturing bases away from fossil fuels. In stark contrast, North Korea presents a unique anomaly as the beneficiary of this asymmetry, consistently exhibiting positive GDP growth relative to the BAU baseline, reaching +10.0% in Scenario 3. In isolated or fragmented scenarios, this growth is fueled by the "Pollution Haven" effect; as China faces strict carbon caps and rising production costs, it increasingly imports basic, carbon-intensive manufactured goods from North Korea, significantly improving the latter's trade balance.

Finally, the scenario-specific mechanisms highlight the impact of an improved carbon trade balance. The economic outcomes shift drastically depending on the availability of cross-border carbon trading, demonstrating how market integration redistributes the economic burden. Comparing the fragmented Isolated_NZ (Scenario 3) to the fully integrated NEAICM_ALL_NZ (Scenario 5) reveals the critical economic benefits of an integrated market for resource-dependent nations. In the integrated market, Mongolia's severe GDP loss is nearly halved from 39.0% to 20.0%. More dramatically, Russia avoids a -4.5% contraction entirely and instead achieves a substantial +17.2% GDP expansion by 2050. By exporting its vast, low-cost emission allowances to the CJK core, Russia successfully substitutes its declining fossil fuel export revenues with lucrative carbon trade surpluses. Conversely, for the CJK core, physical GDP slightly contracts further in the integrated scenario—such as South Korea moving from -9.3% to -10.4%—because the extensive financial outflow to purchase carbon credits from Russia and Mongolia reduces domestic capital formation.

6.3 Carbon Price Evolution and Market Integration

The core premise of an Integrated Carbon Market (ICM) is grounded in classical environmental economics: allowing the trading of emission allowances naturally directs abatement efforts toward regions with the lowest Marginal Abatement Costs (MAC), thereby minimizing the aggregate compliance cost for the entire system. To quantify this efficiency gain within Northeast Asia, we trace the carbon price evolution from a fragmented regime (Isolated_NZ, Scenario 3) to a regional climate club (NEAICM_All_NZ, Scenario 5), and then to a perfectly cooperative global mechanism (Global_NZ, Scenario 2).

As illustrated in Table 5, under the Isolated_NZ scenario, the MACs across the six NEA nations diverge significantly by 2050. Highly industrialized and energy-efficient economies like South Korea and Japan face exceptionally high internal carbon prices that reach $1,246 and $1,149 per tCO_2 respectively as they exhaust their domestic abatement options. Conversely, North Korea and Russia possess abundant, untapped low-cost abatement potentials that yield carbon prices of merely $7 and $265 per tCO_2.

Table 5. Carbon Prices ($100 / tCO_2) across Scenarios for the 6 NEA Nations

Scenario	Year	KOR	CHN	JPN	RUS	MNG	PRK
Global_NZ	2030	1.69					
	2040	3.53					
	2050	6.54					
Isolated_NZ	2030	2.55	1.13	2.26	0.47	0.78	0.36
	2040	5.29	2.15	5.16	2.01	3.03	0.88
	2050	12.46	4.19	11.49	2.65	5.88	0.07
Fragmented_NZ	2030	2.54	1.13	2.25	0	0	0
	2040	5.24	2.14	5.14	0	0	0
	2050	12.37	4.19	11.40	0	0	0
NEAICM_ALL_NZ	2030	1.15					
	2040	2.32					
	2050	4.21					
NEAICM_CJK_NZ	2030	1.23			0.47	0.78	0.36
	2040	2.36			2.01	3.03	0.88
	2050	4.47			2.70	5.83	0.06

The formation of the comprehensive regional integrated market (NEAICM_ALL_NZ) effectively resolves this inefficiency. The heterogeneous MACs of the 6 isolated nations collapse into a single, uniform regional carbon price of $421 per tCO_2 by 2050. This equalization mechanism generates significant efficiency gains as the CJK core drastically reduces its domestic abatement costs by importing cheaper carbon credits.

The efficiency gains of market integration are fundamentally driven by the reallocation of physical abatement efforts. Table 6 illustrates the divergence in physical CO_2 emission reductions (relative to the BAU baseline) across scenarios. Under the Isolated_NZ scenario, each nation is strictly bound to its own domestic target, forcing South Korea and Japan to undertake deep domestic reductions of -94% and -93% by 2050, respectively. However, the introduction of the comprehensive regional market (NEAICM_ALL_NZ) induces a significant shift in the location of physical mitigation. South Korea and Japan alleviate their physical mitigation burden (easing to -83% and -79% reductions) by purchasing imported allowances. Conversely, nations with lower abatement costs, such as Russia and North Korea, dramatically deepen their domestic decarbonization (Russia from -68% to -77%, and North Korea from -66% to -90%) beyond their mandated targets to generate valuable carbon credits for export. China's physical emissions remain perfectly stable at -86%, acting as a structural anchor for the regional market. This spatial reallocation of mitigation efforts ensures overall environmental integrity while optimizing region-wide compliance costs.

Table 6. CO_2 emission changes (% relative to BAU) across Scenarios for the 6 NEA Nations

Scenario	Year	01_KOR	02_CHN	03_JPN	04_RUS	05_MNG	06_PRK
Global_NZ	2030	-45%	-55%	-40%	-41%	-44%	-54%
	2040	-71%	-82%	-66%	-69%	-68%	-82%
	2050	-86%	-94%	-83%	-88%	-81%	-96%
Isolated_NZ	2030	-57%	-46%	-48%	-11%	-31%	-23%
	2040	-81%	-70%	-75%	-49%	-64%	-51%

	2050	-94%	-86%	-93%	-68%	-79%	-66%
Fragmented_NZ	2030	-57%	-46%	-48%	7%	-14%	-2%
	2040	-81%	-70%	-75%	7%	-23%	-17%
	2050	-94%	-86%	-93%	3%	-29%	-49%
NEAICM_ALL_NZ	2030	-37%	-46%	-32%	-31%	-35%	-44%
	2040	-62%	-72%	-56%	-56%	-55%	-71%
	2050	-83%	-86%	-79%	-77%	-70%	-90%
NEAICM_CJK_NZ	2030	-39%	-48%	-34%	-11%	-31%	-23%
	2040	-62%	-72%	-56%	-49%	-64%	-51%
	2050	-83%	-87%	-80%	-68%	-79%	-66%

Furthermore, Table 5 uncovers a notable global dynamic. When moving toward the perfectly cooperative Global_NZ scenario, the single global carbon price settles at $654 per tCO_2, which is significantly higher than the regional price of $421. This demonstrates that Northeast Asia, when taken as a whole, possesses lower abatement costs relative to the global average that is primarily driven up by mature economies in North America and Western Europe. As a result, while global integration minimizes costs worldwide, integrating strictly within the NEA region actually provides the most cost-effective carbon price for the heavily industrialized CJK core.

Additionally, an analysis of the restricted and fragmented scenarios reveals significant vulnerabilities to trade-induced carbon leakage. When neighboring nations like North Korea remain unconstrained (Frag_NZ) or when the market excludes them (NEAICM_CJK_NZ), they increase the production of carbon-intensive goods to supply the heavily constrained CJK core. Consequently, the emissions "saved" within CJK borders are effectively displaced across the border, substantially increasing domestic carbon emissions in neighboring states as they become pollution havens.

6.4 Shifts in Regional Trade Competitiveness

The geopolitical reality of incomplete climate policy cooperation triggers unintended consequences in international trade competitiveness, measured via Terms of Trade (TOT). Table 7 summarizes these changes relative to the BAU baseline. To intuitively understand these dynamics, the results must be compared across specific scenario configurations.

Under the uncoordinated Isolated_NZ scenario, export-driven economies face notable competitiveness challenges. For instance, South Korea experiences a significant -19.0% TOT deterioration by 2050. The underlying causal mechanism is deeply rooted in the structural composition of their industrial sectors. South Korea and Japan rely heavily on the export of advanced manufactured goods (e.g., Machinery), a sector characterized by high electricity intensity. By 2050, to achieve strict Net-Zero targets amidst exceptionally high domestic carbon prices ($1,246/tCO2 for South Korea), these nations are forced to widely deploy Direct Air Capture (DAC) technologies. As DAC operations require massive amounts of energy, this generates a substantial surge in aggregate electricity demand, which consequently drives up domestic electricity prices. This surge in electricity costs substantially inflates the production costs of their core machinery exports. Due to the structurally inelastic energy demand calibrated in our model, these industries face severe limitations in substituting away from expensive electricity in the short-to-medium term. Consequently, to maintain their global market share amidst rising costs, exporters are forced to squeeze their export margins rather than passing the full cost increase onto international buyers. This inability to fully transfer domestic cost burdens to export prices results in a significant deterioration of their macroeconomic purchasing power.

When the region forms a fully integrated market (NEAICM_ALL_NZ), the TOT outcomes for resource-abundant nations reveal a counterintuitive dynamic. For Russia, moving from the isolated regime to the fully integrated market actually worsens its TOT, dropping from -5.4% to a substantial -21.9%. However, this decline is associated with economic expansion, not a downturn. In the integrated market, Russia exports valuable carbon allowances, generating substantial financial surpluses. It uses this newfound revenue to significantly increase physical imports (e.g., advanced machinery). In CGE mechanics, this rapid increase in import volume mathematically drives down the TOT indicator, serving as a symptom of capital influx rather than economic decline.

Comparing the restricted CJK-only market (NEAICM_CJK_NZ) against the fully integrated market explicitly demonstrates how TOT can be a misleading indicator of economic health. If the carbon market is restricted strictly to the CJK core, Russia is barred from exporting its carbon credits. Consequently, its physical economy contracts significantly under its strict domestic emission targets. This substantial industrial contraction creates a scarcity of Russian exports, which mathematically drives up its marginal export prices. This creates a statistical artifact of an "improved" TOT (-5.5% for Russia in the CJK scenario compared to -21.9% in the ALL scenario), masking the underlying economic contraction.

Table 7. Changes in Terms of Trade (TOT, % relative to BAU)

Scenario	Year	KOR	CHN	JPN	RUS	MNG	PRK
Global_NZ	2030	4.1%	3.3%	6.4%	-11.1%	0.0%	-17.7%
	2040	3.6%	3.1%	6.3%	-9.7%	6.4%	-24.4%
	2050	2.2%	2.8%	5.8%	-5.0%	9.7%	-31.4%
Isolated_NZ	2030	4.3%	3.0%	6.5%	-12.0%	-0.7%	-16.1%
	2040	3.4%	3.5%	6.0%	-11.2%	2.2%	-23.8%
	2050	-19.0%	-1.4%	-5.2%	-5.4%	-1.0%	-31.1%
Frag_NZ	2030	4.2%	3.0%	6.4%	-11.5%	-1.8%	-15.7%
	2040	3.3%	3.4%	6.0%	-10.8%	0.0%	-23.8%
	2050	-19.0%	-1.4%	-5.2%	-6.5%	-3.3%	-32.5%
NEAICM_ALL_NZ	2030	3.7%	3.2%	5.9%	-14.4%	-5.0%	-17.5%
	2040	3.0%	3.5%	5.4%	-18.8%	-11.4%	-24.9%
	2050	-16.2%	-1.9%	-6.0%	-21.9%	-21.6%	-31.4%
NEAICM_CJK_NZ	2030	3.7%	3.1%	5.9%	-12.0%	-0.7%	-16.2%
	2040	3.1%	3.6%	5.6%	-11.2%	2.5%	-24.0%

	2050	-16.3%	-0.7%	-5.0%	-5.5%	-0.4%	-31.2%

6.5 Restructuring of Bilateral Trade Flows in Coal and Machinery

To fully understand how cross-border allowance transfers and the resulting shifts in carbon trade balances reshape international supply chains, we isolate the effect of market integration by calculating the difference in 2050 bilateral trade volumes across the various scenarios. In these differential heatmaps, a negative value (red) indicates trade flows that are created or expanded by moving to the fully integrated market (ALL), whereas a positive value (blue) indicates trade that is relatively higher under fragmented conditions but reduced by integration.

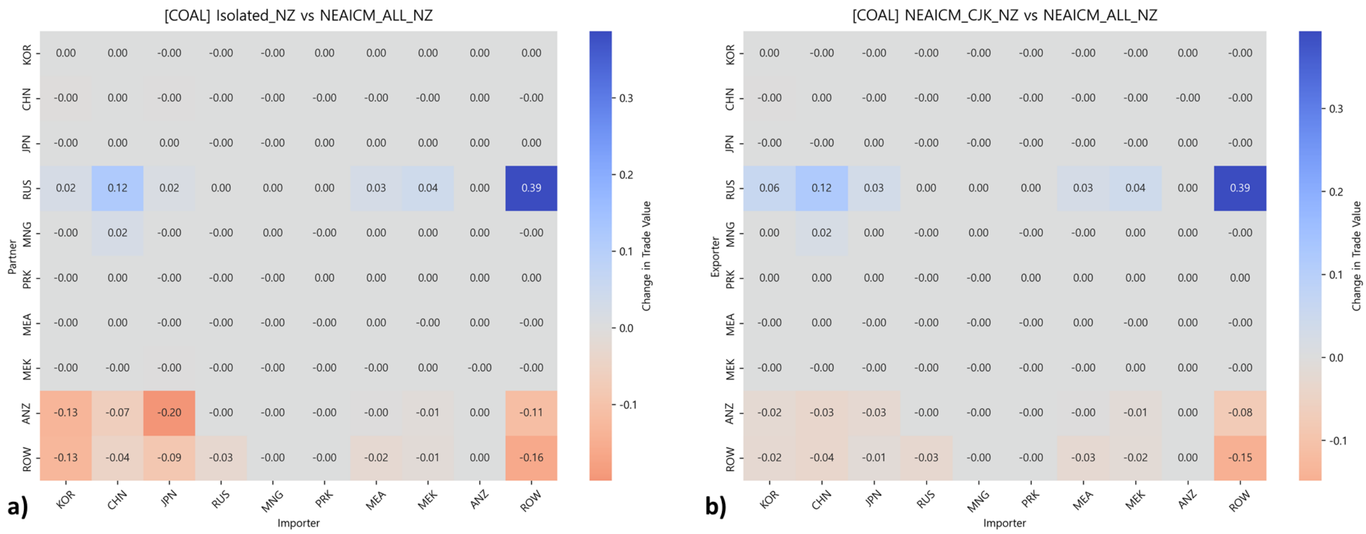

Figure 8. Differential Heatmaps of Bilateral Coal Trade Volumes in 2050 - Panel (a) Isolated vs ALL, Panel (b) CJK-only vs ALL

The differential coal trade heatmap visualizes an asymmetric restructuring of upstream energy flows. As shown in Panel (a), when Northeast Asia fully integrates its carbon market compared to the isolated regime, the industrialized CJK core (particularly Japan and South Korea) increases its coal imports from extra-regional suppliers like Australia and New Zealand (ANZ) and the Rest of the World (ROW), as indicated by the red tiles (e.g., ANZ -> JPN, -0.20). This indicates that by purchasing imported carbon allowances, the CJK core can mitigate its compliance costs, allowing these economies to manage the transition of their conventional fossil-fuel infrastructure with less economic burden rather than facing immediate phase-outs.

Conversely, the integrated market actively suppresses Russia's coal exports to China and ROW (depicted by the blue tiles). Under the integrated regime, Russia relies less on physical fossil fuel exports to maintain its economic output. Instead, it deepens its domestic power grid decarbonization and transitions to generating revenue through carbon allowance exports. Furthermore, Panel (b) illustrates the marginal impact of expanding the climate club from a restricted CJK-only market to a fully inclusive regional market. The prominent blue tiles representing Russia's coal exports in Panel (b) explicitly confirm that it is the inclusion of resource-abundant nations in the carbon market—allowing them to export allowances rather than physical fuels—that triggers this profound upstream restructuring.

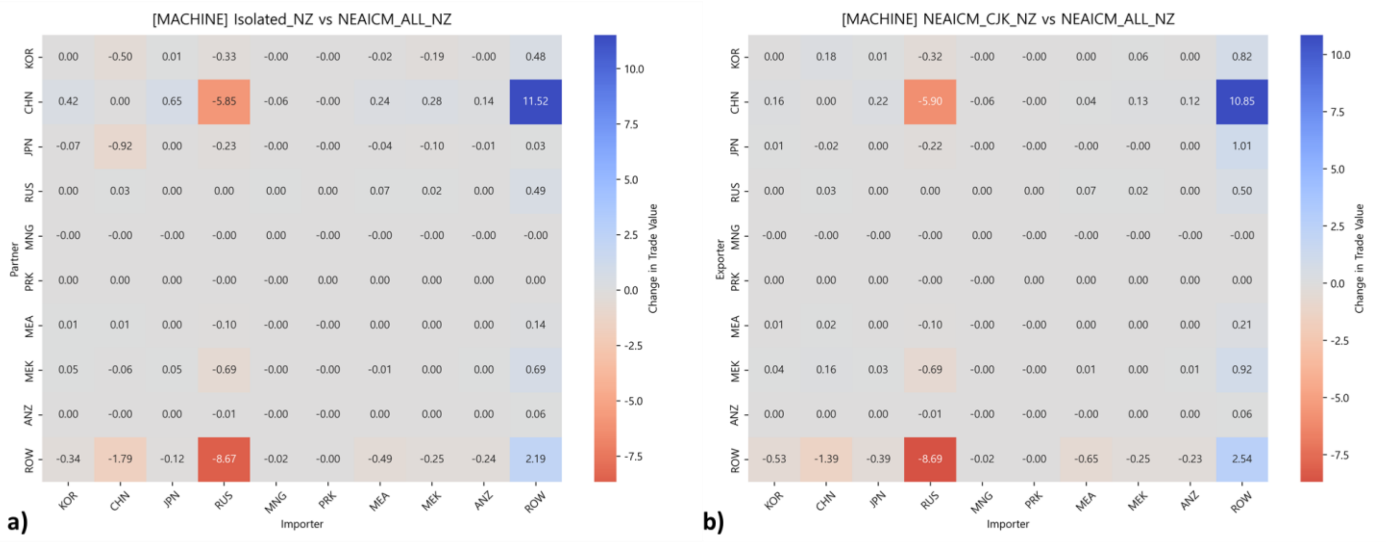

Figure 9. Differential Heatmaps of Bilateral Machinery Trade Volumes in 2050 (Isolated_NZ minus NEAICM_ALL_NZ) - Panel (a) Isolated vs ALL, Panel (b) CJK-only vs ALL]

While the coal heatmap demonstrates upstream shifts, the machinery heatmap reveals a significant transition in downstream advanced manufacturing. A key observation in Panel (a) is the substantial increase in machinery imports into Russia from both China and the Rest of the

World, represented by the distinct red vertical column (ROW -> RUS). In the isolated regime, Russia faces constraints in industrial investment. However, moving to the fully integrated market generates significant carbon trade surpluses. Russia channels the capital acquired from selling carbon credits to the CJK core directly into domestic capital formation, notably increasing imports of advanced machinery to modernize its economy. Table 8 reveals a stark regional divergence in energy transition dynamics.

Panel (b) reinforces this mechanism by isolating the effect of full regional integration compared to the restricted CJK-only market. The persistence of the distinct red column of machinery imports into Russia in Panel (b) explicitly demonstrates that the "Carbon Wealth" reinvestment loop is only activated when these nations are granted access to the integrated market. Without their full inclusion, this vital pipeline for regional industrial modernization remains blocked. Simultaneously, the blue tile representing China's machinery exports to the Rest of the World (CHN -> ROW) in both panels indicates a reorientation of Chinese manufacturing capacity. The formation of the fully integrated market stimulates intra-regional demand, particularly from the newly capitalized Russian economy. Consequently, China redirects a portion of its advanced manufacturing output to fulfill this regional demand, consolidating the Northeast Asian supply chain and reducing its reliance on extra-regional (ROW) export markets.

6.6 Economic Shifts in Energy Demand and the Penetration of Backstop Technologies

Beyond the aggregate macroeconomic indicators, the transition to Net-Zero enforces a fundamental rewiring of the regional energy system. A key indicator of this transition within a CGE framework is the constant-price expenditure share of electricity—measured as the ratio of real electricity demand (ELEC) to total real energy demand (Q), evaluated strictly at 2019 base-year prices. It is crucial to distinguish this economic metric from physical electrification rates (which are measured in purely physical units like Joules or Mtoe).

Because electricity is a highly processed, capital-intensive secondary energy source, its unit price is significantly higher than raw primary fuels. Consequently, in developing or resource-abundant nations like Mongolia and North Korea, while cheap domestic coal heavily dominates the physical volume of energy consumed, the expensive electricity sector consumes a disproportionately massive share of the overall energy expenditure budget (accounting for 64% and 44% in the BAU baseline, respectively). To avoid the price distortions caused by extreme carbon taxes in future years, these shares are calculated based on the constant-price real quantity variables, ensuring a rigorous economic representation of the structural shift toward electricity reliance. Tracking this metric across the predefined scenarios allows us to observe the critical role of technology switching in mitigating economic shocks.

Table 8. Constant-Price Expenditure Share of Electricity in Total Energy Demand (%)

Scenario	Year	KOR	CHN	JPN	RUS	MNG	PRK
Base year	2019	30%	40%	40%	53%	64%	44%
BAU	2030	32%	42%	39%	54%	64%	44%
	2040	32%	42%	38%	54%	64%	44%
	2050	31%	41%	36%	54%	63%	44%
Global_NZ	2030	30%	39%	38%	52%	61%	46%
	2040	29%	42%	38%	50%	57%	45%
	2050	29%	46%	38%	48%	54%	38%
Isolated_NZ	2030	28%	40%	38%	53%	63%	44%
	2040	27%	43%	36%	51%	59%	44%
	2050	25%	48%	34%	51%	56%	36%
Frag_NZ	2030	28%	40%	38%	53%	63%	43%
	2040	27%	43%	36%	53%	63%	42%
	2050	25%	48%	34%	53%	64%	35%
NEAICM_ALL_NZ	2030	30%	40%	38%	53%	63%	44%
	2040	30%	43%	39%	51%	61%	46%
	2050	28%	48%	40%	50%	61%	42%
NEAICM_CJK_NZ	2030	30%	40%	38%	53%	63%	44%

	2040	30%	43%	39%	51%	59%	44%
	2050	28%	48%	40%	51%	56%	36%

China (CHN) exhibits a classic, price-driven economic shift toward electricity. Driven by massive and affordable renewable energy potential, its power sector decarbonizes efficiently, allowing the broader economy to substitute away from direct fossil fuel combustion. Consequently, its economic reliance on electricity rises steadily from 41% in the BAU baseline to 48% under strict compliance scenarios by 2050.

Conversely, mature economies like South Korea (KOR) and Japan (JPN), as well as fossil-reliant nations, demonstrate a counterintuitive stagnation or even a decline in electrification rates under the highly constrained Isolated_NZ scenario. For instance, South Korea's electrification rate drops from 31% in BAU to merely 25% in the isolated Net-Zero pathway.

This anomaly highlights a profound economic mechanism within the CGE framework: the race between Fuel Switching and Demand Destruction. Due to the empirically calibrated, relatively inelastic substitution elasticities between electricity and non-electricity energy sources (as established in Section 4.3), industries face severe structural rigidities in transitioning their heat and power systems. When internal carbon prices skyrocket to extreme levels (e.g., $1,246 for KOR), the massive capital costs required to decarbonize the power grid itself drive up electricity prices. Unable to easily and affordably substitute fossil fuels with clean electricity, the economy responds through massive demand destruction—slashing overall energy use and halting industrial output—rather than smoothly electrifying. In this harsh environment, the consumption of the now highly expensive electricity falls even faster than aggregate energy demand, leading to a suppressed electrification share.

To further unpack the technological response to these economic shocks, Table 9 details the aggregate market penetration rates of advanced Backstop technologies across the highly industrialized CJK core (China, Japan, and South Korea).

Table 9. Penetration Rates of Backstop Technologies in the CJK Core (%)

Scenario	Year	CHEMICAL	NONMET	IRONSTL	LTRP	WTRP	ATRP
BAU	2030	2%	1%	5%	1%	1%	1%
	2040	2%	1%	10%	1%	1%	1%
	2050	1%	1%	10%	1%	1%	1%
Global_NZ	2030	6%	4%	9%	5%	3%	3%
	2040	11%	9%	26%	15%	6%	7%
	2050	18%	14%	37%	26%	8%	10%
Isolated_NZ	2030	6%	4%	9%	5%	3%	3%
	2040	12%	9%	28%	16%	6%	7%
	2050	18%	14%	38%	29%	9%	11%
Frag_NZ	2030	6%	4%	9%	5%	3%	3%
	2040	12%	9%	28%	16%	6%	7%
	2050	18%	14%	38%	29%	9%	11%
NEAICM_ALL_NZ	2030	6%	4%	9%	5%	3%	3%
	2040	12%	9%	28%	16%	6%	7%
	2050	19%	15%	39%	30%	9%	11%
NEAICM_CJK_NZ	2030	6%	4%	9%	5%	3%	3%
	2040	12%	9%	28%	16%	6%	7%
	2050	19%	14%	39%	30%	9%	11%

The data reveals a massive structural shift forced by Net-Zero mandates. For instance, the penetration of hydrogen-based steelmaking (H2-DRI-EAF) in the Iron & Steel sector leaps from a stagnant 10% in the BAU baseline to approximately 37-39% under strict compliance scenarios by 2050. A similar exponential scale-up is observed in land transportation (e.g., BEVs), jumping from 1% to 30%.

Crucially, the data uncovers a fascinating macroeconomic paradox regarding the impact of market integration on technological innovation. A common theoretical assumption is that if heavily industrialized nations can import cheap carbon credits from neighboring countries, they will delay their own domestic green technology investments. However, the simulation results demonstrate the exact opposite trajectory. In the fully integrated NEAICM_ALL_NZ market, the penetration rates of backstop technologies are marginally higher and more robust (e.g., Iron & Steel at 39%, Land Transport at 30%) compared to the strictly localized Isolated_NZ scenario (38% and 29%, respectively).

This anomaly is explained by the fundamental relationship between capital availability and green investment. Under the Isolated_NZ scenario, the CJK core faces exorbitant, unchecked domestic carbon prices that trigger severe demand destruction. Industries are forced to shut down physical production, constraining the economy of the financial capital required to build expensive new green infrastructure. The backstop technologies gain market share mathematically, but primarily because conventional production declines significantly, not necessarily because green capital is thriving.

In stark contrast, the integrated market provides a crucial macroeconomic "soft-landing." By importing affordable carbon allowances, the CJK core prevents a sever contraction collapse of its industrial output and preserves its aggregate investment capacity. The carbon prices in the integrated market remain sufficiently high to trigger backstop competitiveness, but the preserved economic health allows these nations to actively finance and scale up green technologies like H2-DRI and BEVs without completely destroying their foundational energy-intensive sectors. Thus, the simulation confirms that regional market integration does not delay green technology; rather, it provides the essential financial buffer that makes physical decarbonization economically viable.

6.7 Decarbonization of the Power Sector: The Shift in Generation Mix

Achieving absolute emission targets alongside rising electrification demand necessitates a radical structural transformation of the power generation sector. Figure 10 illustrates this profound shift by comparing the 2050 power generation mix across three distinct pathways: the unconstrained BAU baseline, the highly uncoordinated Isolated_NZ regime, and the fully cooperative integrated market (NEAICM_ALL_NZ).

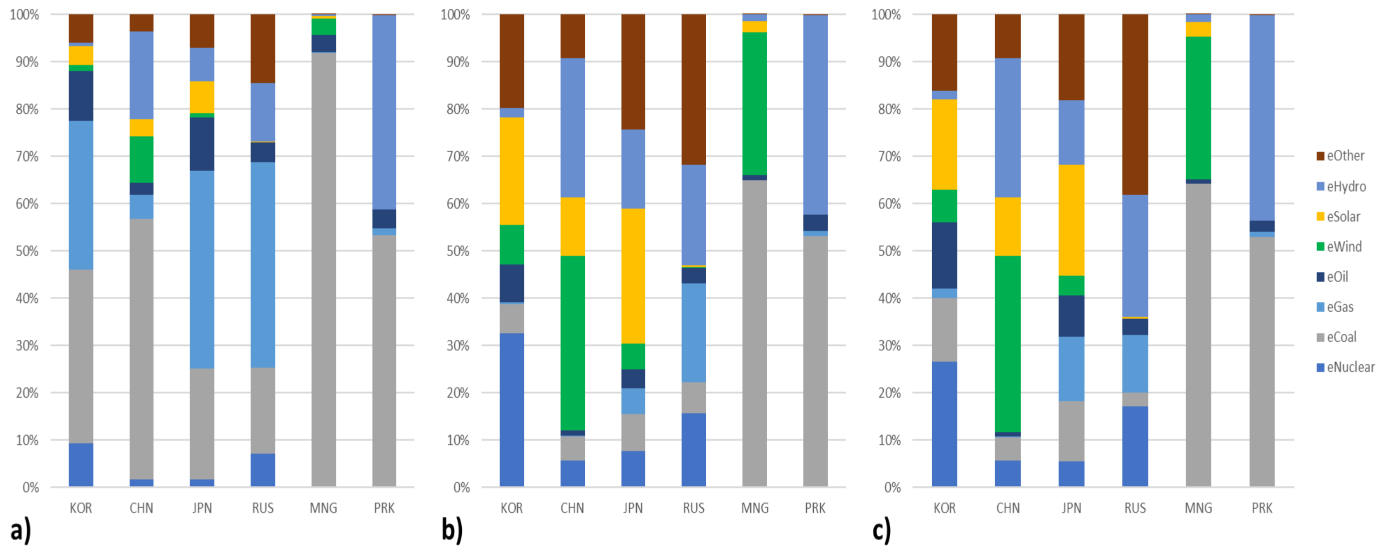

Figure 10. 2050 Power Generation Mix Panel (a) BAU, Panel (b) Isolated_NZ, and Panel (c) Integrated Market (NEAICM_ALL_NZ) for the 6 NEA Nations

Panel (a) establishes the baseline under the unconstrained BAU scenario. The Northeast Asian power grid remains predominantly reliant on conventional fossil fuels, with coal (eCoal) and natural gas (eGas) dominating the generation mix, particularly in China, Mongolia, Russia, and North Korea. This illustrates the structural inertia and the scale of the decarbonization effort required to reach Net-Zero.

Panel (b) illustrates the substantial compliance pressures placed on the region under the Isolated_NZ regime. When comparing the generation shares against the BAU baseline (Isolated_NZ minus BAU), a rapid phase-out of fossil fuels is observed across the board. Coal generation declines significantly in China (-50%p), South Korea (-30%p), and Mongolia (-27%p), while natural gas decreases in Japan (-36%p) and South Korea (-31%p). To fill this supply gap without external support, nations are forced to maximize their domestic low-carbon endowments. South Korea scales up Nuclear (+23%p) and Solar (+19%p), while China and Mongolia substantially expand their Wind capacity (both +27%p). In an isolated setup, this shift represents a highly rigid and costly decarbonization pathway, driven entirely by domestic compliance.

Panel (c) and the quantitative deviations between the integrated and isolated scenarios (NEAICM_ALL_NZ minus Isolated_NZ) illustrate the asymmetrical mechanisms of the regional carbon market. Three distinct national responses emerge:

First, China acts as a structural anchor. China exhibits effectively zero change (0%p) in its power generation mix between the isolated and integrated scenarios. This indicates that China's power sector decarbonization pathway is largely dictated by internal structural optimization and scale, making its electricity mix relatively insensitive to the marginal incentives of the regional carbon market.

Second, the CJK core (specifically South Korea and Japan) moderates its transition speed. By importing allowances, KOR and JPN adjust their deployment of Nuclear (-6%p) and Solar (-4%p), allowing them to retain slightly more fossil generation (KOR: Coal +7%p, Gas +2%p) to manage grid stability and compliance costs.

Third, Russia emerges as the primary supplier of abatement in Northeast Asia. To supply the allowances demanded by KOR and JPN, Russia deepens the decarbonization of its own grid, reducing reliance on Gas (-9%p) and Coal (-4%p) while scaling up Hydro (+4%p) and Other zero-carbon generation (+6%p).

Consequently, the generation mix under the integrated market reveals that regional cooperation alters the physical power infrastructure. It allows resource-abundant nations to monetize their structural transition, thereby assisting the industrialized, energy-constrained economies of South Korea and Japan in managing their grid stability and mitigation costs.

6.8 Sensitivity Analysis

A common critique of CGE modeling pertains to parameter uncertainty, particularly regarding substitution elasticities which dictate the economy's responsiveness to price shocks. To assess the robustness of our findings, we conduct a sensitivity analysis comparing the outcomes under our systematically recalibrated energy substitution elasticities (the "Low Substitution/Calibrated" baseline utilized throughout Section 5) against the initial pre-calibrated elasticities derived from the baseline database (the "High Substitution/Initial Point" case). The initial parameters inherently assume a much higher degree of structural flexibility within energy markets.

We focus our sensitivity test on the macroeconomic disruptions induced by the highly fragmented Isolated_NZ scenario in 2050, tracing how elasticity calibration intrinsically alters the general equilibrium ripple effects across GDP, Terms of Trade (TOT), and Carbon Prices (CTAX). It should be noted that the reported impacts on Real GDP and TOT represent the percentage deviations from the unconstrained BAU baseline in the target year 2050. Meanwhile, the Carbon Price reflects the absolute marginal abatement cost required to achieve the emission constraints in that same year.

Table 10. Sensitivity Analysis: Macroeconomic Impacts under Isolated_NZ (2050)

Metric	Parameter Set	KOR	CHN	JPN	RUS	MNG	PRK
GDP Change (%)	High Sub. (Before)	-10.0%	-12.3%	-11.5%	-7.7%	-40.4%	10.0%
	Low Sub. (After)	-9.3%	-11.8%	-10.9%	-4.5%	-39.0%	10.0%
TOT Change (%)	High Sub. (Before)	-5.9%	1.5%	1.1%	-5.8%	1.4%	-31.0%
	Low Sub. (After)	-19.0%	-1.4%	-5.2%	-5.4%	-1.0%	-31.1%
Carbon Price($100/t$CO_2$)	High Sub. (Before)	12.46	4.19	11.49	2.65	5.88	0.07
	Low Sub. (After)	11.88	4.21	13.14	2.59	5.40	0.09

The sensitivity analysis, summarized in Table 10, reveals a complex non-linear macroeconomic mechanism that highlights the critical importance of realistic parameterization. Intuitively, one might assume that lower (inelastic) substitution possibilities would uniformly exacerbate GDP losses and force carbon prices substantially higher across all regions. However, by shifting from the highly flexible initial parameters to our empirically calibrated, structurally inelastic ranges (e.g., significantly lowered σ_{KLE} and σ_{elec} as detailed in Table B3 of Appendix B), the general equilibrium results reveal a much more complex, heterogeneous reality.

Under the highly flexible "High Substitution (Initial Point)" parameters, the economic shocks on international trade are significantly muted. South Korea's TOT drops by only -5.9%. However, when energy demand is properly calibrated as rigid (Calibrated), export-driven economies like South Korea and Japan cannot seamlessly substitute away from fossil fuels. Faced with high domestic abatement costs, industries maintain production volumes while incorporating the increased carbon costs into their export prices. Consequently, to retain international market share without reducing output capacity, these nations experience a loss in purchasing power, leading to a significant TOT deterioration (e.g., South Korea declines to -19.0%). Interestingly, this significant TOT adjustment acts as a buffer for physical production: because they export at reduced margins rather than ceasing operations, the physical GDP loss is counterintuitively mitigated (South Korea improves from -10.0% to -9.3%).

The rigidity of energy demand also drives mixed trajectories in marginal abatement costs. For Japan, inelasticity strictly makes abatement more difficult, forcing the required carbon price higher (from 11.49 to 13.14). However, for South Korea, the carbon price actually drops slightly (from 12.46 to 11.88). This result is driven by the magnitude of South Korea's macroeconomic adjustment: the -19.0% decline in TOT depresses aggregate domestic income and overall economic activity, causing baseline energy demand to decrease. This substantial demand reduction consequently lowers the marginal carbon price required to hit the absolute emission cap.

Finally, for fossil-fuel exporters, structural inelasticity provides a slight buffer. If global energy demand is rigid, the rest of the world cannot instantaneously abandon Russian and Mongolian energy exports in response to carbon pricing. Consequently, their baseline export revenues are relatively better protected under the calibrated parameters, noticeably reducing Russia's GDP loss from -7.7% to -4.5%.

This divergence fundamentally validates the necessity of our recalibration procedure detailed in Section 5.3. Initial parameters that assume frictionless energy substitution create an overly optimistic transition pathway, underestimating the compliance costs and subsequent structural trade distortions. By constraining these elasticities to align with empirical, real-world rigidities in the energy transition, our calibrated model accurately captures the severe, amplified risks of isolated climate policies, indicating that significant TOT deterioration and carbon leakage are highly plausible outcomes of uncoordinated regional decarbonization.

7. Conclusion and Policy Implications

While previous climate-economic analyses of Northeast Asia have predominantly confined their focus to the industrialized "CJK core" (China, Japan, and South Korea), this study broadens the analytical horizon to encompass the broader regional economic bloc. By integrating adjacent, resource-abundant, and data-scarce economies—specifically the Russian Federation, Mongolia, and an independently reconstructed North Korea—into a global recursive dynamic CGE framework, we provide a comprehensive assessment of regional decarbonization pathways toward 2050. Our simulation results reveal that the transition to a Net-Zero economy is not merely a localized technological challenge, but a highly complex geopolitical and structural transition associated with risks of cross-border carbon leakage and asymmetric economic impacts.

The findings yield four critical policy implications. First, the analysis demonstrates that an Integrated Carbon Market covering all six NEA nations (NEAICM_All_NZ) is the most economically efficient pathway to achieve regional climate goals. By harmonizing marginal abatement costs, the integrated market significantly reduces the aggregate compliance burden compared to isolated national efforts.

Second, for the technologically advanced "CJK core," expanding the climate club is essential to ensure environmental integrity. As demonstrated in Scenario 6, if the carbon market is restricted only to China, Japan, and South Korea, it can trigger substantial trade-induced carbon leakage to neighboring unconstrained economies like North Korea. A localized climate club may protect CJK industries, but it compromises overall emission reduction goals, potentially shifting emission-intensive production to neighboring states.

Third, and perhaps most importantly, the results highlight significant economic implications for fossil-fuel-dependent nations such as Russia and Mongolia. For these nations, participating in a regional integrated carbon market is not simply a climate obligation, but an important macroeconomic strategy. By joining the market, they can monetize their low-cost abatement potentials, converting emission reductions into a valuable export commodity (carbon credits). This influx of carbon trade revenues provides the necessary capital to restructure their economies away from fossil fuel dependence, mitigating the risk of significant output contractions.

Fourth, the analysis highlights the broader global spillover effects of Northeast Asia's energy transition. As the NEA region—historically a major sink for global primary energy—systematically phases out its reliance on imported fossil fuels, traditional extra-regional suppliers such as Australia (for coal) and the Middle East (for oil and gas) may face notable structural contractions in their export markets. As demonstrated by the trade diversion heatmaps, this demand reduction is further amplified under the integrated market regime, where Russia captures a larger share of the residual regional fossil fuel demand. This signals that the decarbonization of Northeast Asia is a structural shift that may prompt traditional global energy exporters to diversify their macroeconomic portfolios.

Ultimately, realizing a sustainable and economically resilient Net-Zero future in Northeast Asia requires moving beyond fragmented national policies toward a fully inclusive, pan-regional Climate Club that aligns environmental targets with regional economic stability.

8. Limitations and Future Work

Despite the methodological contributions of this study, several important limitations remain, which provide critical avenues for future research.

First, regarding regional representation and data constraints, two major limitations must be acknowledged. While the reconstruction of the North Korean SAM successfully anchored macroeconomic targets, the granular decomposition of domestic absorption relies heavily on optimization algorithms due to severe data opacity, and standard market-clearing CGE assumptions do not perfectly align with its centrally planned command economy. Concurrently, a significant spatial aggregation limitation exists concerning the Russian Federation. Although Northeast Asian economic integration primarily interacts with the Russian Far East, our model represents Russia at the national level due to the inherent structure of the GTAP database. This macroscopic aggregation may overestimate the sheer volume of Russian carbon allowances practically accessible to the NEA market and obscure the specific logistical and infrastructural bottlenecks of the Far Eastern region. Future iterations should aim to develop customized, non-market institutional closures for North Korea and implement sub-national regionalization for transcontinental economies like Russia.

Second, the current modeling framework faces limitations in capturing extra-regional policy interactions due to the regional aggregation bias. As the non-NEA world is aggregated into 11 macro-regions, the model cannot granularly assess the impacts of specific climate trade policies implemented outside Northeast Asia, such as the European Union’s Carbon Border Adjustment Mechanism (CBAM). Furthermore, within the region, the model does not explicitly capture the potential development of a physical "Northeast Asia Super Grid." If large-scale electricity trading occurs across NEA borders, it could drastically alter domestic generation requirements and abatement costs. Future studies must expand the scenario design to explicitly incorporate these external global regulatory shifts (e.g., CBAM) and physical cross-border power grid connectivity to evaluate how they might further optimize regional compliance costs.

Third, the reliance on price-driven substitution elasticities highlights a structural limitation in capturing policy-mandated technology transitions. As observed in the suppressed economic transitions toward electricity under extreme carbon constraints, standard CGE models with empirically calibrated rigidities tend to simulate demand destruction rather than forced technology adoption. While this accurately reflects short-to-medium-term economic frictions, future modeling efforts must better integrate explicit regulatory mandates (e.g., bans on internal combustion engine vehicles) directly into the behavioral equations to reflect non-price-driven structural transformations.

Finally, this study operates on the theoretical assumption that a fully functioning Integrated Carbon Market (ICM) can be smoothly established across the region. In reality, as consistently highlighted by previous political economy literature, overcoming the stark political, institutional, and regulatory disparities among the six NEA nations is a formidable challenge that extends beyond the analytical boundaries of a standard CGE framework. While we assumed a seamless policy linkage to isolate the economic impacts of carbon trading, future interdisciplinary research must address the geopolitical feasibilities and institutional designs necessary to overcome these barriers and facilitate practical cross-border climate cooperation.

Declaration of generative AI in scientific writing

Generative AI was used exclusively to assist with English translation and language refinement. No AI tools were used for conceptual development, analysis, or interpretation of results. The author assumes full responsibility for all content.

Funding

This work was supported by Korea Environmental Industry & Technology Institute(KEITI) through Climate Change R&D Project for New Climate Regime, funded by Korea Ministry of Environment(MOE)(RS-2022-KE002096).

9. Reference

Adams, P. D., Dixon, J., & Horridge, J. M. (2015). The Victoria University regional model (VURM): Technical documentation. *Centre of Policy Studies, Victoria University*.

Aggarwal, V. K., & Koo, M. G. (2005). Beyond network power? The dynamics of formal economic integration in Northeast Asia. *The Pacific Review*, 18(2), 189-216.

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R., & van der Mensbrugghe, D. (2022). The GTAP Data Base: Version 11. *Journal of Global Economic Analysis*, 7(2), 1-36.

Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics*, 65(2), 421-445.

Bank of Korea (BOK). (2025). *Gross domestic product by economic activity in North Korea: Estimates of North Korea's economic growth in 2024*. Economic Statistics Department.

Beckman, J., Hertel, T., & Tyner, W. (2011). Validating energy-oriented CGE models. *Energy Economics*, 33(5), 799-806.

Böhringer, C. (2002). Climate politics from Kyoto to Bonn: from little to nothing?. *The Energy Journal*, 23(2), 51-71.

Böhringer, C., & Rutherford, T. F. (2002). Carbon abatement and international spillovers. *Environmental and Resource Economics*, 22(3), 391-417.

Böhringer, C., Balistreri, E. J., & Rutherford, T. F. (2012). The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study. *Energy Economics*, 34(S2), S97-S110.

Böhringer, C., Carbone, J. C., & Rutherford, T. F. (2016). The strategic value of carbon tariffs. *American Economic Journal: Economic Policy*, 8(1), 29-51.

Burniaux, J. M., & Truong, T. P. (2002). GTAP-E: an energy-environmental version of the GTAP model. *GTAP technical papers*, 16.

Capros, P., Van Regemorter, D., Paroussos, L., Karkatsoulis, P., Fragkiadakis, C., Tsani, S., ... & Abrell, J. (2013). GEM-E3 model documentation. *JRC Scientific and Policy Reports*, 26034.

Chen, Y. H., Paltsev, S., Reilly, J. M., Morris, J. F., & Babiker, M. H. (2015). The MIT EPPA6 model: Economic growth, energy use, and food consumption. *MIT Joint Program on the Science and Policy of Global Change*.

Corong, E. L., Hertel, T. W., McDougall, R., Tsigas, M. E., & Van Der Mensbrugghe, D. (2017). The standard GTAP model, version 7. *Journal of Global Economic Analysis*, 2(1), 1-119.

de Bruin, K., Dellink, R., & Agrawala, S. (2009). Economic aspects of adaptation to climate change: Integrated assessment modelling of adaptation costs and benefits. *OECD Environment Working*

Papers, No. 6.

EDGAR. (2025). *Emissions Database for Global Atmospheric Research (EDGAR) GHG Emissions of All World Countries*. European Commission, Joint Research Centre (JRC).

Effendi, Y., & Resosudarmo, B. P. (2025). The socio-economic and environmental implications of decarbonization strategies in East Asia. *Energy Policy*, 190, 114132.

Fricko, O., Havlik, P., Rogelj, P., Klimont, Z., Gustave, M., Johnson, N., ... & Riahi, K. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, 42, 251-267.

He, Y. X., Yang, L. F., He, H. Y., Luo, T., & Wang, Y. J. (2011). Electricity demand price elasticity in China based on computable general equilibrium model analysis. *Energy*, 36(2), 1115-1123.

Horridge, M. (2008). *SAMBAL: A GEMPACK program to balance square SAMs* [Computer software manual]. Centre of Policy Studies, Monash University.

IEA (International Energy Agency). (2019). *World Energy Balances 2019*. OECD Publishing, Paris.

IEA (International Energy Agency). (2024). *World Energy Balances Database Documentation 2024 edition*. OECD Publishing, Paris.

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Jang, Y., Hu, H., Kim, B., Kim, Y., Yoo, S. J., Jang, K., ... & Woo, J. H. (2024). Assessing the impact of climate and air quality policies on future emissions in Korea through quantification of control and co-control effects. *Atmospheric Pollution Research*, 15(1), 101952.

KC, S., Dhakad, M., Potancokova, M., Adhikari, S., Yildiz, D., Mamolo, M., Sobotka, T., Zeman, K., Abel, G., Lutz, W., & Goujon, A. (2024b). *Population and human capital projections by IIASA and Wittgenstein Center (WIC)*. Data prepared by the authors.

KC, S., Potancokova, M., Adhikari, S., Yildiz, D., Mamolo, M., Sobotka, T., Zeman, K., Abel, G., Lutz, W., & Goujon, A. (2024a). Updating the Shared Socioeconomic Pathways (SSPs) Global Population and Human Capital Projections. *IIASA Working Paper: WP-24-003*.

Korea Trade-Investment Promotion Agency (KOTRA). (2025). *North Korea's foreign trade trends*. Korean Statistical Information Service (KOSIS). https://www.google.com/search?q=https://kosis.kr/statHtml/statHtml.do%3ForgId%3D101%26tblId%3DDT_1ZGA99A

Krey, V., Havlik, P., Kishimoto, P. N., Fricko, O., Zilliacus, J., Gidden, M., ... & Riahi, K. (2020). *MESSAGEix-GLOBIOM Documentation – 2020 release*. Technical Report, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. https://doi.org/10.22022/iacc/03-2021.17115

Kunimitsu, Y. (2024). Regional aggregation bias in the global computable general equilibrium model: Issues in assessing the economic impact of climate change and trade liberalization. *Economic Modelling*, 141, 106885.

Lemelin, A., Robichaud, V., Decaluwé, B., & Maisonnave, H. (2013). The PEP-w-t standard computable general equilibrium model: Single-country, recursive dynamic version. *PEP Network*.

Li, G., & Yao, J. (2024). Direct air capture (DAC) for achieving net-zero CO2 emissions: advances, applications, and challenges. *Eng*, 5(3), 1298-1336.

Li, W., & Zhang, Y. (2018). Institutional challenges of linking heterogeneous carbon markets in the China-Japan-Korea (CJK) region. *Energy Economics*, 72, 1-13.

Ma, X., Wang, C., Dong, B., Gu, G., Chen, R., Li, Y., ... & Chu, J. (2019). Carbon emissions reduction targets and the economic impacts in the China-Japan-Korea core: A GTAP-E-DYN analysis. *Journal of Cleaner Production*, 215, 1332-1343.

Matsumoto, K., & Andriosopoulos, K. (2016). Energy security in East Asia under climate mitigation scenarios in the 21st century. *Omega*, 59, 60-71.

Morris, J., Paltsev, S., & Reilly, J. (2012). Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: Results from the EPPA model. *Environmental Modeling & Assessment*, 17(4), 325-336.

Morris, J., Reilly, J., & Chen, Y. H. H. (2014). *Advanced Technologies in Energy-Economy Models for Climate Change Assessment*. MIT JPSPGC Report. Forthcoming, 29 p.

Nordhaus, W. (2015). Climate Clubs: Overcoming Free-riding in International Climate Policy. *American Economic Review*, 105(4), 1339-1370.

Pant, H. M. (2007). *GTEM: Global Trade and Environment Model*. ABARE Technical Report, Australian Bureau of Agricultural and Resource Economics, Canberra.

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, 10(1), 3277.

Robinson, S., Cattaneo, A., & El-Said, M. (2001). Updating and estimating a social accounting matrix using cross entropy methods. *Economic Systems Research*, 13(1), 47-64.

Serletis, A., Timilsina, G. R., & Vasetsky, O. (2010). Interfuel substitution in the United States. *Energy Economics*, 32(3), 737-745.

Stern, D. I. (2012). Interfuel substitution: A meta-analysis. *Journal of Economic Surveys*, 26(2), 307-331.

van der Mensbrugghe, D. (2019). The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model. *Center for Global Trade Analysis, Purdue University*.

Victor, D. G., Akimoto, K., Kaya, Y., Yamaguchi, M., Cullenward, D., & Hepburn, C. (2017). Prove Paris was more than paper promises. *Nature*, 548(7665), 25-27.

Von Hippel, D., Savage, T., & Hayes, P. (2011). Energy security and sustainability in Northeast Asia. *Energy Policy*, 39(11), 6719-6730.

Weyant, J. P., & Hill, J. N. (1999). Introduction and overview: the costs of the Kyoto Protocol: a multi-model evaluation. *The Energy Journal*, 20(Special Issue), vi-xliv.

Winchester, N., & White, J. (2022). The C-PLAN Model: A framework for economy-wide climate policy analysis. *Climate Change Economics*, 24(2), 2250005.

World Bank. (2024). *GDP (current US$)*. World Bank Open Data. https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

Zhang, Y., Li, W., & Wang, H. (2016). Mitigating GDP losses through regional market integration: Evidence from computable general equilibrium modeling of East Asia. *Environmental and Resource Economics*, 64(4), 621-645.

Appendix A. Data Sources Summary Table

To ensure macroeconomic consistency and empirical rigor, the GUIDE-GLOBAL-CGE model integrates multiple distinct datasets. Table A1 summarizes the primary data sources utilized for benchmark calibration, regional SAM reconstruction, and long-term baseline projections.

Table A1. GUIDE-GLOBAL-CGE Data Sources Summary

Category	Data Source	Role in the Model
Global Macroeconomics & Trade	GTAP 11 Database c (Aguiar et al., 2022)	Provides the core multi-regional Input-Output (MRIO) tables, baseline production structures, and bilateral trade matrices (base year updated to 2017 to 2019).
Socioeconomic Projections	IIASA SSP2 ("Middle of the Road")	Supplies exogenous population and GDP growth trajectories up to 2050 to establish the Business-as-Usual (BAU) baseline and endogenize Total Factor Productivity (TFP).
Physical Energy & Emissions	IEA World Energy Balances (2024) EDGAR (2025)	Used to recalibrate energy substitution elasticities and ensure that economic energy aggregates strictly align with physical energy flows and baseline CO_2 emission factors.
North Korea (PRK) Macro Structure	Bank of Korea (BOK)	Serves as the primary targeting data for the Cross-Entropy SAM balancing procedure to accurately reconstruct North Korea's Value-Added and industrial output structure from the GTAP xea region.
North Korea (PRK) Trade Flows	Korea Trade-Investment Promotion Agency (KOTRA)	Provides the precise bilateral trade volumes and import-export commodity structures required to calibrate North Korea's isolated international trade network.

Appendix B. Empirical Estimation and Iterative Calibration of Energy Substitution Elasticities

Standard Computable General Equilibrium (CGE) models, such as those relying purely on GTAP default parameters, often utilize generic substitution elasticities (e.g., Armington elasticities for trade, CES for production) that assume a relatively high degree of structural flexibility. Directly using these default settings effectively assumes an ex-ante theoretical nested CES structure that can result in economy-wide energy price elasticities significantly deviating from historically observed, empirical econometric estimates, ultimately yielding mathematically overly optimistic simulations of fuel switching and demand destruction under extreme carbon pricing.

To rectify this structural discrepancy and ensure robust behavioral responses, this study employs a rigorous iterative calibration algorithm tailored to the distinct economic context of Northeast Asia.

Step 1: Empirical Target Formulation

To establish empirical targets, we constructed a comprehensive meta-dataset comprising 598 elasticity estimates extracted from 99 empirical studies published between 1977 and 2024. The sample encompasses own-price and cross-price elasticities for four primary energy sources: coal, oil, natural gas, and electricity, covering 38 individual countries and broader regional aggregates.

While the collected empirical studies estimate elasticities across a diverse range of economic agents (e.g., specific manufacturing sectors, residential households, and commercial entities) and temporal horizons, this study strategically synthesizes these micro-level and sector-specific estimates. Within the context of our recursive dynamic CGE framework simulating pathways to 2050, these aggregated values are interpreted and applied as the long-term, macro-level own-price elasticities of the energy market, reflecting structural demand adjustments over a 10- to 20-year horizon.

To ensure statistical reliability and account for methodological heterogeneity (e.g., functional forms like Translog, CES, or dynamic vs. static models), we employed clustered robust standard errors to correct for within-study correlation when multiple estimates were reported in a single study. Furthermore, to prevent statistical distortion from extreme outliers, the dataset was subjected to a 2.5% two-sided trimming procedure.

As summarized in Table B1, the descriptive statistics of the trimmed sample confirm the inelastic nature of energy demand, with all mean and median own-price elasticities falling between -1 and 0. Notably, coal exhibits the highest price responsiveness (mean: -0.829) and the widest variance, while electricity demand remains the most rigid (mean: -0.413).: Empirical Target Formulation

As summarized in Table B1, the descriptive statistics of the trimmed sample confirm the inelastic nature of energy demand, with all mean and median own-price elasticities falling between -1 and 0. Notably, coal exhibits the highest price responsiveness (mean: -0.829) and the widest variance, while electricity demand remains the most rigid (mean: -0.413).

Table B1. Descriptive Statistic of Trimmed Energy Price Elasticities

Energy Source	Observations	Mean	SD	Min	Q1	Median	Q3	Max
Coal	283	-0.829	0.601	-2.740	-1.242	-0.730	-0.347	0.179
Oil	465	-0.733	0.627	-2.748	-0.996	-0.576	-0.252	0.224
Gas	353	-0.740	0.535	-2.390	-1.000	-0.667	-0.362	0.847
Electricity	475	-0.413	0.330	-1.530	-0.550	-0.342	-0.174	0.160

Subsequently, an Ordinary Least Squares (OLS) dummy variable regression was applied to this robust dataset, setting Western Europe (WEU) as the reference baseline:

$$\mathrm{Elasticity}_{\mathrm{ene,z}} = \beta_0 + \sum_{k \neq \mathrm{WEU}} \beta_k \cdot D_k + \epsilon$$

where β_0 represents the baseline elasticity for WEU, D_k is a binary dummy variable indicating whether the observation belongs to region k ($D_k = 1$ if true, 0 otherwise), β_k

isolates the regional deviation for region k, and ϵ represents the error term.

Based on this econometric estimation, Table B2 presents the final calibrated target own-price elasticities specifically for the six Northeast Asian nations, which are directly utilized as the convergence targets in our algorithm.

Table B2. Target Economy-Wide Own-Price Elasticities for the 6 NEA Nations

Commodity	KOR	CHN	JPN	RUS	MNG	PRK
COAL	-0.88	-0.46	-0.74	-0.30	-0.58	-0.30
GAS	-0.74	-1.16	-0.52	-0.30	-0.67	-0.15
PETROLCOAL	-0.52	-0.34	-0.54	-0.15	-0.66	-0.15
ELEC	-0.48	-0.42	-0.45	-0.21	-0.35	-0.21

As shown in Table B2, certain data-scarce or structurally unique regions required specific proxy mapping from the econometric results. For the Russian Federation (RUS), we utilized the estimated values from the culturally and geographically adjacent "Rest of Former Soviet Union (RFS)" region, assuming particularly lower price elasticities for coal and natural gas commodities. For Mongolia (MNG), we applied the average estimated values of China and South Asia to reflect its transitional economic characteristics. Most notably, for North Korea (PRK), acknowledging the profound absence of market mechanisms in its centrally planned economy, we strictly applied the lowest absolute elasticity values observed across all 16 regional estimation results to reflect its extreme energy demand rigidity.

Step 2: Analytical Calculation of Theoretical Economy-Wide Elasticities

While empirical studies often report both own-price and cross-price elasticities, calibrating both simultaneously within a strictly nested CES framework is mathematically over-identified and intractable without violating structural consistency. Therefore, our calibration strategy focuses exclusively on aligning the model's theoretical *own-price elasticities* with the empirical targets established in Step 1.

The algorithm begins by analytically calculating the theoretical, *ex-ante* aggregate own-price elasticity ($\text{Elas\_Total\_ECON}_{ene,z}$) implied by the initial baseline values and the deep hierarchical nesting structure of the CGE model. This is performed in two sub-steps:

1. **Industry Level (CES Nests):** For each industry (j), the theoretical composite price elasticity ($\text{Elas\_Comp\_IND}_{ene,j,z}$) is calculated as a weighted combination of specific nested substitution elasticities ($\sigma_{KLE}, \sigma_{elec}, \sigma_{nelec}, \sigma_{coalgas}, \sigma_{oilprod}$), guided by the specific cost share of each energy source within the nest (e.g., S_{Coal_CG}, S_{CG_NE}).
2. **Macro Level (Armington Aggregation):** The overall domestic elasticity ($\text{Elas\_Total\_DDO}_{ene,z}$) is derived by aggregating the industry responses with household (LES function), investment, and government demands, weighted by their respective consumption shares. The final economy-wide elasticity ($\text{Elas\_Total\_ECON}_{ene,z}$) is then computed by incorporating the export elasticity ($\text{Elas\_EXP}_{ene,z}$), which is driven by the import substitution elasticity (σ_{M2}) of trading partners.

Step 3: Iterative Update Algorithm

The core calibration loops over these calculations iteratively. In each iteration, an error ratio is defined:

$$\text{Ratio}_{ene,z} = \frac{\text{Target\_ECON}_{ene,z}}{\text{Elas\_Total\_ECON}_{ene,z}}$$

To converge upon the target, the algorithm updates both the Armington elasticities (σ_{M1}, σ_{M2}) and the internal CES elasticities simultaneously using a proportional damping factor ($\text{step} = 0.15$):

$$\sigma_{new} = \sigma_{old} \cdot [1 + \text{step} \cdot (\text{Ratio} - 1)]$$

To respect the mathematical partial derivative structure of the CES nests, higher-level nests (e.g., σ_{KLE}) are updated based on the integrated, weighted-average error of the entire energy bundle. Conversely, lower-level cross-nests dynamically track the errors of specific fuels.

Step 4: Logical Constraints and Stability Bounds

To maintain the mathematical stability of the model, strictly bounded constraints are enforced at the end of each iteration loop. For instance, the top-level industry substitution elasticity is constrained to $0.5 \leq \sigma_{KLE} \leq 3.0$, and the primary Armington elasticity is bounded at $0.5 \leq \sigma_{M1} \leq 15.0$. Furthermore, an explicit computational deadzone is established around the value of 1.0 (i.e., values falling between 0.9 and 1.1 are pushed to the boundaries) to avoid singularities associated with strictly Cobb-Douglas transformations.

This iterative algorithm ensures that the simulated, economy-wide energy demand in the GUIDE-GLOBAL-CGE model accurately and conservatively reflects the inelastic realities of structural decarbonization.

To provide transparency regarding the magnitude of these structural adjustments, Table B3 summarizes the regional ranges (minimum and maximum) of the key CES and Armington substitution parameters before (Initial Point) and after the iterative calibration process. As shown, the calibration consistently scaled down the structural flexibility across the nesting hierarchy—particularly for energy-value-added (σ_{KLE}) and electricity substitution (σ_{elec})—to align with the inelastic empirical targets.

Table B3. Ranges of Key Substitution Parameters Before and After Calibration

Parameter	Description (CES Nest)	High Sub. (Before)		Low Sub. (After)	
		Min.	Max.	Min.	Max.
Sigma_KLE	Capital-Labor vs. Energy	0.1	1.1	0.5	1.1
Sigma_elec	Electricity vs. Fossil Fuel	1.5	1.5	0.5	1.1
Sigma_nelec	CoalGas vs.OilOilprod	0.5	0.5	0.5	0.5
Sigma_coalgas	Coal vs. Gas	2.0	2.0	0.5	1.6
Sigma_oilprod	Oil vs. Oilprod	0.5	0.5	0.5	0.9
Sigma_M1	Armington (COAL, OIL, GAS, ELEC)	2.8	6.0	0.5	5.2

Appendix C. Isolated_NZ Scenario Emission Constraints

Table C1 summarizes the prescribed CO2 emission reduction targets for the 17 regions across the key milestone years, expressed as a percentage relative to their 2019 baseline emissions.

Table C2. Isolated_NZ Scenario Emission Constraints (2019 = 1)

Region Code	Description	2019	2030	2035	2040	2045	2050
KOR	South Korea	1	0.66	0.52	0.37	0.24	0.10
CHN	China	1	0.97	0.83	0.68	0.49	0.30
JPN	Japan	1	0.67	0.52	0.38	0.24	0.10
RUS	Russia	1	0.97	0.83	0.68	0.59	0.50
MNG	Mongolia	1	0.97	0.83	0.68	0.59	0.50
PRK	North Korea	1	0.97	0.83	0.68	0.59	0.50
NAM	North America	1	0.50	0.40	0.30	0.18	0.05
LAM	Latin America and the Caribbean	1	0.97	0.83	0.68	0.52	0.35
WEU	Western Europe	1	0.50	0.40	0.30	0.18	0.05
EEU	Central and Eastern Europe	1	0.50	0.40	0.30	0.18	0.05
RFS	Rest of Former Soviet Union	1	0.97	0.83	0.68	0.59	0.50
MEA	Middle East and North Africa	1	0.97	0.83	0.68	0.59	0.50
AFR	Sub-Saharan Africa	1	0.97	0.83	0.68	0.59	0.50
MEK	Mekong Region	1	0.97	0.83	0.68	0.59	0.50
SAS	South Asia	1	0.97	0.83	0.68	0.59	0.50
SEA	Southeast Asia and Taiwan	1	0.97	0.83	0.68	0.59	0.50
ANZ	Australia and New Zealand	1	0.66	0.52	0.37	0.24	0.10

Appendix D. Complete Mathematical Formulation of the GUIDE-GLOBAL-CGE Model

Due to the large-scale and complex nature of the GUIDE-GLOBAL-CGE model, the complete set of mathematical formulations, GAMS source codes, and dataset structures are hosted in an open-access GitHub repository to ensure full transparency and reproducibility.

GitHub Repository: The complete source code and equation set can be accessed at: https://github.com/kimjintae9011/GUIDE_GLOBAL_CGE.git

Read the Docs: A comprehensive, interactive web-based documentation detailing every parameter, variable, and block of equations is currently under development and will be published via Read the Docs in the final version of this manuscript.