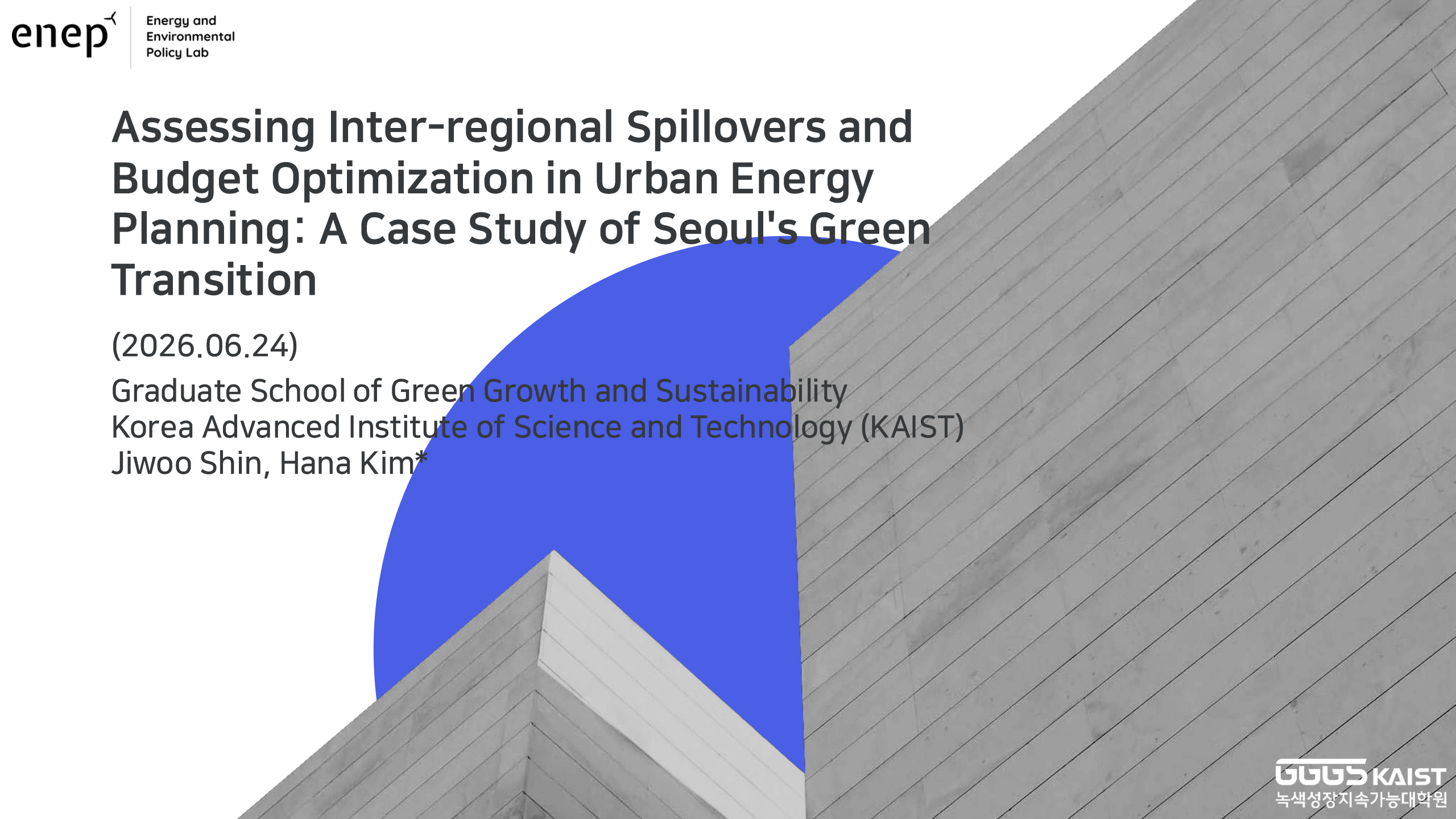
enep Energy and Environmental Policy Lab

Assessing Inter-regional Spillovers and Budget Optimization in Urban Energy Planning: A Case Study of Seoul's Green Transition

(2026.06.24)

Graduate School of Green Growth and Sustainability
Korea Advanced Institute of Science and Technology (KAIST)
Jiwoo Shin, Hana Kim*



GGGS KAIST 녹색성장지속가능대학원

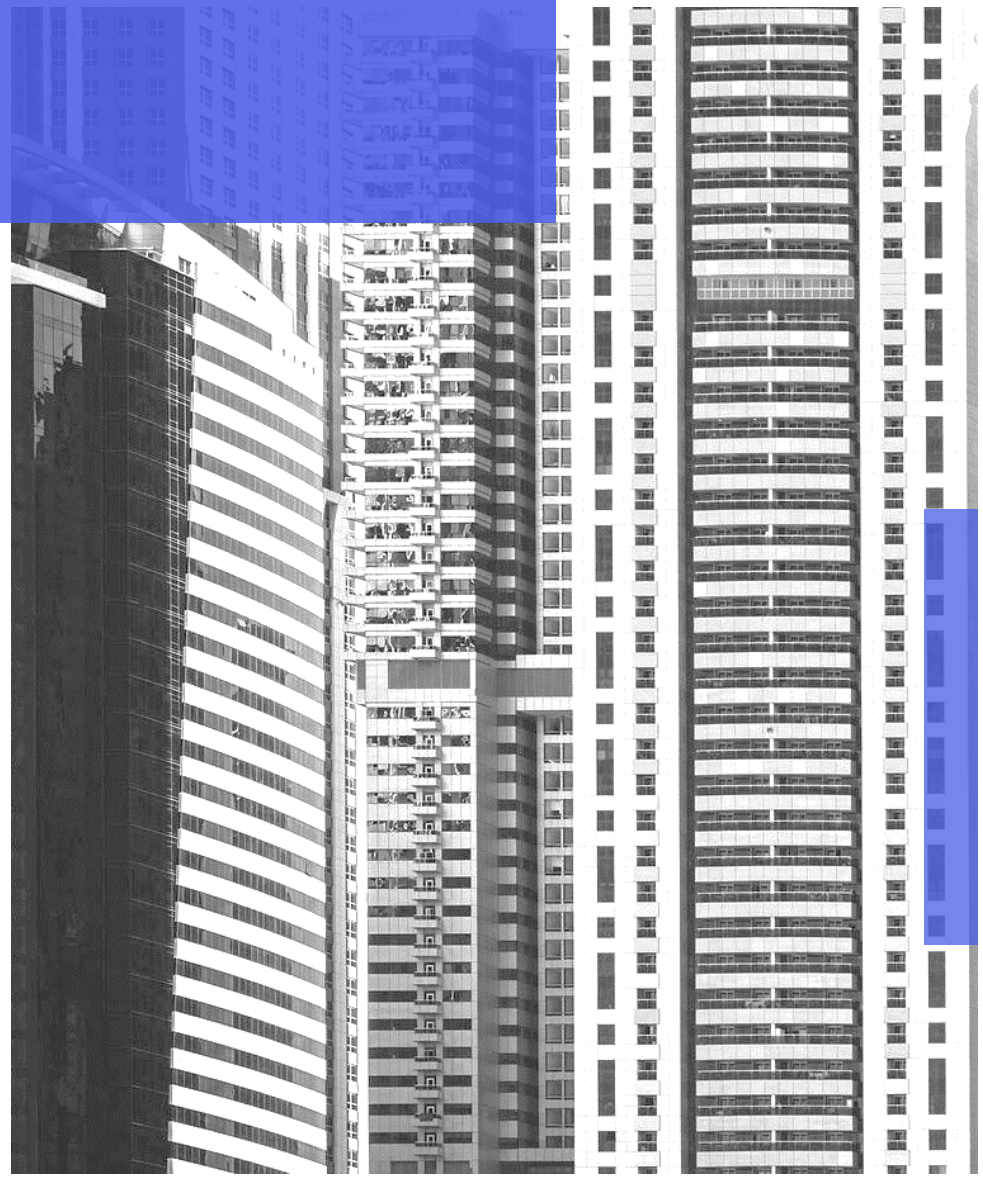
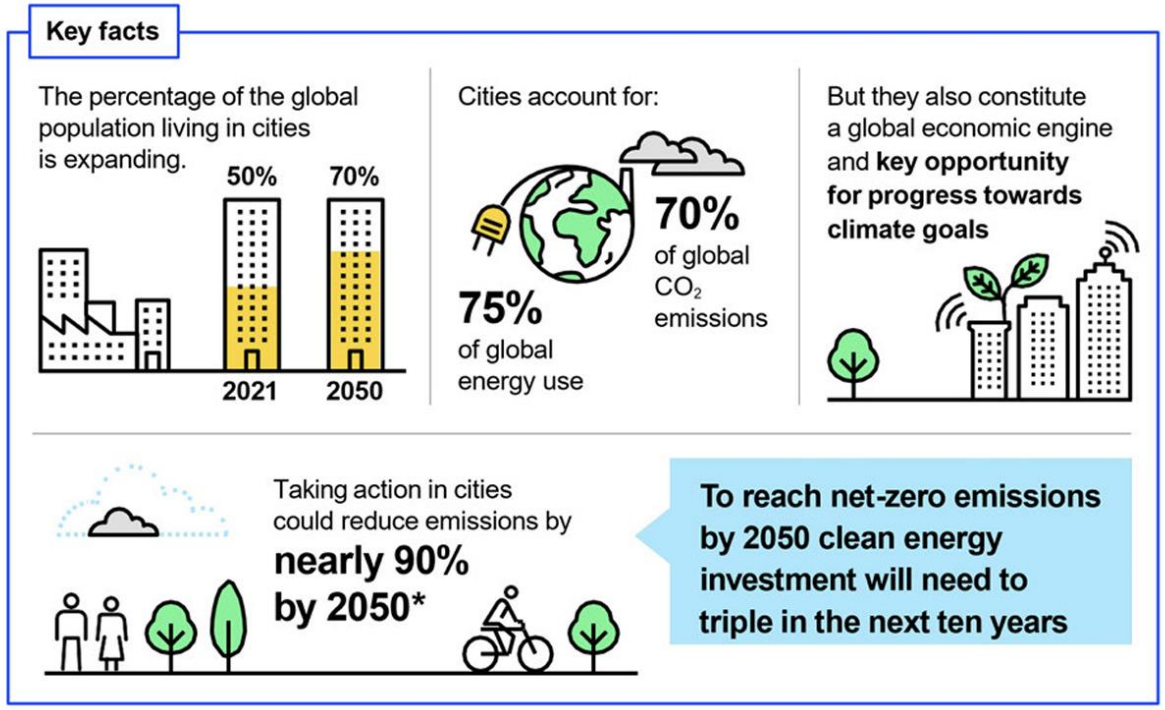


Table of Contents

Part 1

Research Background and Significance

Cities and Climate Change: Small in Size, Central to the Crisis



- The Urban Paradox: Covers just 2% of land, but causes 70% of global CO_2 emissions.
- Paradigm Shift: Climate action has evolved from regulation to a catalyst for economic growth. (Barbier, 2020)
- The Green Advantage: Green investments trigger higher economic multipliers than fossil-fuel stimuli. (Garrett-Peltier, 2017; Hepburn et al., 2020)

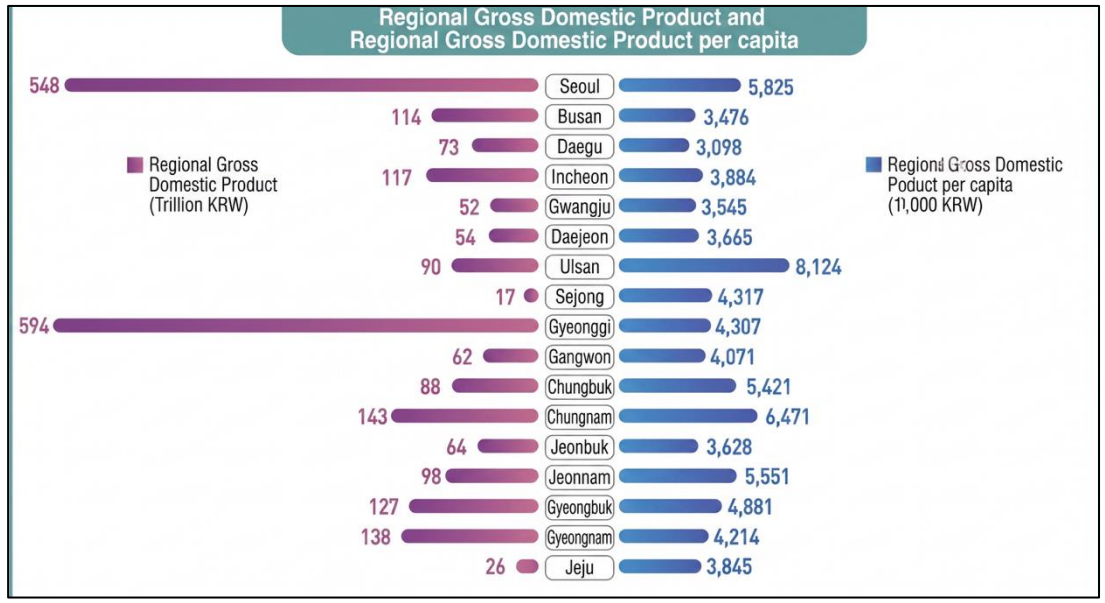
Therefore, evaluating the economic impacts of large-scale urban green transition policies is essential.

Source: International Energy Agency. (2021). *Empowering cities for a net zero future: Unlocking resilient, smart, sustainable urban energy systems.* OECD/IEA. https://www.iea.org/reports/empowering-cities-for-a-net-zero-future

Part 1

Research Background and Significance

Structural Vulnerabilities of Seoul



- Economic Hub vs. Emissions: Generates 22.5% of national GRDP from just 0.6% of the land, yet emits 3.3% of national GHGs (Statistics Korea, 2025a; 2025b; GIR, 2025).
- Skewed Energy Demand: Highly concentrated in the **building (44.1%) and transport (39.9%) sectors**, revealing structural vulnerabilities (Seoul Metropolitan Government, 2024).

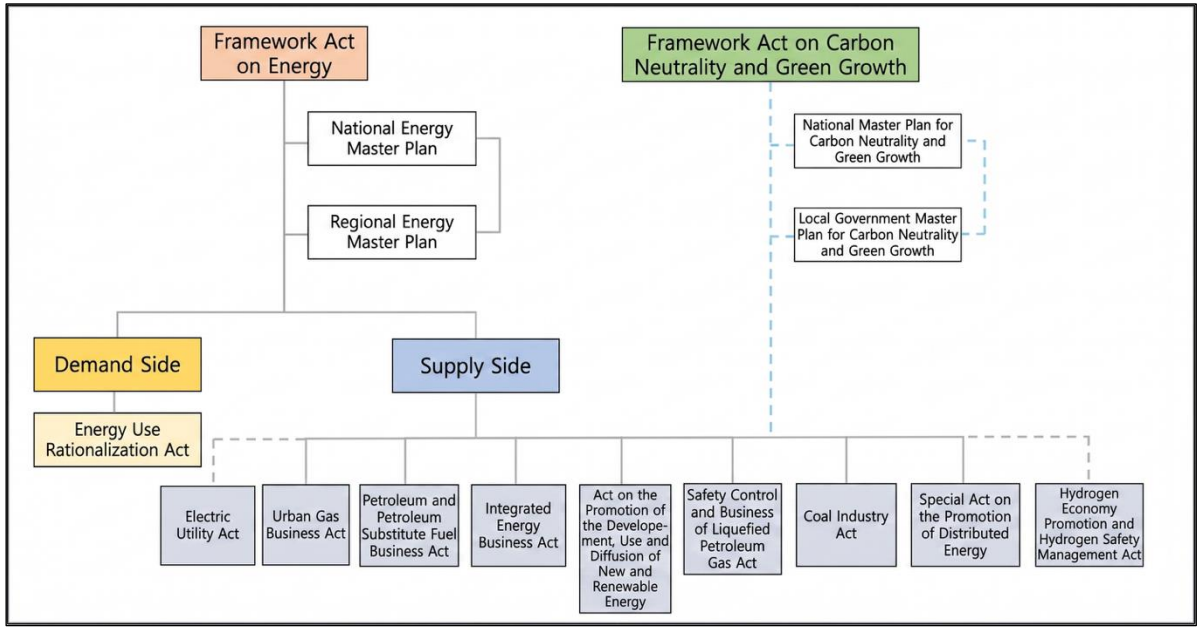
To address these vulnerabilities, Seoul established **the「2045 Regional Energy Plan」** and the **「Master Plan for Carbon Neutrality and Green Growth」** to drive urban GHG reduction and energy transition.

Sources: Statistics Korea (2024), *2022 Gross Regional Domestic Product (GRDP) Press Release*; Seoul Metropolitan Government (2024), *Carbon Neutral Green Growth Basic Plan (2024–2033)*

Part 1

Research Background and Significance

Policy Context: Legal & Institutional Framework



Policy Context

- Energy Act Mandate: Requires local governments to establish 'Regional Energy Plans' aligned with national energy strategies (MOTIE, 2019)
- Carbon Neutrality Framework Act & Ordinance: Mandates the legal establishment of the 'Master Plan for Carbon Neutrality and Green Growth' and obliges the city to achieve 2050 net-zero targets.

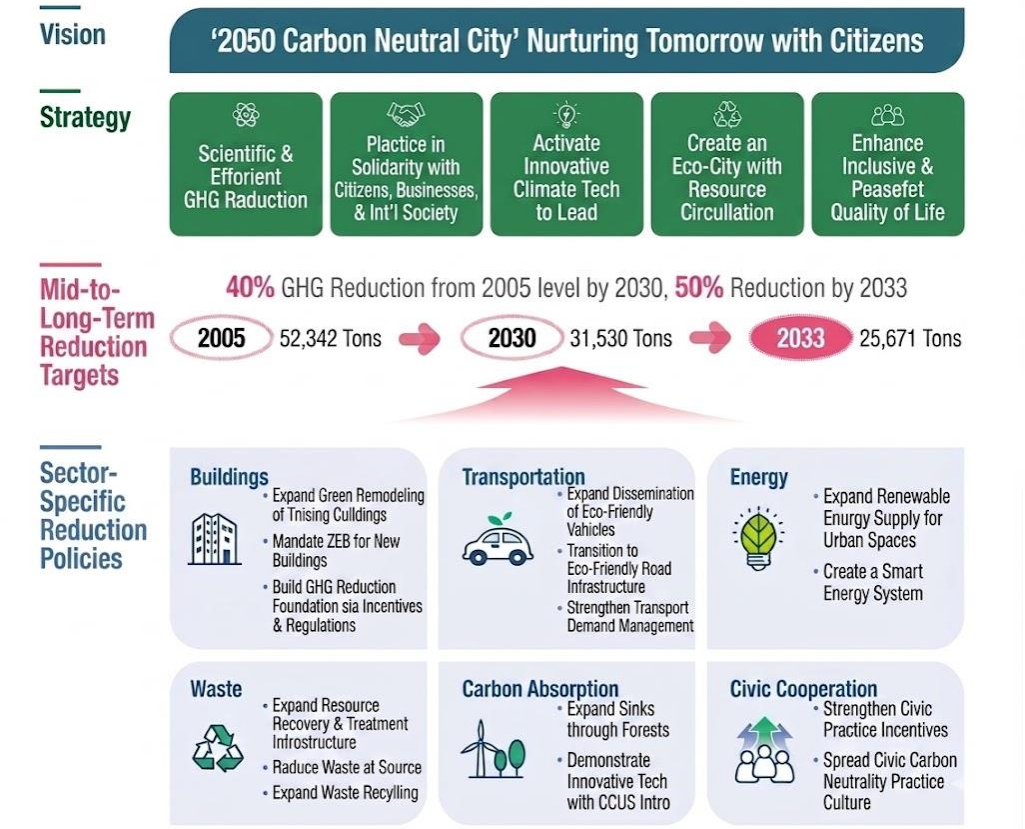
Based on this legal foundation, Seoul concurrently implements the「2045 Regional Energy Plan」(supply & demand) and the「Master Plan」(mitigation & adaptation)

Sources: Seoul Metropolitan Government (2024), *Carbon Neutral Green Growth Basic Plan (2024–2033)* and *The 5th Seoul Metropolitan Government Regional Energy Plan*; Ministry of Trade, Industry and Energy (2019), *The 3rd National Energy Master Plan.*

Part 1

Research Background and Significance

Policy Context: Legal & Institutional Framework



POLICY TO STRENGTHEN THE IMPLEMENTATION FOUNDATION	Climate Crisis Adaptation	Impact on Shared Property and Response	International and Local Cooperation	Education and Public Relations	Green Growth
	▪ Heavy Rain and Storm Damage Prevention ▪ Establishing a Sound Water Cycle System ▪ Expansion of Sustainable Urban Forests ▪ Safel Urban Facility Management ▪ Protecting Citizen Health and Vulnerable Groups	▪ Public Buildings: Enhancing Climate Resilience and Using for Energy Saving & Production Hubs ▪ Public Property (Roads, Parking Lots, Parks): Multi-purpose Use for Climate Crisis ▪ Corporiate Property (Hospitals, Urban Railways): Securing Stable Operations and Establishing Disaster Recovery Systems	▪ Leading Role in International Climate Change City Networks ▪ Strengthening Information Sharing and Cooperation between Cities in Various Climate and Environmental Fields ▪ Expansion of Seoul Policy Consulting and Green Investment ▪ Vitalizing Joint Research and Cooperation between Local Governments	▪ Strengthening Public Relations on the Climate Crisis and Climate Policies in Citizen Living Spaces ▪ Establishing a Carbon Neutral Citizen Learning and Education Foundation ▪ Strengthening PR and Implementation Projects for Autonomous Districts and Corporations	▪ Climate Change Response Innovative Technology Demonstration Projects ▪ Fostering Green Industries, Startups, Startups, and Workforce Training ▪ Supporting Green Enterprise ESG and Green Product Purchasing

Achieving carbon neutrality triggers economy-wide financial inputs, extending economic ripple effects far beyond Seoul.

Source: Seoul Metropolitan Government (2024), *Carbon Neutral Green Growth Basic Plan (2024–2033)*,

Part 1

Research Background and Significance

Limitations of Existing I-O Models

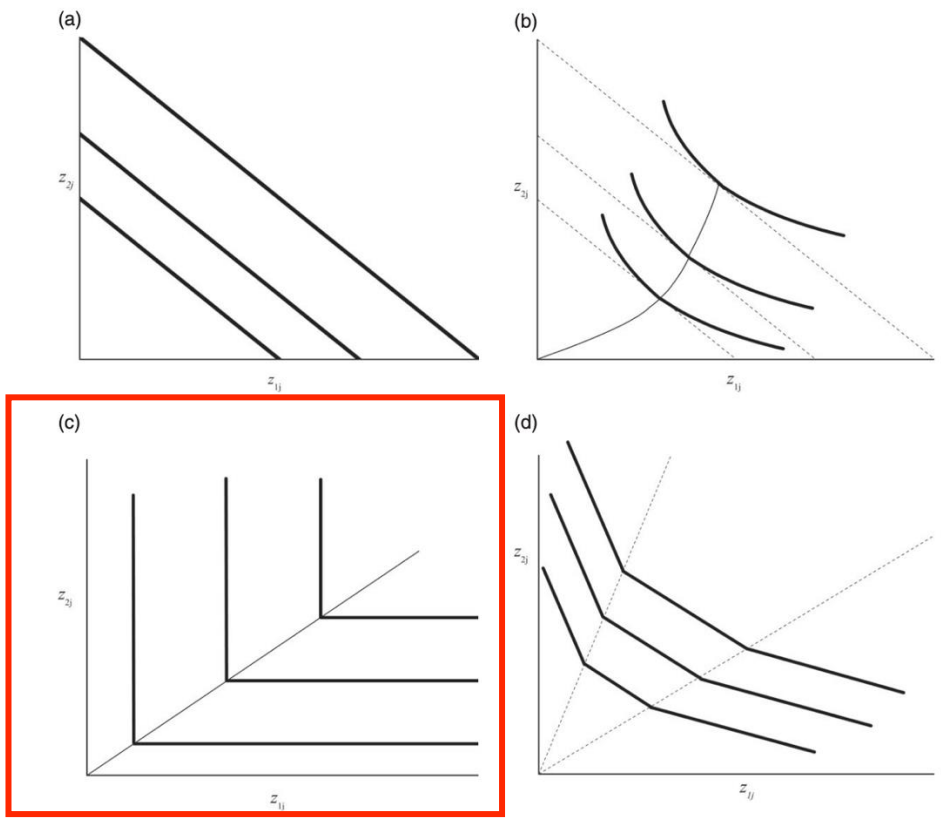


Figure 2.1 Production functions in input space. (a) Linear production function. (b) Classical production function. (c) Leontief production function. (d) Activity analysis production function

- Constant Returns to Scale (The Diagonal Path)
  - Production expands infinitely along the expansion path without any physical or financial boundaries.
  - **Infinite Budget Assumption**: Inherently ignores real-world fiscal limits and capacity constraints (Miller & Blair, 2022).

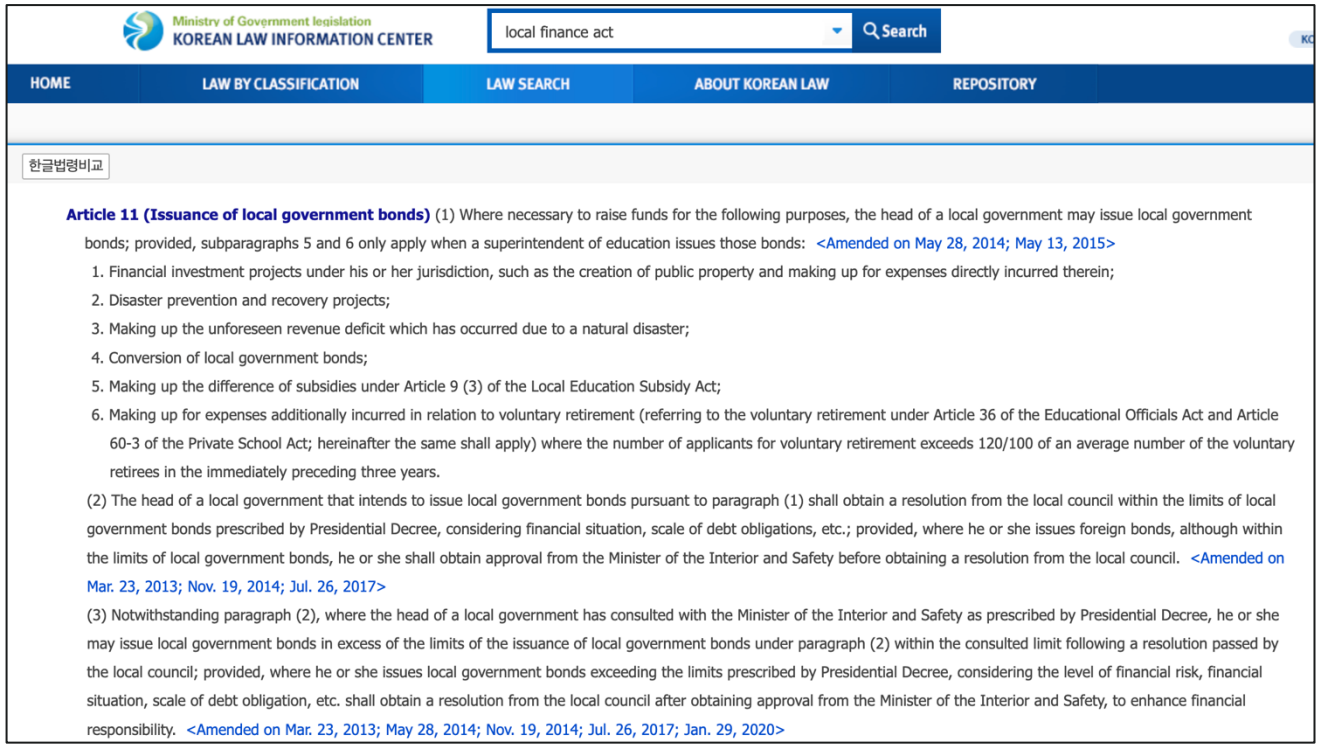
"Overestimation Bias"

Source: Miller, R. E., & Blair, P. D. (2022). Foundations of Input-Output Analysis. In Input-Output Analysis: Foundations and Extensions (pp. 10-62). chapter, Cambridge: Cambridge University Press., https://doi.org/10.1017/9781108676212.003

Part 1

Research Background and Significance

Fiscal Realities: The Necessity of Budget Reallocation



Ministry of Government legislation
KOREAN LAW INFORMATION CENTER

local finance act Search

HOME | LAW BY CLASSIFICATION | LAW SEARCH | ABOUT KOREAN LAW | REPOSITORY

한글법령비교

Article 11 (Issuance of local government bonds) (1) Where necessary to raise funds for the following purposes, the head of a local government may issue local government bonds; provided, subparagraphs 5 and 6 only apply when a superintendent of education issues those bonds: <Amended on May 28, 2014; May 13, 2015>

1. Financial investment projects under his or her jurisdiction, such as the creation of public property and making up for expenses directly incurred therein;
2. Disaster prevention and recovery projects;
3. Making up the unforeseen revenue deficit which has occurred due to a natural disaster;
4. Conversion of local government bonds;
5. Making up the difference of subsidies under Article 9 (3) of the Local Education Subsidy Act;
6. Making up for expenses additionally incurred in relation to voluntary retirement (referring to the voluntary retirement under Article 36 of the Educational Officials Act and Article 60-3 of the Private School Act; hereinafter the same shall apply) where the number of applicants for voluntary retirement exceeds 120/100 of an average number of the voluntary retirees in the immediately preceding three years.

(2) The head of a local government that intends to issue local government bonds pursuant to paragraph (1) shall obtain a resolution from the local council within the limits of local government bonds prescribed by Presidential Decree, considering financial situation, scale of debt obligations, etc.; provided, where he or she issues foreign bonds, although within the limits of local government bonds, he or she shall obtain approval from the Minister of the Interior and Safety before obtaining a resolution from the local council. <Amended on Mar. 23, 2013; Nov. 19, 2014; Jul. 26, 2017>

(3) Notwithstanding paragraph (2), where the head of a local government has consulted with the Minister of the Interior and Safety as prescribed by Presidential Decree, he or she may issue local government bonds in excess of the limits of the issuance of local government bonds under paragraph (2) within the consulted limit following a resolution passed by the local council; provided, where he or she issues local government bonds exceeding the limits prescribed by Presidential Decree, considering the level of financial risk, financial situation, scale of debt obligation, etc. shall obtain a resolution from the local council after obtaining approval from the Minister of the Interior and Safety, to enhance financial responsibility. <Amended on Mar. 23, 2013; May 28, 2014; Nov. 19, 2014; Jul. 26, 2017; Jan. 29, 2020>

- **Legal basis**: Local Finance Act (Article 11)
- Local governments can only issue municipal bonds under **specific, exceptional circumstances**:
  - Disaster prevention and recovery
  - Unforeseeable urgent financial needs
  - Development of public property/infrastructure
  - …

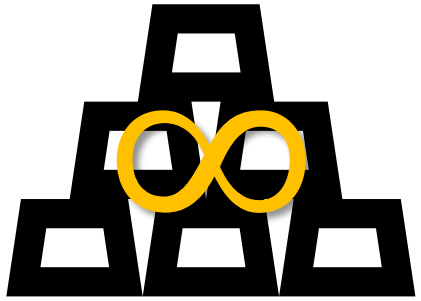
<u>New projects must be funded by reallocating existing resources</u>

Source: Ministry of the Interior and Safety (2024), *Local Finance Act*.

Part 1

Research Background and Significance

Methodological Rationale: Beyond the Infinite Budget Assumption



Traditional IO Approach

- Overestimation bias
- Focusing only on the “Positive Injection”

Proposed Optimization Model

- Principle of fiscal neutrality.
- Accounts for opportunity costs (budget withdrawals/cuts)

$$Net\ Economic\ Impact = Injection - Withdrawl$$

Part 2

Research Objectives and Questions

Objectives

- **To empirically assess** the multi-regional and sectoral economic impacts of Seoul's energy policies
- **To propose** an optimal budget reallocation framework maximizing net positive impacts under strict fiscal neutrality.
- To identify the **optimal investment pathways** that minimize economic opportunity costs while maximizing interregional spillover effects to the national economy.

Questions

- What is the magnitude of regional spillover effects on production, value-added, and employment?
- Can the energy transition be macroeconomically viable relying solely on internal budget reallocation?
- What are the economic and policy implications of the optimal budget allocation scenarios?

Part 3

Literature Review

IO-Based Economic Spillovers of Sectoral Green Transitions

Implications

- Strategic Optimization: The literature indicates that green transitions do not guarantee unconditional economic benefits. Moving beyond mere ex-post evaluations, it is imperative to apply a **constrained optimization framework** to strategically allocate resources under strict budgetary and spatial limitations.

- Building: High labor intensity boosts regional GDP and employment (Hartwig & Kockat, 2016; Mikulić et al., 2016), but household rebound effects may **offset** environmental benefits (Cellura et al., 2013). Acts as a new growth engine rather than mere regulation (Jo et al., 2024).
- Transport: EV supply chains **increase national output** (Guo et al., 2022; Pirmana et al., 2023), though benefits are unevenly distributed by regional specialization (Shibusawa & Miyata, 2017; Shibusawa & Xu, 2013). High import reliance can trigger **negative feedback** like capital leakage and job losses (Leurent & Windisch, 2015; Yamada et al., 2019).
- Energy: Clean energy investments drive **net job creation and stable employment** (Garrett-Peltier, 2017; O'Sullivan & Edler, 2020; Černý et al., 2022). However, reliance on imported equipment (Marinos et al., 2025; Markaki et al., 2013) and unequal policy costs **hinder positive spillover effects** (Nakano et al., 2017).

Part 3

Literature Review

Research Gaps and Contributions

Research Gap

- **Lack of City-Level Empirical Analysis**: Existing macroeconomic spillover studies are predominantly national, limiting insights into specific urban policy interventions.
- **Fallacy of Infinite Capital**: Traditional IO and optimization models often assume unlimited capital, leading to an overestimation bias in economic impacts.
- **Neglect of Local Fiscal Constraints**: Few studies integrate the strict budgetary limitations and restricted bond issuance unique to local governments into optimization frameworks.

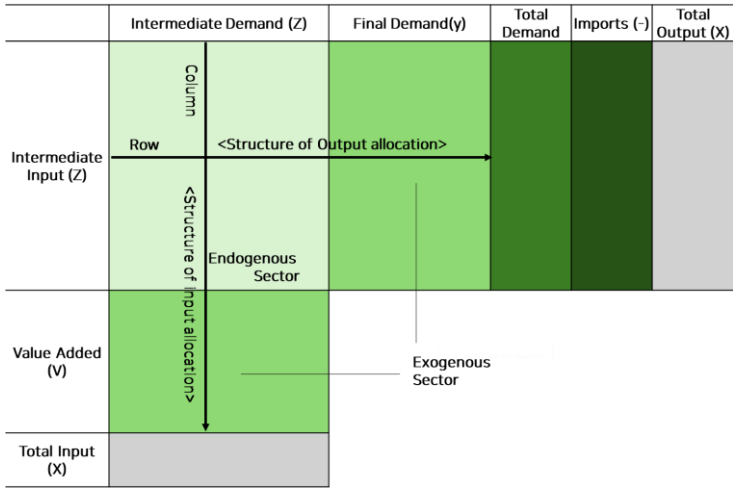
Contribution

- **Quantification of Macroeconomic Spillovers**: Empirically quantifies the economic spillovers induced by Seoul's specific energy policy portfolio.
- **Proposed Constrained Optimization Model**: Reflects zero-debt constraints by modeling 'budget reallocation' as a final demand change vector.
- **Optimal Policy Portfolio Derivation**: Identifies the optimal municipal policy strategy that maximizes economic benefits within strict local fiscal boundaries.

Part 4

Methodology

Input-Output Analysis



[Basic Structure of the IO Table]

[Characteristics of the Korean Input-Output Table (Bank of Korea, 2020)]

Feature	Description
Type & Coverage	Multi-Regional IO table (IRIO), 17 regions; survey-based benchmark, compiled every 5 years (2020 latest)
Valuation	Producer's prices
Import Treatment	Non-competitive import type: domestic and import transaction tables compiled separately
Byproduct & Scrap	Negative-entry method (R. Stone): negative production-inducement coefficients reflect the reduced output requirement from scrap generation
Sector Resolution	380 basic → 165 small → 83 medium (used here) → 33 large

Purpose

- To quantify how changes in final demand affect **output, value added, employment, and import** through inter-industry linkages.
- To assess the economic impacts of sectoral investments in **Seoul's Regional Energy Plan**.

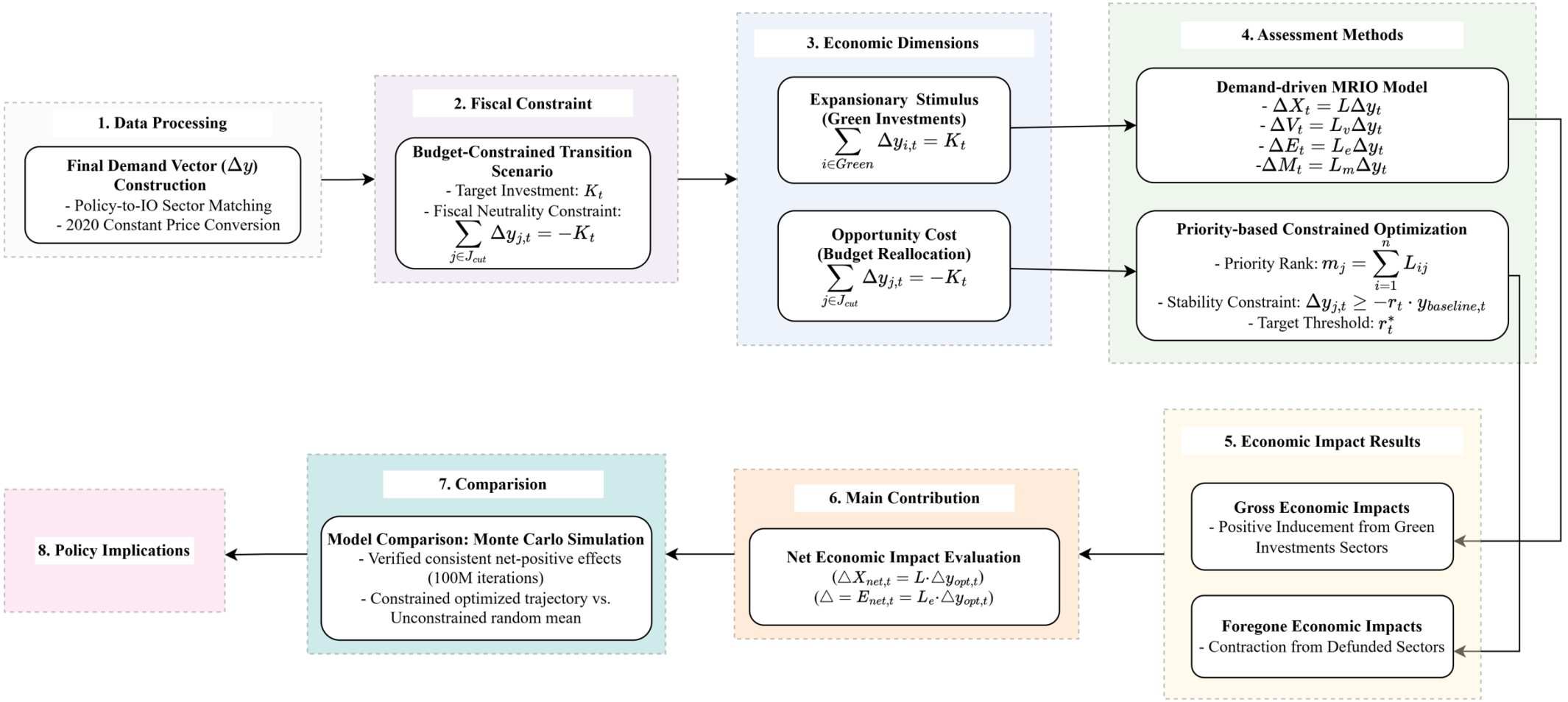
Scope of Analysis

- Demand-driven Leontief Model
- Equation: $\Delta X = (I - A)^{-1}\Delta y$
- Time Frame: Up to 2045 (21-year projection)
- Policy Input: Final demand changes derived from the 6th Seoul Regional Energy Plan

Part 4

Methodology

Research Framework



[Research Framework Used in this Study]

Part 4

Methodology

Data

[Data Sources and Use]

Source	Data Description	Purpose of Use
Seoul Metropolitan Government	6th Seoul Regional Energy Plan: Project-level budgets and investment details	Estimating economic ripple effects of regional energy investments
	Basic Plan for Carbon Neutrality and Green Growth (2024–2033): Sectoral emission-reduction programs	Sectoral matching for policy-driven final demand changes
Bank of Korea	2020 Regional Input–Output Table (IO & Employment coefficients)	Regional economic impact analysis
	Explanation of the 2020 IO Table and Statistics	Sector classification & investment structure matching
	Producer Price Index (PPI), 2015–2024	Converting monetary values to constant 2020 prices

Part 4

Methodology

Data Processing

Policy-to-IO Sector Matching

- Mapped 42 budgeted projects from Seoul's energy plans to the 2020 Multi-Regional Input-Output (MRIO) table (83 sectors).
- Focused strictly on the Building, Transport, and Energy sectors.
  - Building Sector (15)
  - Transport Sector (18)
  - Energy Sector (9)

Constant Price Conversion

- Deflated 2025–2045 nominal budgets to 2020 constant prices to ensure **temporal consistency** with the base year.
- Applied sector-specific CAGRs derived from the Producer Price Index (PPI).
- **Equal budget distribution** (1:1:1) applied to single projects spanning multiple I-O sectors.

Final Demand Vector (Δy) Construction

- Constructed a final demand change vector for 17 regions and 83 sectors ($\Delta \boldsymbol{y}$, 1,411×1)
- Allocated the entire municipal investment exclusively to Seoul's regional demand (other regions = 0).
- Constructed vector serves as the core **exogenous shock** for the optimization model.

Part 4

Methodology

Measurement of Economic Ripple Effect

[Ripple Effect Types and Interpretation in IO Analysis]

Ripple Effect Type	Equation	Interpretation
Output	$\Delta X_t = (I - A)^{-1}\Delta y_t = L\Delta y_t$	- Change in **total output induced** by final demand shifts from Seoul's energy investments.
Value-added	$\Delta V_t = v' \cdot \Delta X_t = L_v \Delta y_t$	- Additional **value added** (wages, operating surplus, etc.) generated through industry linkages.
Employment	$\Delta E_t = e' \cdot \Delta X_t = L_e \Delta y_t$	- Number of **new jobs created** due to final demand changes from policy investments.
Import	$\Delta M_t = m' \Delta X_t = L_m \Delta y_t$	- **Imported inputs** induced by final demand changes. (i.e., The portion of demand met by imports rather than domestic production.)

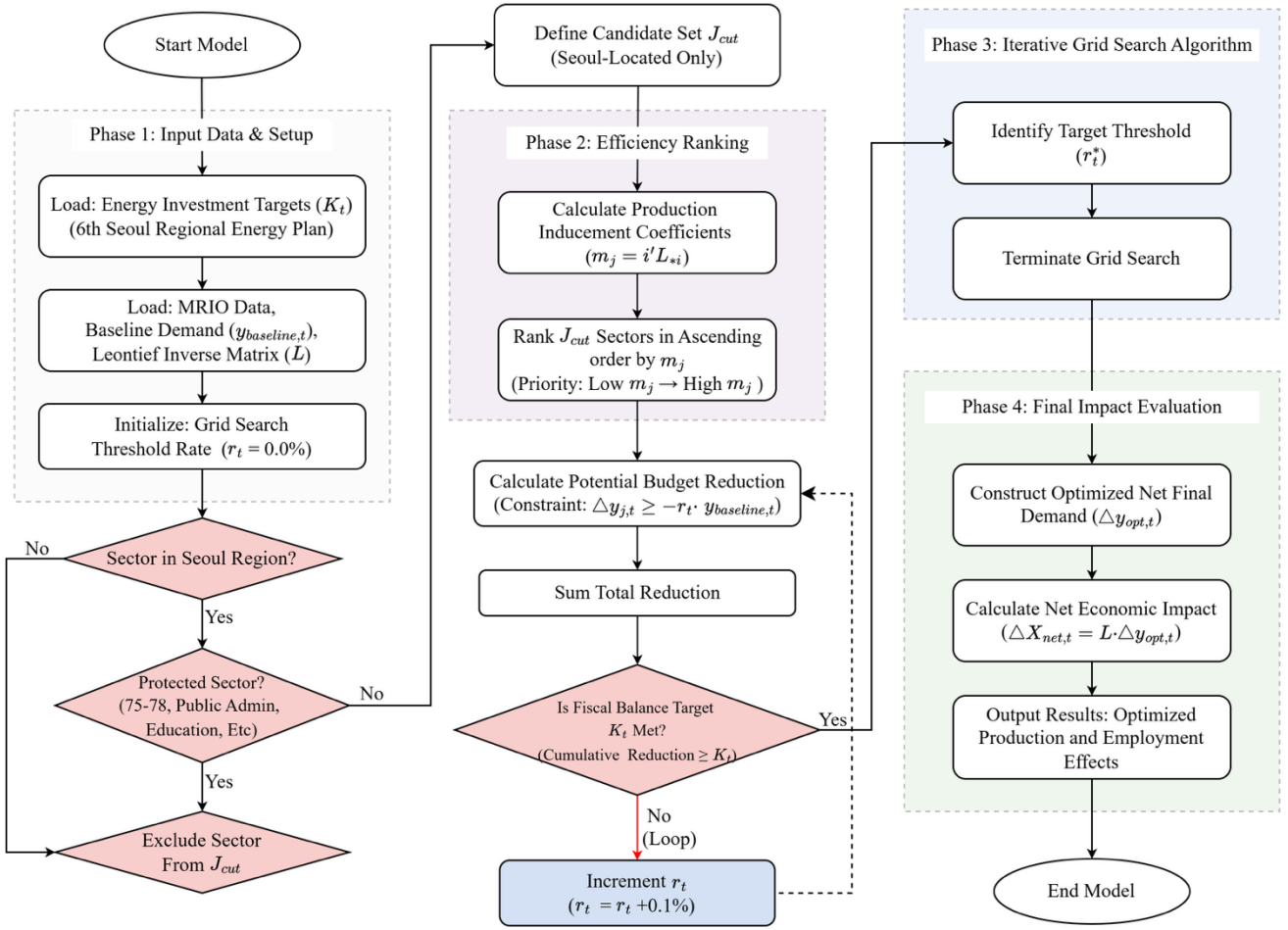
Definitions of Key Variables

- X_t, V_t , E_t , M_t : Output, value-added, employment, and import effect vectors in year t.
- $L = (I - A)^{-1}$: Leontief inverse matrix.
- Δy_t: Final demand change vector in year t resulting from Seoul's energy policy investments
- v', e', m': Value-added, employment and import coefficient vectors
- L_v, L_e, L_m : Value-added, employment , and import inducement matrices

Part 4

Methodology

Priority-based Budget Reallocation Optimization Model



- **Objective**: Maximize **"Net Economic Impact"** under **Fiscal Neutrality**
  - **Net Impact** = Expansionary Stimulus (Green) – Opportunity Cost (Cuts)
  - $\Delta X_{net,t} = L \cdot \Delta y_{opt,t}$

    $= L \cdot (y_{scenario,t} - y_{baseline,t})$

    $\rightarrow \Delta E_{net,t} = L_e \cdot \Delta y_{opt,t}$

- Fiscal **Constraint**
  - Grounded in the **Local Finance Act**: No external debt or municipal bonds (Republic of Korea, 2026)
  - **Internalization**: 100% self-financed through existing budget reallocation

Part 4

Methodology

Priority-based Budget Reallocation Optimization Model

1. Target Sector Filtering

- Limit budget cut candidates (J_{cut}) exclusively to the **Seoul region**
- Exclude essential public services (e.g., education) to ensure administrative stability.

2. Prioritizing Budget Cuts

- Calculate the column sum of **production inducement multiplier** (m_j) for each candidate
- Prioritize cuts in sectors with the **lowest multipliers** to minimize economic opportunity costs.

3. Establish Budget Cut Cap

- Establish a **budget cut cap** (r_t) to prevent the total depletion of any single sector's budget
- Iteratively increase the cap (by 0.1%p) to identify the **target threshold rate** (r_t^*) that exactly satisfies the target investment constraint (K_t) using Grid Search.

4. Net Economic Impact

- Compute the **net economic impact** (total output change) induced by the optimized final demand change vector ($\Delta y_{opt,t}$) → Compute net employment
- $\Delta X_{net,t} = L \cdot \Delta y_{opt,t}$ → $\Delta E_{net,t} = L_e \cdot \Delta y_{opt,t}$

Part 4

Methodology

Monte Carlo Simulation via Random Reallocation

Objective

- Establishes a **baseline** to compare the proposed constrained optimization model against unconstrained random policy decisions
- Generates a probability **distribution of net economic impacts** under random budget cut scenarios.

Stochastic Algorithm

- **Uniform Dirichlet Distribution (α_i=1):** Applied to enforce **fiscal neutrality**. Setting the parameter to 1 ensures an unbiased, zero-sum budget reallocation without subjective weights.
- Statistical Convergence: Executed 100M

Implications

Methodological Validity

- Evaluates **relative performance** by mapping the constrained, realistic optimal portfolio onto the unconstrained random probability distribution.

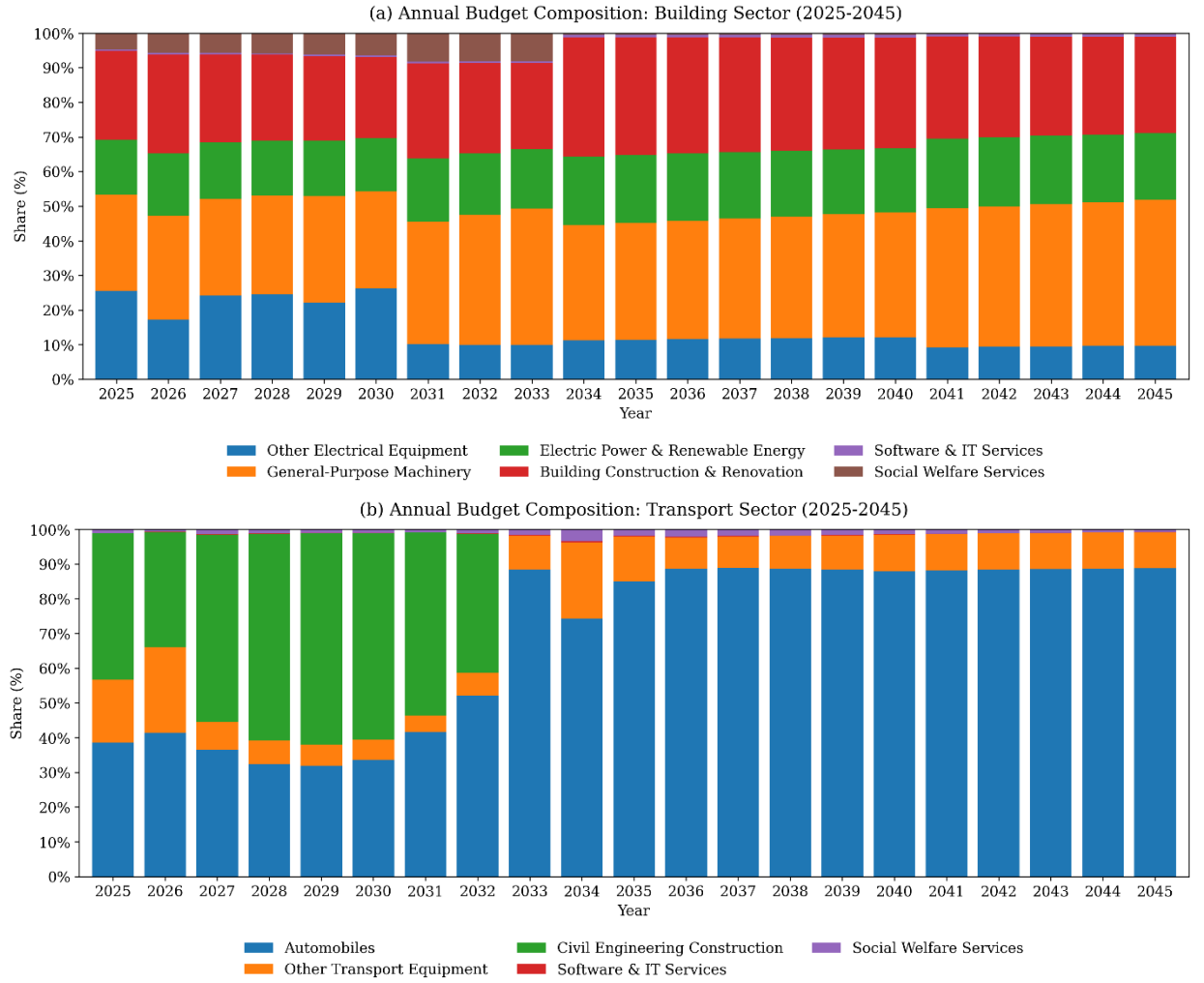
Benchmarking

- Visualizes the trade-off between theoretical macroeconomic maximization and real-world policy constraints, providing an objective **benchmark.**

Part 5

Results

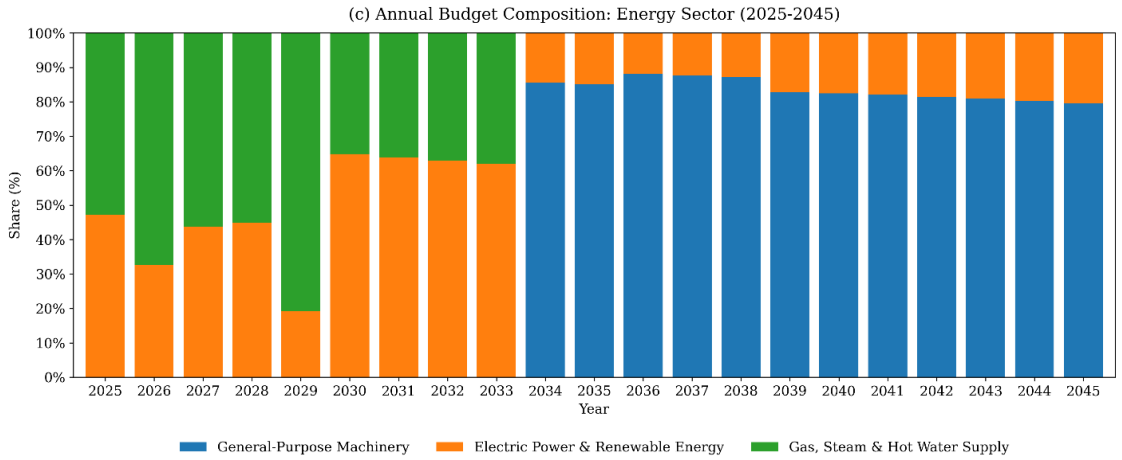
Sectoral Investment Patterns and Timing (2025–2045)



Part 5

Results

Sectoral Investment Patterns and Timing (2025–2045)



Category	Total Budget (Million USD)	Major IO Sector
Building	35.0-105.6	Electrical equipment, general machinery, electricity & RE, construction, IT services, social welfare services
Transport	287.9-1,673.8	Automobiles, transportation equipment, construction, IT services, social welfare services
Energy	4.0-47.4	General machinery, electricity & RE, gas supply, steam & air-conditioning supply

The exchange rate applied is 1,180 KRW = 1 USD, based on the 2020 average rate consistent with the input-output data base year.

Implications

> Because the timing and scale of sectoral investments in Seoul's Regional Energy Plan vary substantially, the magnitude and timing of economic ripple effects are also expected to **differ across budget sectors**—even when the same multipliers are applied.

Part 5

Results

Sectoral Breakdown of Economic Impacts (2025-2045)

Category		Unit	Building	Transport	Energy	Total
Investment		Mil USD	1,302	17,626	324	19,252
Output Inducement	Total Effect	Mil USD	2,501	36,220	623	39,344
	Factor	ratio	1.92	2.05	1.92	2.04
Value-Added Inducement	Total Effect	Mil USD	1,034	13,803	226	15,063
	Factor	ratio	0.79	0.78	0.70	0.78
Employment Inducement	Total Effect	Persons	14,804	188,874	2,545	206,223
	Factor	Jobs/Mil USD	11.4	10.7	7.9	10.7
Import Inducement	Total Effect	Mil USD	260	3,734	96	4,091
	Factor	Ratio	0.20	0.21	0.30	0.21

- Building sector achieves the **highest** qualitative efficiency by maximizing real regional income and job creation through its labor-intensive green retrofitting activities
- Transport sector serves as the primary engine for quantitative growth, utilizing its dominant investment share to trigger massive industrial output across manufacturing supply chains (**strong backward linkages**).
- Energy sector reflects the capital-intensive nature of utility infrastructure, showing **lower direct inducement factors due to its reliance on automated facilities.** However, it shows the **highest import dependency** among the three, as Korea relies heavily on imported fuels for energy production.

Part 5

Results

Regional Distribution of Sectoral Impacts (2025–2045)

[Building] [Transport] [Energy]

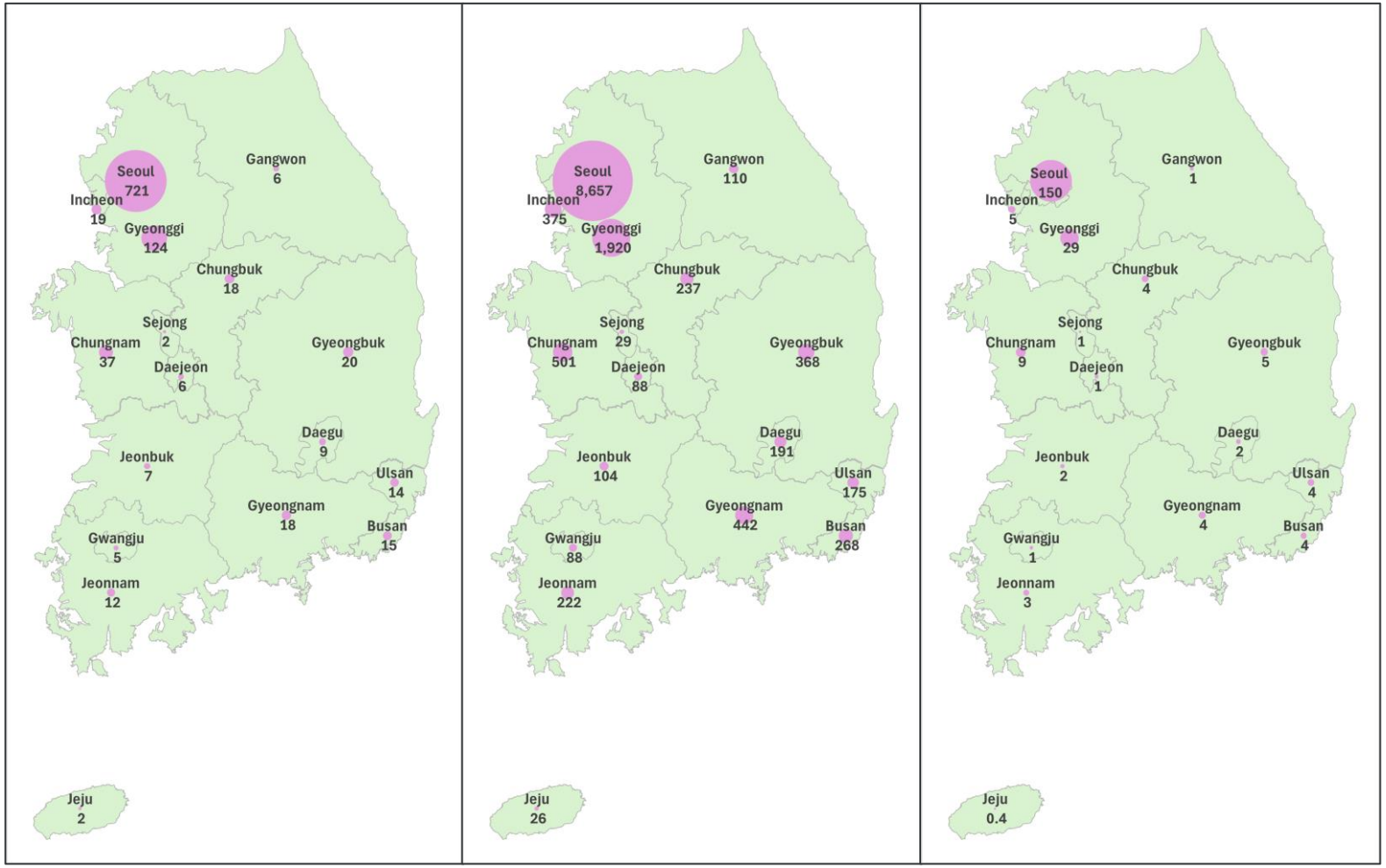
Output Effect

- Building: Retains 66.2% of production within Seoul, 12.4% spillover to Gyeonggi for electrical equipment supply.
- Transport: Shows the highest leakage, with only 60.6% remaining in Seoul, effectively stimulating the Southeastern industrial belt (Gyeongnam 3.9%, Gyeongbuk 3.0%).
- Energy: Maintains a 65.6% intra-regional share, but triggers significant utility-linked spillovers in Gyeonggi (12.3%) and Chungnam (4.2%).

Part 5

Results

Regional Distribution of Sectoral Impacts (2025–2045)



[Building] [Transport] [Energy]

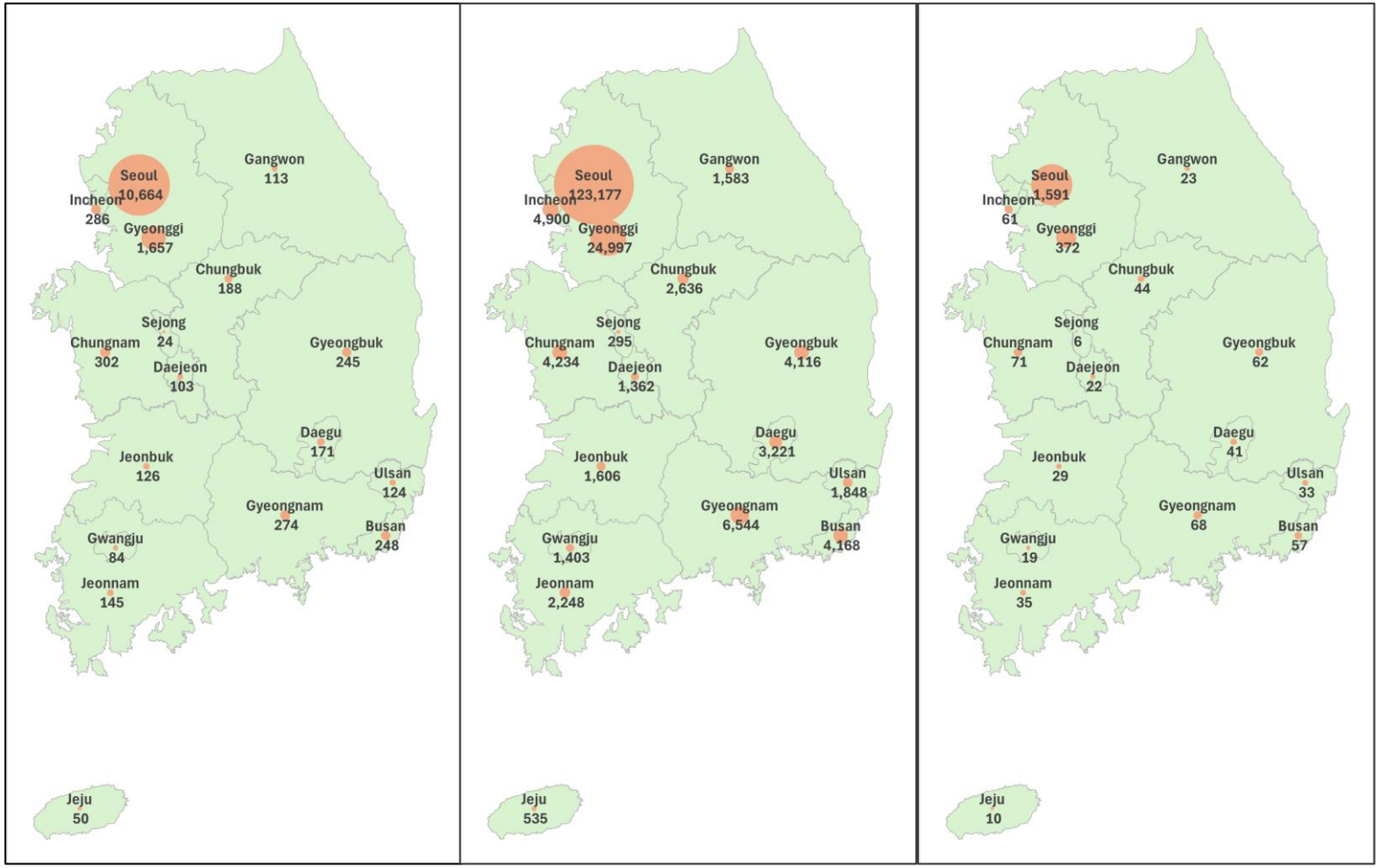
Value-added Effect

- Building: Captures **69.7% (higher than output share)** in Seoul by concentrating high-value design and consulting services.
- Transport: Retains **62.7%** of value-added by functioning as a service control tower for e-mobility software and platforms, despite manufacturing leakage.
- Energy: Records a high value-added share of **66.5%**, keeping core economic value in the capital through centralized utility management and R&D activities.

Part 5

Results

Regional Distribution of Sectoral Impacts (2025–2045)



[Building] [Transport] [Energy]

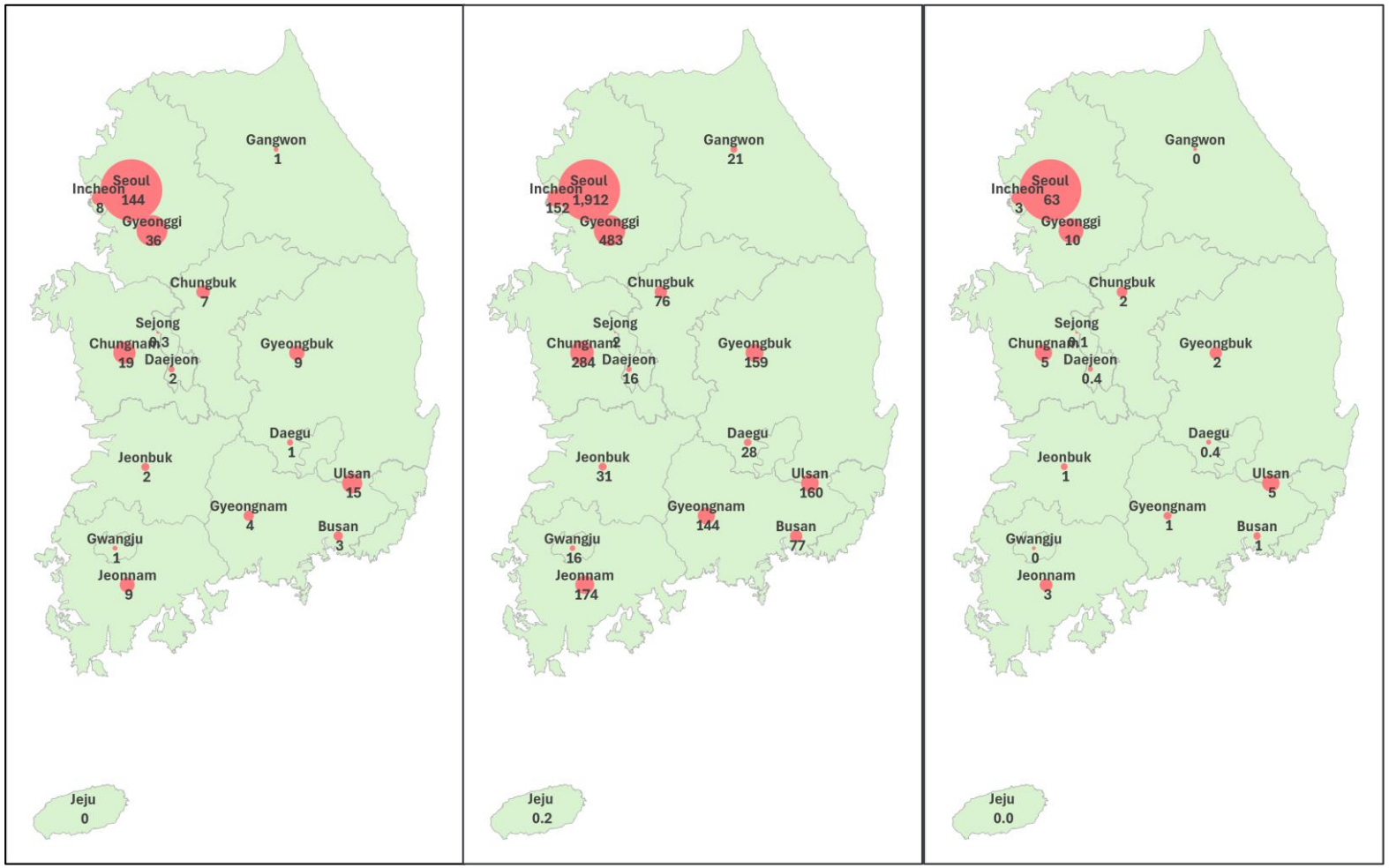
Employment Effect

- **Building**: Achieves the highest local job security at **72.0%**, driven by the non-tradable and labor-intensive nature of on-site green retrofitting.
- **Transport**: Drives assembly jobs in the South; **Gyeongnam (3.5%)** captures double the Building sector's job share.
- **Energy**: Exhibits the lowest intra-regional share (**62.5%**) but triggers a remarkable **14.6%** job surge in **Gyeonggi** for equipment manufacturing.

Part 5

Results

Regional Distribution of Sectoral Impacts (2025–2045)



[Building] [Transport] [Energy]

Import Effect

- Building: **Lowest** intra-regional share among all indicators (55.2%), with import-intensive inputs sourced from regions like Gyeonggi (13.8%).
- Transport: Most **dispersed pattern** (51.2% in Seoul); Chungnam (petrochemicals, steel) and Gyeonggi (electronics, machinery) absorb the inputs.
- Energy: Unlike the others, **highest share in Seoul (64.9%),** reflecting reliance on imported fuels at the point of final demand.

Part 5

Results

Budget Reallocation Optimization Results

Year	Target Investment (K_t, Mil USD)	Target Threshold (r_t^*, %)	Net Economic Impact (Mil USD)	Net Employment Impact (Persons)
2025	1,217	21.1	+207	-3,454
2026 (Max K_t)	1,795	31.1	+340	-6,071
...				
2034 (Min K_t)	342	6.0	+115	-1,523
...				
2045	1,146	19.9	+485	-5,688
Total	19,252	-	+5,388	-70,284

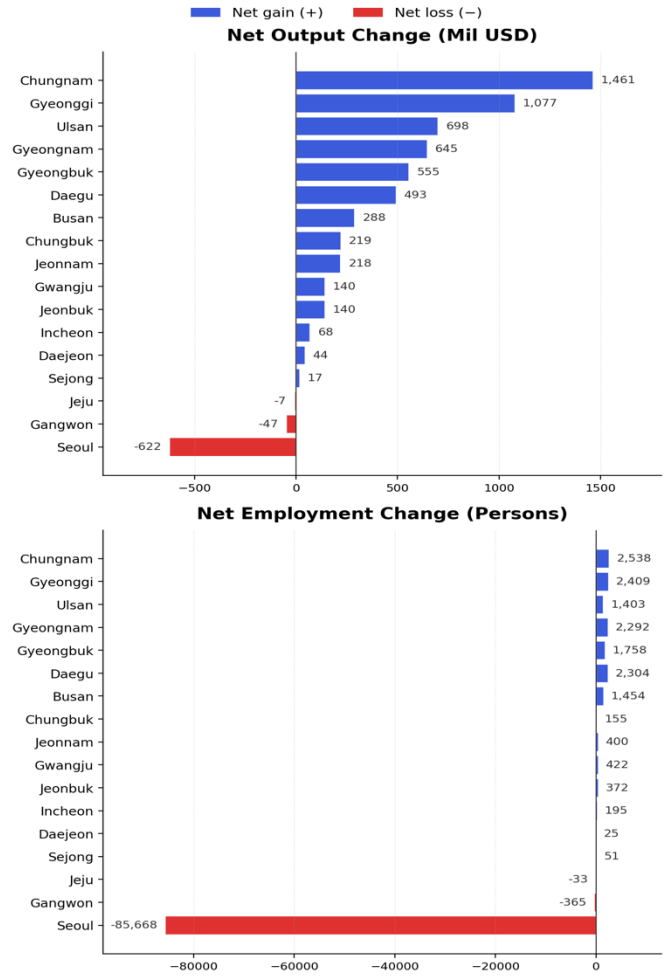
Summary

- **Consistent Positive Output(Nation-wide):** Net-positive (+) economic impact every year without exception, totaling +$5.39 billion in induced economic growth.
- **Employment Trade-off**: Despite the output gain, net employment falls by **–70,284 person** negative in every year. Output-maximizing reallocation does not translate into job creation.

Part 5

Results

Spatial Decomposition of the Optimized Reallocation



[Regional Decomposition of the Optimized Reallocation Effects (2025–2045)]

Summary

- **National Catalyst**: Almost the entire net output gain (+6,009 Mil USD) accrues outside Seoul, while Seoul itself records a net decline (–622
- **Manufacturing Belt Gains**: The largest output gains go to manufacturing regions — Chungnam (+1,461), Gyeonggi (+1,077), Ulsan (+698), and Gyeongnam (+645).
- **Spatial Employment Trade-off**: The employment loss concentrates in Seoul (–85,668 persons) while other regions gain (+15,382), as defunded labor-intensive services are local to Seoul.

Part 5

Results

Budget Reallocation Optimization Results and Policy Implications

Net-Positive, but Uneven

- Net output positive every year (+$5.39B) but concentrated outside Seoul (+6,009 vs Seoul −622).
- Employment falls (−70,284), mostly in Seoul

Peak Budget Cut Rate of 31.1% (2026)

- High target threshold required in the peak investment year.
- Potential risk to public service provisioning.

Policy Implications

Climate Policy as a National Growth Driver

- The urban energy transition is not a fiscal burden but a net-positive mechanism (+$5.39B), stimulating national growth.
- Yet gains accrue mostly outside Seoul, while the city bears the net decline and job loss — calling for employment-aware prioritization and inter-regional cost-sharing.

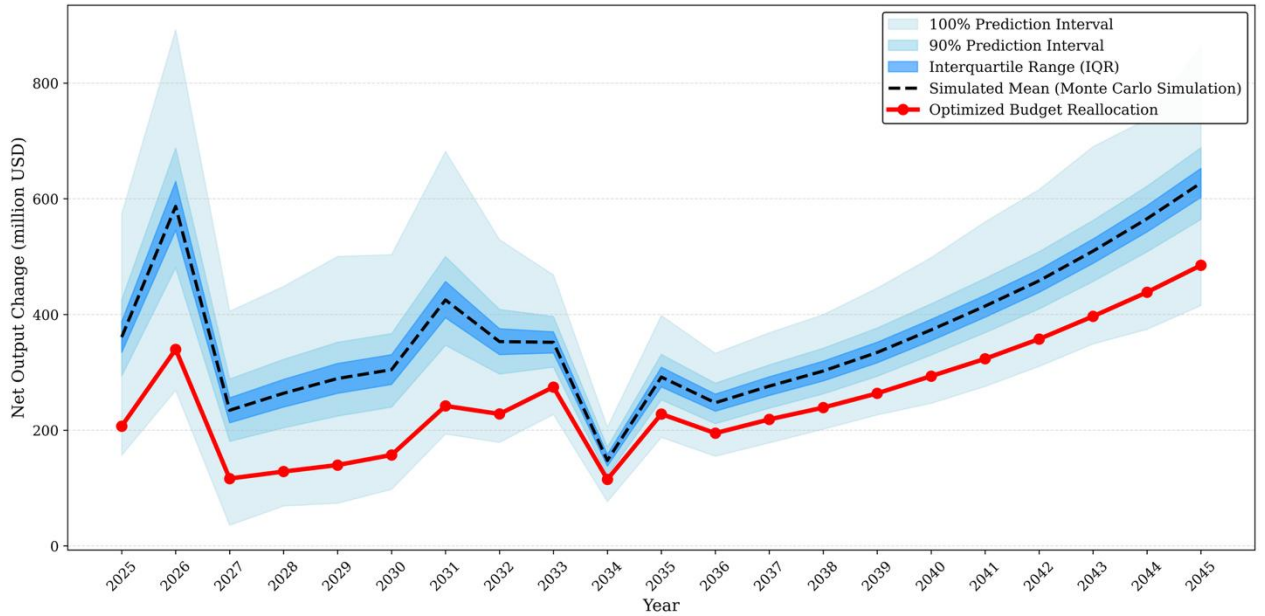
Administrative Safeguards

- Enforce sector-specific budget cut caps to ensure administrative stability and protect essential public services.

Part 5

Results

Monte Carlo Simulation via Random Reallocation



[Comparison of Budget Optimization Results (2025–2045): Unconstrained vs. Constrained Simulation]

Summary

- **Consistent Net-Positive Effects:** Executing 1M random budget reallocation scenarios annually yielded net-positive (+) economic benefits without a single exception.
  (Multiplier effect of Seoul's green investments > Opportunity cost of random cuts)
- **Model Trajectory:** The trajectory of the proposed constrained optimization model (red solid line) is positioned slightly below the mean of the unconstrained random simulation (black dotted line).

Part 5

Results

Monte Carlo Simulation via Random Reallocation

Constrained vs. Unconstrained

- The optimized trajectory (red line) is positioned slightly below the unconstrained random mean.

Consistent Net-Positive Effects

- Verified stable net-positive outcomes across 100M random simulations.

Policy Implications

Resolving Trade-offs

- **Quantitatively illustrates** the inherent trade-off between maximizing macroeconomic spillovers and adhering to strict administrative constraints.
- Resolves this conflict by integrating real-world policy limitations directly into the model.

Ex-ante Evaluation Framework

- Establishes a methodological baseline for quantitatively verifying economic impacts.
- Enables proactive evaluation under varying policy parameters, such as adjustable upper bounds and protected sectors.

Part 6

Conclusion

Key Findings and Policy Implications

- Green Investment as a National Catalyst
  - **National Spillover:** Almost the entire output gain accrues outside Seoul, driving manufacturing growth in regional hubs (Chungnam, Gyeonggi, Ulsan), while Seoul itself records a net decline.
  - **Output–Employment Trade-off**: Output rises (+$5.39B), but net employment falls (−70,284), as output-based ranking defunds labor-intensive services concentrated in Seoul.
- Net Positive Growth Under Fiscal Constraints
  - Achieves **$5.39 billion** in net macroeconomic benefits via budget reallocation, despite rigid municipal budget structures.
  - Demonstrates the urban energy transition is an effective growth strategy nationally, though the funding city bears the local cost.
- Imperative for Balanced Policy Design
  - **Beyond Output**: Sector prioritization should weigh employment-inducement alongside production, since output-only ranking erodes jobs.
  - **Safeguards & Cost-sharing**: Enforce sector-specific cut caps for administrative stability, and consider inter-regional cost-sharing to reflect national returns.

Part 6

Conclusion

Limitations and Future Works

- Limitations
  - **Static IO Constraints**: While macroeconomic structures (A-matrix) exhibit short-to-medium term rigidity (Cameron, 1952; Dietzenbacher & Hoen, 2006), the static Leontief model limits the reflection of long-term technological progress and price shifts (Carter, 1967 ; Dobrescu, 2013) (→ Requires advancement to a Dynamic IO model).
  - **Scope Limitations**: Excludes the qualitative aspects of employment and environmental impacts like GHG reduction (→ Requires integration with EEIO models).
  - **Data Assumptions**: Due to the lack of granular long-term budget data, the model relies on simplified sectoral allocation assumptions (e.g., equal 1:1:1 distribution).
- Future Works
  - **Multi-objective Optimization**: Jointly optimizing output and employment, rather than ranking on output inducement alone, to address the output–employment trade-off.
  - **Cross-City Comparative Analysis**: Evaluating how regional energy plans generate varying spillovers across municipalities with different industrial structures.
  - **Validating Seoul's Uniqueness**: Highlighting Seoul's distinct role as a service-oriented megacity, contrasting with traditional industrial cities.

THANK YOU

Jiwoo Shin, Hana Kim*

Jiwoo.shin77@kaist.ac.kr

Appendix

Literature Review

Literature Review: Urban Spatial Constraints and Policy Optimization

- Urban Level & Spatial Constraints: Megacities rely on external electricity, causing regional asymmetries where coastal areas bear environmental costs while industrial hubs absorb economic benefits (Jo et al., 2026; Jia et al., 2023; Sato & Narita, 2023). **Applying Multi-Regional Input-Output (MRIO)** models is essential to accurately capture these regional spillover effects (Zheng et al., 2019).
- Policy Optimization & Heuristic Allocation: **Multi Objective Linear Programming (MOLP)** is introduced to overcome traditional IO limits and endogenously resolve **trade offs** between economic and environmental goals using Pareto curves (Zhang et al., 2022; Pascual González et al., 2016; Lochot et al., 2024). However, to address operational realities and severe resource bottlenecks, literature successfully adopts **heuristic algorithms,** such as the **Adaptive Regional Input Output (ARIO)** framework (Hallegatte, 2008; Guan et al., 2020; Zhu et al., 2024).
- Fiscal Constraints & Opportunity Costs: Renewable infrastructure is highly capital-intensive, meaning capital scarcity can increase economy-wide capital prices and offset benefits (Bachner et al., 2019). Therefore, it is crucial to derive optimal configurations within strict budget limits to **avoid distorted fiscal policie**s (Dobkowitz, 2026; Prina et al., 2020).

Appendix

Methodology

Data Processing: Sector Matching for Energy Demand & Supply Projects

- Project items in the 6th Seoul Regional Energy Plan were matched with the 2020 Regional IO Table (83 sectors).
- The plan's budget is concentrated in buildings, transport, and energy supply sectors.
- Sectoral details were cross-checked with the Basic Plan for Carbon Neutrality and Green Growth (2024–2033).
- Projects without budget information were excluded from the analysis.

[Sector Matching Summary]

Category	# of Projects	IO Sector Codes	Main Matched Sectors
Buildings	15	37, 38, 45, 50, 62, 78	Electrical equipment, general machinery, construction services, ICT services, social services
Transport	18	40, 42, 51, 62, 78	Automobiles, transportation services, logistics, ICT services, public services
Energy	9	38, 45, 46	Electricity generation, gas supply, steam & air-conditioning supply

Appendix

Methodology

Data Processing: Sector Matching for Energy Demand & Supply Projects

No.	Sector	Unit Project	Major Classification	Detail Project	IO Industry Se	IO Industry Sector Name	Detail Plan (Description within Admin Card)	Final Demand Code	Final Demand Sector Name
1	Buildings	Existing Buildings	Public Building Green Remodeling	Vulnerable Group Facility BRP	38, 45, 50	General Purpose Machinery, Electric Power & Renewable Energy, Building Construction & Maintenance	Insulation reinforcement, replacement of windows, cooling/heating systems, etc. - aesthetic improvement, solar panel installation, etc.	9122	Government Fixed Capital Formation
2	Buildings	Existing Buildings		Seoul Public Building BRP	38, 45, 50	General Purpose Machinery, Electric Power & Renewable Energy, Building Construction & Maintenance	Improving energy performance by converting (city-owned buildings) to low-carbon buildings (Promoted as BRP for public buildings in the city)	9122	Government Fixed Capital Formation
3	Buildings	Existing Buildings	Public Rental Housing Green Remodeling	Eco-friendly Condensing Boiler	38	General Purpose Machinery		9122	Government Fixed Capital Formation
4	Buildings	Existing Buildings		High-efficiency LED	37	Other Electrical Equipment		9122	Government Fixed Capital Formation
5	Buildings	Existing Buildings	Private Building Energy Efficiency Project	Seoul BRP Loan	37, 38, 45, 50	Other Electrical Equipment, General Purpose Machinery, Electric Power & Renewable Energy, Building Construction & Maintenance	Architecture (insulation windows, insulation materials, etc.), Machinery (replacement with high-efficiency energy equipment certified products), Electrical (LED lighting, etc.), Renewable Energy	9121	Private Fixed Capital Formation
16	Buildings	Reduction Foundation	Establishing GHG Reduction Foundation	GHG Cap-and-Trade Energy Savings	62	Software Development & Supply, Other IT Services	Operating GHG Monitoring System	9112	Government Consumption Expenditure
17	Buildings	Civic Cooperation	Eco Mileage	Number of New Members	78	Social Welfare Services	Voluntary GHG reduction program that provides mileage for energy-saving activities such as electricity, water, and city gas used in buildings. Use of incentives: mobile gift certificates, cash conversion and tax payment (ETAX), donation, etc.	9112	Government Consumption Expenditure
19	Transportation	Eco-friendly Vehicle Dissemination	Mandatory Introduction of Zero-Emission Vehicles in Public Institutions	Public Electric Vehicle Dissemination	40	Automobiles		9122	Government Fixed Capital Formation
20	Transportation	Eco-friendly Vehicle Dissemination		Public Hydrogen Vehicle Dissemination	40	Automobiles		9122	Government Fixed Capital Formation
21	Transportation	Eco-friendly Vehicle Dissemination	Promotion of Electric Vehicle Dissemination	Electric Vehicle Dissemination	40	Automobiles	Purchase subsidies for electric vehicles and electric two-wheelers, inducing private voluntary purchases through infrastructure construction and price cuts, BSS facility installation, etc.	9121	Private Fixed Capital Formation

[Data Preprocessing Example]

Appendix

Methodology

Data Processing: Converting Budgets to 2020 Constant Prices

- All annual budgets (2025–2045) were converted to 2020 constant prices for consistency with the IO base year.
  - **Producer Price Index (PPI)** from the Bank of Korea (2015–2024, 10-year series) was used to calculate **sector-specific CAGR.**
  - Future PPI values (2025–2045) were projected using the calculated CAGR and applied to adjust budget values
  - Nominal budgets were converted into real 2020 prices using

    : $Real\ Budget = Nomital\ Budget \times \frac{PPI_{2020}}{PPI_t}$
  - For projects linked to multiple IO sectors, budgets were **evenly allocated** across related sectors (1:1:1).

[PPI-Based Adjustment Example]

Indicator	Sector	CAGR	2025	…	2035	…	2045
PPI	Automobiles	1.11%	108.5661	…	121.2855	…	135.4950

Appendix

Methodology

Data Processing: Converting Budgets to 2020 Constant Prices

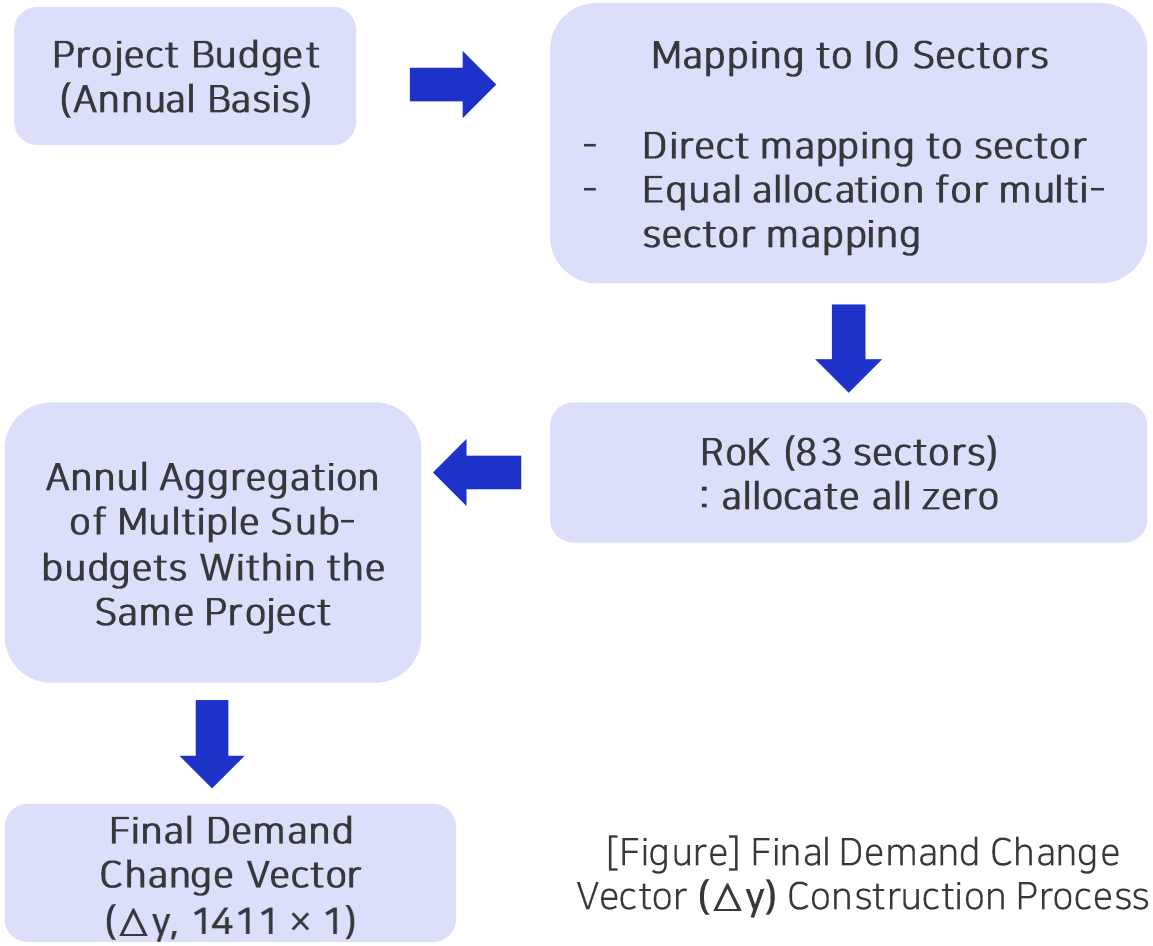
Carbon Neutrality Plan	Unit 1Milion KRW	~2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Eco-friendly Vehicle Dissemination	Other Electrical Equipment	37	121.042811	123.03798	125.066028	127.127507	129.222967	131.35297	133.51807	135.71887	137.95594	140.22989	142.541317	144.8908446	147.2790996	149.7067206	152.1743564	154.68267
	General Purpose Machinery	38	119.881078	121.84377	123.838597	125.866083	127.926763	130.02118	132.14989	134.31345	136.51243	138.74741	141.01898	143.3277428	145.6743049	148.0592849	150.4833119	152.94702
	Electric Power & Renewable Energy	45	117.039021	119.05208	121.099765	123.182669	125.301399	127.45657	129.64881	131.87876	134.14706	136.45438	138.801378	141.1887486	143.6171813	146.0873829	148.6000716	151.15598
	Building Construction & Maintenance	50	159.665387	166.26254	173.132285	180.285875	187.735042	195.492	203.56946	211.98067	220.73943	229.86008	239.357585	249.247514	259.5460817	270.2701723	281.4373677	293.06598
	Soft Development, Supply& Other IT Services	62	140.638185	148.58097	156.972343	165.83763	175.203601	185.09853	195.55229	206.59645	218.26435	230.59121	243.614251	257.3727918	271.9083705	287.2648714	303.4886576	320.62871
	Social Welfare Services	78	113.978851	116.07558	118.210871	120.385447	122.600026	124.85534	127.15215	129.49121	131.87329	134.2992	136.769733	139.2857128	141.8479761	144.4573741	147.1147739	149.82106
Green Remodeling		100	121.042811	123.03798	125.066028	127.127507	129.222967	131.35297	133.51807	135.71887	137.95594	140.22989	142.541317	144.8908446	147.2790996	149.7067206	152.1743564	154.68267
Vulnerable Group Facility BRP			55	60	61	61	67	70	70	70	70	100	100	100	100	100	100	100
	National Budget		8,250	9,000	9,150	9,150	10,050	10,500	10,500	10,500	10,500	15,800	15,800	15,800	15,800	15,800	15,800	15,800
	Municipal Budget		8,250	9,000	9,150	9,150	10,050	10,500	10,500	10,500	10,500	15,800	15,800	15,800	15,800	15,800	15,800	15,800
	Total Budget		16,500	18,000	18,300	18,300	20,100	21,000	21,000	21,000	21,000	31,600	31,600	31,600	31,600	31,600	31,600	31,600
	Distribution by participating Sector		5,500	6,000	6,100	6,100	6,700	7,000	7,000	7,000	7,000	10,533	10,533	10,533	10,533	10,533	10,533	10,533
Distribution by IO Industry Sector		38	4,699	5,040	5,037	4,952	5,347	5,492	5,399	5,308	5,218	7,719	7,589	7,460	7,334	7,210	7,088	6,969
		45	3,445	3,609	3,523	3,384	3,569	3,581	3,439	3,302	3,171	4,582	4,401	4,226	4,058	3,897	3,743	3,594
		50	3,911	4,038	3,886	3,678	3,824	3,782	3,580	3,388	3,207	4,568	4,324	4,093	3,874	3,667	3,471	3,285
Seoul Public Building BRP			280	280	280	300	300	300	300	300	300	100	100	100	100	100	100	100
	National Budget		5,600	5,600	5,600	6,000	6,000	6,000	6,000	6,000	6,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
	Municipal Budget		50,400	50,400	50,400	54,000	54,000	54,000	54,000	54,000	54,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000
	Total Budget		56,000	56,000	56,000	60,000	60,000	60,000	60,000	60,000	60,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
	Distribution by participating Sector		18,667	18,667	18,667	20,000	20,000	20,000	20,000	20,000	20,000	6,667	6,667	6,667	6,667	6,667	6,667	6,667
Distribution by IO Industry Sector		38	15,949	15,679	15,414	16,236	15,962	15,692	15,426	15,165	14,909	4,886	4,803	4,722	4,642	4,563	4,486	4,410
		45	11,691	11,227	10,782	11,093	10,653	10,231	9,825	9,435	9,060	2,900	2,785	2,675	2,569	2,467	2,369	2,275
		50	13,273	12,563	11,892	12,060	11,415	10,805	10,227	9,681	9,163	2,891	2,737	2,590	2,452	2,321	2,197	2,079

[Example: Converting Budgets to 2020 Constant Prices Using PPI]

Appendix

Methodology

Constructing the Final Demand Change Vector (Δy)



[Figure] Final Demand Change Vector (△y) Construction Process

- The final demand change vector Δy (1,411×1) was constructed based on 17 regions × 83 sectors.
- Δy was derived from project budgets in the Seoul Basic Plan for Carbon Neutrality and Green Growth (2024–2033).
- For each year (2025–2045), budgets were aggregated by IO sector and reflected in the vector.
- Δy is used as the input for estimating **output, value-added, and employment effects.**

Appendix

Methodology

Constructing the Final Demand Change Vector (Δy)

[Example of Δy Construction by IO Sector]

(Unit: Million KRW)

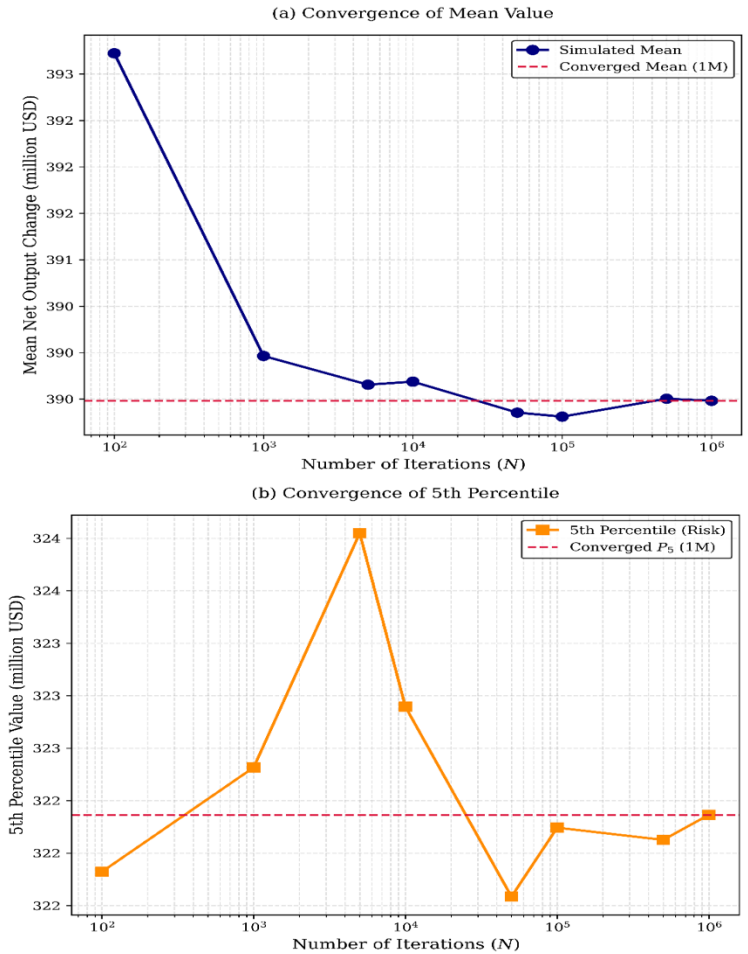
Year	Electrical equipment (37)	General Machinery (38)	Electricity Generation(45)	Construction Services (50)	ICT Servicis(62)	Social Services (78)	Total
2025	31,960	34,469	19,833	32,034	439	6,399	125,135
2026	18,630	32,332	19,347	30,658	431	6,705	108,104
2027	27,564	31,767	18,637	29,083	423	6,996	114,470
2028	28,853	33,335	18,637	29,237	415	7,272	117,750
2029	25,392	35,202	18,217	28,017	408	7,534	114,769
2030	29,824	32,017	17,648	26,681	400	7,822	114,393
…	…	…	…	…	…	…	…
2043	4,811	20,790	9,995	14,501	316	184	50,597
2044	4,733	20,439	9,598	13,901	310	181	49,162
2045	4,657	20,093	9,218	13,324	305	177	47,773

Note: Sector codes in parentheses correspond to the 2020 Input–Output Table classification

Appendix

Methodology

Monte Carlo Simulation via Random Reallocation



[Statistical Convergence of Monte Carlo Simulation by Iteration Count (N)]

Stochastic Algorithm

- **Uniform Dirichlet Distribution (α_i=1):** Applied to enforce **fiscal neutrality**. Setting the parameter to 1 ensures an unbiased, zero-sum budget reallocation without subjective policy weights.
- Statistical Convergence: Executed 1M iterations, confirming that both the mean and 5th percentile (downside risk) reach a stable equilibrium → further iterations only increase computational cost without improving convergence.

Appendix

Results

Why the Net Effect Is Always Positive

- **Structural coefficient gap**: Green investment flows into high-linkage sectors, whose injection coefficient exceeds that of the sectors being cut.
- **Budget-bounded withdrawal**: Each random cut is capped at a sector's existing budget. Small high-coefficient sectors are quickly exhausted, while large low-coefficient public sectors absorb most cuts, pushing the effective withdrawal coefficient even lower.
- **Condition, not general**: This result follows from the coefficient structure of Seoul's green investment. For policies whose investment targets carry coefficients comparable to or below the reduction pool, the same mechanism could yield neutral or negative effects.

	Injection (Green investment)	Reduction Pool (31 candidates)
Production-inducement coefficient	2.15 (investment-weighted)	1.85 (unweighted avg.)

The injection coefficient (2.15) exceeds the reduction-pool average (1.85), and budget-bounded cuts push the effective withdrawal coefficient even lower — keeping the net effect positive across all 1M iterations.

Appendix

Methodology

Comparison of Optimization Framework

Classification	Conventional MOLP Models	Proposed Optimization Model
Reference	(e.g., Pascual-González et al., 2016; Rojas Sánchez et al., 2019; De Carvalho et al., 2016; Lochot et al., 2024)	(This Study)
Primary Objective	**Exploring Pareto Optimal Pathways** - Minimizing emissions while maximizing GDP, employment, etc. - $minPx \quad s.t. \quad x \in S$	**Maximizing Net Economic Impact** - Evaluating the differential between green stimulus and opportunity costs under fiscal limits. - $\Delta X_{net,t} = L \cdot \Delta y_t$
Core Constraints	**Simple Demand Bounds** - Capping final demand by an arbitrary percentage (α) of original demand. - $S = \{\alpha y_0 \leq [I - A]x \leq y_0\}$	**Fiscal Neutrality (Zero-sum)** - $\sum_{j \in J_{cut}} \Delta y_{j,t} = -K_t$
Solution Method	**Mathematical Programming Solvers** - Solves simultaneous equations to find theoretical extreme points - e.g., CPLEX via GAMS, Bensolve, or TRIMAP	**Priority-based Heuristic Optimization Algorithm** - Combines priority allocation (via Leontief multipliers) with iterative Grid Search for threshold limits.
Policy Realism	**Unconstrained Financing** - Limits cuts in outputs via adjustment parameter α without modeling fiscal origins.	**Integrating Real-world Limitations** - Follows the Local Finance Act, internally reallocating resources.
Legends of Mathematical Notations	- P: Objective matrix / x: Variable total output vector / S :Feasible polyhedron set / α: Adjustment parameter for minimum demand / y_0: Original final demand	- $\Delta X_{net,t}$: Net economic impact at year t/ L: Leontief inverse / Δy_t: Net final demand change vector / J_{cut}: Set of candidate sectors for budget reductio/ K_t: Target investment

Appendix

Methodology

Comparison of Allocation Framework

Classification	Adaptive Regional Input Output (ARIO)	Proposed Optimization Model
Reference	(e.g., Hallegatte, 2008; Liu et al., 2019; Guan et al., 2020; Zhu et al., 2024)	(This Study)
Primary Objective	**Assessing Short-term Indirect Losses** - Evaluating indirect economic losses and propagation effects from exogenous negative shocks. - $PEI_{i,r} = TEI_{i,r} - DEI_{i,r}$ - $TEI_{i,r} = \overline{va_{i,r}} \times T - \sum_{t=1}^{T} va_{i,r}^{a}(t)$	**Maximizing Net Economic Impact** - Evaluating the differential between green stimulus and opportunity costs under fiscal limits. - $\Delta X_{net,t} = L \cdot \Delta y_t$
Core Constraints	**Multi-variate Supply Constraints** - Production capacity is bottlenecked by the scarcest resource, such as available labor or intermediate product inventories. - $x_i^{max}(t) = \min(x_i^L(t),\ for\ all\ p, x_i^p(t))$ - Actual production is constrained by total orders - $x_i^a(t) = \min(x_i^{max}(t), TD_i(t-1))$	**Fiscal Neutrality (Zero-sum)** - $\sum_{j \in J_{cut}} \Delta y_{j,t} = -K_t$
Behavioral Parameters	**Subjective Behavioral Calibration** - Requires extensive calibration of exogenous behavioral parameters - Includes parameters for overproduction (α^{max}, α^b, τ_a), adaptation times (τ), and price elasticities (ξ, γ_p)	**Empirical Data Driven** - Operates without subjective behavioral parameters. - Relies on empirical Leontief multipliers and predefined municipal budget limits.

Appendix

Methodology

Comparison of Allocation Framework

Classification	Adaptive Regional Input Output (ARIO)	Proposed Optimization Model
Solution Method	**Proportional Rationing Scheme** - Allocates insufficient products to clients in proportion to their orders when production is constrained by primary inputs. - Priorities may be given to intermediate consumptions over final demands.	**Priority-based Heuristic Optimization Algorithm** - Combines priority allocation (via Leontief multipliers) with iterative Grid Search for threshold limits.
Policy Realism	**Dynamic Post disaster Reality** - Models the short-term dynamics of sudden capital loss, labor shortages, inventory depletion, and sequential bottlenecks.	**Integrating Real-world Limitations** - Follows the Local Finance Act, internally reallocating resources.
Legends of Mathematical Notations	- PEI, TEI, DEI: Propagated, Total, and Direct economic impacts/ $\overline{va}$, va^a: Equilibrium and actual value-added/ x^{max}: Maximum supply capacity/ x^L, x^p: Labor and intermediate product constrained capacity/ TD: Total orders received/ α^{max}, τ, ξ: Behavioral parameters for overproduction, adaptation, and elasticity	- $\Delta X_{net,t}$: Net economic impact at year t/ L: Leontief inverse / Δy_t: Net final demand change vector / J_{cut}: Set of candidate sectors for budget reductio/ K_t: Target investment

* Note: The mathematical formulations of the ARIO framework presented here are primarily adopted from its advanced multi-regional applications (e.g., Guan et al., 2020; Zhu et al., 2024) to illustrate its core allocation mechanisms.