Assessment of Decarbonization Pathways of Japan

by

Sadami Suto

B.S. Physics, Tohoku University, 2014
M.S. Physics, Tohoku University, 2016

Submitted to the System Design and Management Program
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING AND MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2025

Authored by: Sadami Suto
MIT System Design and Management Program
May 9, 2025

Certified by: Sergey Paltsev
Deputy Director, MIT Center for Sustainability Science and Strategy
Senior Research Scientist, MIT Energy Initiative

Accepted by: Joan Rubin
Executive Director
MIT System Design and Management Program

Assessment of Decarbonization Pathways of Japan

by

Sadami Suto

Submitted to the System Design and Management Program
on May 9, 2025 in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING AND MANAGEMENT

ABSTRACT

Developing realistic pathways for decarbonization is crucial for the success of climate change mitigation actions. To evaluate Japan's pathways toward achieving carbon neutrality, this study enhances the MIT Economic Projection and Policy Analysis (EPPA) model and analyzes a suite of policy scenarios that combine domestic mitigation measures such as emissions targets from the updated Japan's Nationally Determined Contribution (NDC), power mix goals, and availability of carbon capture and storage (CCS) with international emissions trading. The impacts on CO_2 emissions, GDP, consumption, carbon prices, and sectoral output in Japan between 2030 and 2050 are assessed.

Under the baseline scenario, emissions over time remain flat at about 1,000 $MtCO_2e$, far exceeding the carbon neutrality goal. Even when Japan's 2030 and 2040 NDC for CO_2 and power mix targets are fully achieved, residual emissions of 100 – 200 $MtCO_2e$ remain, which calls for a need of carbon offsets. Relying on domestic-only measures is costly for Japan. In high-ambition domestic-only scenarios without CCS, carbon prices soar to over \$46,000/tCO_2 by 2050, leading to GDP losses exceeding \$1.5 trillion (23% of GDP) and significant contractions in key sectors of the economy.

In contrast, scenarios incorporating international emissions trading enable Japan to achieve comparable total emissions reductions by partially relying on imported carbon credits. This mechanism significantly lowers marginal abatement costs, allowing carbon prices to stabilize at \$20 –\$30/tCO_2 and reducing GDP losses to about \$100 billion (1.6% of GDP) by 2050.

Scenarios that emphasize domestic reductions while flexibly using international credits emerge as manageable pathways. These scenarios achieve domestic emissions reductions of 40 – 60% by 2050, with carbon prices ranging from \$140 to \$340/tCO_2 and GDP losses contained between \$150 and \$290 billion (2.3% and 4.3% of GDP). Importantly, these scenarios incorporate the deployment of CCS, which plays a critical role in reducing marginal costs and enabling deeper abatement in hard-to-decarbonize sectors. Most industrial sectors maintain stable output, while carbon-intensive sectors undergo gradual structural transitions.

Overall, these findings suggest that Japan can achieve carbon neutrality through an integrated strategy that combines strengthened domestic action, technological deployment, and international cooperation. This study provides a robust quantitative foundation for designing feasible, equitable, and cost-effective climate policies.

Thesis supervisor: Sergey Paltsev
Title: Deputy Director, MIT Center for Sustainability Science and Strategy
Senior Research Scientist, MIT Energy Initiative

Acknowledgments

I would like to express my deepest gratitude to my thesis advisor, Dr. Sergey Paltsev. This thesis would not have been possible without his exceptional guidance, insightful advice, and unwavering support. I am especially grateful for his deep expertise in energy-economic modeling and climate policy, as well as for his respect for my professional background and perspective as a policymaker. He encouraged me to integrate my practical experience into academic inquiry and helped me refine it into a rigorous analytical framework.

Throughout every stage of this research, Dr. Paltsev challenged my thinking while fully supporting my independence as a researcher. I am also sincerely thankful for his understanding of the real-world relevance of this study, particularly its potential application to Japan's energy and climate policymaking. His mentorship enabled me to explore the important connection between theory and practice with both confidence and clarity.

This thesis owes its completion to Dr. Paltsev's generous and dedicated mentorship, for which I am profoundly thankful.

I am deeply grateful to Dr. Yen-Heng Henry Chen of the MIT Joint Program for his generous and sustained support throughout this research. His extensive knowledge of the EPPA model and his clear, thoughtful advice guided me through countless challenges in scenario construction, model calibration, and results interpretation. His consistent support helped me build not only technical skills but also a broader understanding of energy-economic modeling and its policy applications.

Dr. Chen's mentorship exemplifies the collaborative and intellectually vibrant environment of the MIT Center for Sustainability Science and Strategy, which played a vital role in shaping this thesis. I am truly thankful for the time and expertise he devoted to my development as a researcher.

My sincere appreciation also goes to Dr. Jennifer Faye Morris for her generous support at the outset of this research. By providing a comprehensive set of EPPA training materials and guidance on how to approach the model, she played an important role in helping me build the foundational understanding necessary to engage with the analysis. Her contributions reflect the collaborative and inclusive spirit of the MIT Center for Sustainability Science and Strategy, which has provided an intellectually rich environment that made this research possible.

Contents

Acknowledgments **5**

List of Figures 9

List of Tables 11

1 Introduction: Challenges and Strategies for Japan's Decarbonization Pathways **13**

1.1 Research Background and Motivation 13

1.2 Research Objectives and Questions 14

1.3 Positioning and Contributions of This Study 15

1.4 Structure of This Thesis 16

2 Japan's Climate and Energy Policy Landscape: Mid-Term Targets, Strategic Planning, and Research Perspectives **19**

2.1 Japan's Current Climate Policy and Mid-Term Targets 19

2.2 Japan's Strategic Energy Policy and the 7th Strategic Energy Plan 21

2.3 Previous Studies on Japan's Net-Zero Strategy 23

3 Overview of the EPPA Model and Perspectives on Energy-Economic Modeling for Decarbonization Policy **25**

3.1 Structure and Applicability of the EPPA Model 25

3.2 Applications of the EPPA Model to Japan's Climate Policy Analysis 26

3.3 Scenario Design and Comparative Framework 26

3.4 Key Analytical Indicators 28

3.5 Analysis Items and Model Outputs 29

4 Overview of the Baseline Scenario **31**

4.1 Macroeconomic and Demographic Trends 31

4.2 Long-Term Outlook for GHG Emissions 33

4.3 Current Energy Structure and Future Outlook 33

4.4 Sectoral Output Trends 37

4.5 Carbon Price 39

5 Policy Scenarios Based on Domestic-Only Emissions Mitigation **41**

5.1 Policy Design and Scenario Overview 41

5.2 Changes in GHG Emissions 42

5.3 Energy Generation Structure and Low-Carbon Power Technologies 44
5.3.1 Deployment of Low-Carbon Power Technologies 48
5.4 Economic Impact Analysis 49
5.4.1 Trends in Real GDP under Mitigation Scenarios 49
5.4.2 Impact on Total Household Consumption 50
5.4.3 Cumulative Policy Cost Comparison 51
5.5 Sectoral Economic Impacts 53
5.5.1 Industrial Sectoral Economic Impacts 53
5.5.2 Energy-related Sectoral Economic Impacts 55
5.6 Carbon Prices 56
5.7 Limitations of Domestic-Only Measures and the Need for International Cooperation 59

6 Policy Scenarios with International Emissions Trading 61
6.1 Policy Design and Scenario Overview 61
6.2 Changes in GHG Emissions 62
6.3 Electricity Generation Structure 63
6.4 Economic Impact Analysis 67
6.5 Sectoral Economic Impacts 70
6.5.1 Industrial Sectoral Economic Impacts 70
6.5.2 Energy-related Sectoral Economic Impacts 72
6.6 Carbon Prices 73
6.7 Policy Implications of International Emissions Trading 75

7 Integrated Policy Scenarios 77
7.1 Policy Design and Scenario Overview 77
7.2 Changes in Greenhouse Gas Emissions 78
7.3 Energy Generation Structure 79
7.4 Economic Impacts (Limited Emissions Trade) 83
7.5 Sectoral Economic Impacts 86
7.5.1 Industrial Sectoral Economic Impacts 86
7.5.2 Energy-related Sectoral Economic Impacts 88
7.6 Carbon Prices 89
7.7 Summary 90

8 Conclusion 93
8.1 Research Objective and Analytical Framework 93
8.2 Feasibility of Energy Policies and Emissions Reduction Targets 94
8.3 Comparison of Economic and Industrial Impacts 95
8.4 The Role of International Cooperation and Credit Mechanisms 96
8.5 Policy Significance of Intermediate Reduction Strategies (Scenarios 5a and 5b) 97
8.6 Policy Implications 97
8.7 Future Work 98

References 101

List of Figures

2.1 Japan's GHG Emissions and Progress Toward NDC Targets 20

4.1 Trends in Japan's GDP and Consumption (2020 – 2050) 32
4.2 Trends in Japan's Population and GDP per Capita (2020 – 2050) 32
4.3 Japan's GHG Emissions in the Baseline Scenario 33
4.4 Trends in Primary Energy Supply (2020–2050, EJ) in the Baseline Scenario 34
4.5 Trends in Electricity Generation by Source (2020–2050, TWh) in the Baseline Scenario 35
4.6 Power Generation Mix in the Baseline Scenario (%) 36
4.7 Sectoral Output Indices under the Baseline Scenario (2025 = 1) 38
4.8 Sectoral Output Indices under the Baseline Scenario (2025 = 1) 39
4.9 Carbon Price in the Baseline Scenario (US$/t$CO_2$) 40

5.1 Trends in GHG Emissions by Scenario (2020 – 2050, MtCO_2e) 43
5.2 Power Generation Mix by Scenario in 2030 (%) 45
5.3 Power Generation Mix by Scenario in 2040 (%) 45
5.4 Power Generation Mix by Scenario in 2050 (%) 46
5.5 Electricity Generation by Source in 2030 (TWh) 46
5.6 Electricity Generation by Source in 2040 (TWh) 47
5.7 Electricity Generation by Source in 2050 (TWh) 47
5.8 Real GDP Trajectory under Each Policy Scenario (Billion US$ of 2015) . . . 50
5.9 Trajectory of Consumption Expenditure under Each Policy Scenario (Billion US$ of 2015) 51
5.10 Policy Costs under Each Scenario (2030 – 2050) (Billion US$ of 2015) 52
5.11 Policy Costs under Each Scenario (2030 – 2050) (%GDP) 52
5.12 Sectoral Output Index (2025 = 1) across Industrial and Service Sectors . . . 55
5.13 Sectoral Output Index (2025 = 1) in Energy-related Sectors 56
5.14 Trajectory of Carbon Prices in Different Scenario (US$/t$CO_2$) 58

6.1 GHG Emissions Trajectory under Scenarios with International Trading (MtCO_2e) 62
6.2 Power Generation Mix by Scenario in 2030 (%) 64
6.3 Power Generation Mix by Scenario in 2040 (%) 65
6.4 Power Generation Mix by Scenario in 2050 (%) 65
6.5 Electricity Generation by Source in 2030 (TWh) 66
6.6 Electricity Generation by Source in 2040 (TWh) 66

6.7 Electricity Generation by Source in 2050 (TWh) 67
6.8 Real GDP (Billion US$ of 2015) 68
6.9 Real Household Consumption (Billion US$ of 2015) 69
6.10 Policy Cost (2030 – 2050) (Billion US$ of 2015) 69
6.11 Policy Cost (2030 – 2050) (%GDP) 70
6.12 Sectoral Output Index (2025 = 1) across Industrial and Service Sectors . . . 72
6.13 Sectoral Output Index (2025 = 1) in Energy-related Sectors 73
6.14 Carbon Price With International Emissions Trading (US$/t$CO_2$) 74
6.15 Carbon Price Without International Emissions Trading (US$/t$CO_2$) *(Reproduced from Chapter 5)* 75

7.1 CO_2 Emissions Trajectory in Scenarios 5a and 5b 79
7.2 Power Generation Mix by Scenario in 2030 (%) 80
7.3 Power Generation Mix by Scenario in 2040 (%) 81
7.4 Power Generation Mix by Scenario in 2050 (%) 81
7.5 Electricity Generation by Source in 2030 (TWh) 82
7.6 Electricity Generation by Source in 2040 (TWh) 82
7.7 Electricity Generation by Source in 2050 (TWh) 83
7.8 Real GDP (Billion US$ of 2015) 84
7.9 Real Consumption (Billion US$ of 2015) 84
7.10 Policy Cost (2030 – 2050) (Billion US$ of 2015) 85
7.11 Policy Cost (2030 – 2050) (%GDP) 86
7.12 Sectoral Output Index (2025 = 1) across Industrial and Service Sectors . . . 88
7.13 Sectoral Output Index (2025 = 1) in Energy-related Sectors 89
7.14 Carbon Price Trends in Scenarios 5a and 5b (US$/t$CO_2$) 90

List of Tables

3.1 Integrated Summary of Scenario Assumptions 28
3.2 Analysis Items and Corresponding EPPA Outputs 30

4.1 Japan's Macroeconomic Indicators in the Baseline Scenario 32
4.2 Japan's GHG Emissions in the Baseline Scenario ($MtCO_2e$) 34
4.3 Primary Energy Use by Source (2025–2050, EJ) in the Baseline Scenario . . 35
4.4 Electricity Production by Source (2025–2050, TWh) in the Baseline Scenario 36
4.5 Sectors Analyzed and Output in 2025 (10 billion US$) 37
4.6 Primary Energy Inputs and Electricity Generation in 2025 38

5.1 GHG Reduction Targets (NDCs) 42
5.2 Power Generation Mix Targets 42
5.3 Composition of Policy Scenarios 42
5.4 Cumulative GHG Emissions (2030–2050, $MtCO_2e$) 43
5.5 Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050) . 53
5.6 Carbon Prices in Different Scenario (US$/$tCO_2$) 57

6.1 Composition of International Emissions Trading Scenarios (2A – 4B) 61
6.2 Cumulative GHG Emissions (2030–2050, $MtCO_2e$) 63
6.3 Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050) . 70

7.1 Composition of Intermediate Domestic Mitigation Scenarios (5a – 5b) 78
7.2 Cumulative GHG Emissions (2030–2050, $MtCO_2e$) 79
7.3 Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050) . 85

Chapter 1

Introduction: Challenges and Strategies for Japan's Decarbonization Pathways

1.1 Research Background and Motivation

Climate change poses a long-term threat to both the sustainability of human society and the stability of the global economy. In response, countries around the world are rapidly developing decarbonization strategies. Among these efforts, achieving the 1.5°C target under the Paris Agreement requires net-zero greenhouse gas (GHG) emissions by the end of the century (and CO_2-only net-zero emissions by around 2050), necessitating comprehensive transformations in industrial structure, energy systems, and regulatory frameworks.

In 2020, the Japanese government officially announced its commitment to achieving carbon neutrality by 2050 [1]. This involves major shifts in the country's energy supply mix, the decarbonization of industrial sectors, and systemic regulatory reforms. However, there are growing concerns that the continuation of existing policies alone will be insufficient to meet the long-term target [2, 3]. Several structural constraints contribute to this challenge. First, Japan's energy supply remains heavily dependent on fossil fuels, which account for nearly 80% of its primary energy [4]. Although renewable energy deployment is expanding, its growth is hindered by land use and cost limitations, limited grid flexibility, and the intermittency of power generation. Second, a significant portion of Japan's economy depends on energy-intensive sectors, particularly manufacturing and heavy industry. In these sectors, achieving emissions reductions often involves difficult trade-offs with maintaining economic performance.

Due to its resource constraints and energy-intensive industrial structure, Japan often faces challenges in identifying policy combinations that are both effective and feasible under its specific conditions. While short-term compliance with the Nationally Determined Contribution (NDC) targets is a necessary step, it does not ensure sustained emissions reductions over the long term. Recent international assessments emphasize that achieving deep decarbonization requires a broader, multi-dimensional policy approach—one that integrates power sector reform, deployment of emerging technologies such as carbon capture and storage (CCS), and strategic participation in international carbon markets [3, 5]. These integrated policy packages are shown to generate greater mitigation impact when designed with attention to complementarities and trade-offs among instruments, and when tailored to national contexts.

Nevertheless, the actual environmental outcomes, economic burdens, and institutional feasibility of such integrated policy configurations remain underexplored in quantitative terms. In particular, for countries like Japan, where physical and structural constraints are pronounced, conventional policy evaluation methods may fall short in accurately assessing the effectiveness and trade-offs of different decarbonization strategies.

This study begins from this recognition and aims to identify policy configurations that balance environmental integrity, economic feasibility, and institutional realism. Specifically, it develops and analyzes multiple carbon neutrality policy scenarios to evaluate their impacts on GHG emissions, macroeconomic indicators, and industrial structure. The overarching goal is to present empirically grounded insights into which combinations of measures may offer Japan the most viable pathways to achieving its long-term climate objectives.

1.2 Research Objectives and Questions

Building on the issues and analytical gaps outlined in the previous section, the objective of this study is to identify a set of feasible and economically efficient policy combinations that can enable Japan to achieve its carbon neutrality target. It aims to quantitatively assess the environmental, economic, and industrial impacts of such configurations. Specifically, the study examines a wide array of policy instruments—such as the expansion of renewable energy, the phase-out of fossil fuel dependence, the implementation of carbon pricing mechanisms, the deployment of carbon capture and storage (CCS) technologies, and the use of international emissions trading schemes—within the context of Japan's unique structural constraints, to explore realistic and effective decarbonization pathways.

To achieve this goal, the study enhances the Economic Projection and Policy Analysis (EPPA) model developed by the Massachusetts Institute of Technology (MIT) Center for Sustainability Science and Strategy (CS3). The EPPA model is a multi-region multi-sector energy-economic-environmental dynamic model of the world economy, where Japan is represented as one of the model regions of the world. The model is adjusted to reflect the updated data for Japan and used for conducting long-term, multi-dimensional scenario analysis. The analysis is carried out from the following three perspectives:

- **(1) Evaluation of Integrated Policy Scenarios:**
  Multiple scenarios are constructed by combining core policy elements—such as Nationally Determined Contributions (NDCs), power generation mix targets, CCS deployment, and the use of international credits. Each scenario is evaluated in terms of its GHG reduction potential and its technical and institutional feasibility.

- **(2) Quantitative Assessment of Economic and Industrial Impacts:**
  The study analyzes the macroeconomic impacts of each scenario—on GDP, household consumption, and carbon prices—as well as structural changes in sectoral production. The compatibility between decarbonization and economic stability is also examined.

- **(3) Japan's Role in the International Climate Policy Framework:**
  The study assesses the cost-saving potential of international emissions trading and identifies areas where Japan can exercise leadership in technology and institutional innovation. The geopolitical significance of Japan's contributions to global climate action is also considered.

Through this analysis, the study aims to answer the following key research questions:

- **Q1.** What combination of policies is most effective for Japan to achieve carbon neutrality by 2050?
- **Q2.** How do different policy scenarios affect Japan's economy and industrial structure?
- **Q3.** To what extent can international emissions trading reduce Japan's mitigation costs?
- **Q4.** In which domains can Japan demonstrate leadership in international climate policy?

1.3 Positioning and Contributions of This Study

This study contributes to the strategic design of Japan's decarbonization policies by quantitatively assessing alternative pathways that integrate environmental, economic, and energy-related dimensions. While existing studies in Japan have typically focused on individual sectors or technologies, comprehensive evaluations that explore the combined effects of multiple policy instruments remain limited.

In response, this study makes the following three contributions:

- **(1) Integrated Scenario Design for Practical Policy Packages:**
  By constructing policy scenarios that combine renewable energy expansion, fossil fuel phase-out, CCS deployment, and international carbon crediting, this study visualizes key trade-offs, complementarities, and synergies among instruments. The results provide actionable insights into realistic and effective policy combinations.
- **(2) Structural Impact Assessment on Economy and Industry:**
  Beyond macroeconomic indicators such as GDP and consumption, the analysis captures sectoral output dynamics, highlighting the resilience and vulnerabilities of energy-intensive industries and service sectors. This sheds light on the medium- to long-term transformation of Japan's industrial structure under different mitigation pathways.
- **(3) Quantitative Evaluation of International Market Participation:**
  Recognizing Japan's relatively high marginal abatement costs, the study assesses the economic efficiency gains from international emissions trading mechanisms, such as the Joint Crediting Mechanism (JCM) [6] and Article 6.2 of the Paris Agreement [7]. It also explores Japan's potential leadership role in global rule-making and climate diplomacy.

Methodologically, the study enhances the MIT Economic Projection and Policy Analysis (EPPA) model—a dynamic multi-region multi-sector computable general equilibrium (CGE) model [8]—to the latest energy and economic data and applies the model to policy scenarios tailored to Japan's institutional and energy context. This approach bridges globally recognized modeling techniques with Japan-specific policy challenges, offering a unique contribution to both domestic and international policy research.

1.4 Structure of This Thesis

This thesis investigates Japan's decarbonization pathways toward achieving carbon neutrality target through a scenario-based quantitative analysis that integrates economic, energy, and environmental dimensions. The analysis uses the EPPA model to evaluate trends in GHG emissions, macroeconomic indicators, electricity generation structure, and sectoral output across a range of policy scenarios.

The structure of the thesis is as follows:

- **Chapter 1: Introduction**
  Outlines the background, motivation, research objectives, analytical framework, and contributions of the study.
- **Chapter 2: Review of Japan's Climate and Energy Policy and Related Literature**
  Summarizes the evolution of Japan's climate and energy policy, including NDC targets and Basic Energy Plans, and reviews key findings and limitations of prior studies using energy-economic models.
- **Chapter 3: Model Overview and Scenario Design**
  Introduces the EPPA model, including its sectoral and regional coverage, calibration data, and modeling assumptions. It also details the design and classification of the policy scenarios used in the analysis.
- **Chapter 4: Baseline Scenario (1a)**
  Analyzes projected GHG emissions, economic growth, and energy supply composition under a baseline scenario that assumes no additional mitigation policies beyond those in place as of 2025.
- **Chapter 5: Domestic Mitigation Scenarios (2a – 4b)**
  Evaluates scenarios relying solely on domestic efforts, including renewable expansion and CCS deployment, and assesses their environmental, economic, and sectoral implications.
- **Chapter 6: Scenarios with International Emissions Trading (2A – 4B)**
  Investigates the cost-effectiveness and structural impacts of integrating international emissions credit mechanisms into domestic policy portfolios.
- **Chapter 7: Integrated Strategies (5a and 5b)**
  Explores balanced approaches that combine domestic mitigation with selective use

of international credits, assessing trade-offs between ambition, cost, and institutional feasibility.

- **Chapter 8: Conclusion**
  Synthesizes the key findings and provides policy recommendations related to Japan's long-term decarbonization strategy, with a focus on technological, economic, and diplomatic dimensions.

Chapter 2

Japan's Climate and Energy Policy Landscape: Mid-Term Targets, Strategic Planning, and Research Perspectives

2.1 Japan's Current Climate Policy and Mid-Term Targets

The Japanese government officially declared its commitment to achieving carbon neutrality by 2050 in October 2020, and subsequently formulated a long-term decarbonization strategy [1]. In line with this goal, Japan has progressively strengthened its mid-term GHG reduction targets. In April 2021, the 2030 NDC (Nationally Determined Contribution) target was raised significantly—from a 26% reduction from 2013 levels to a 46% reduction, with efforts to reach as high as 50%. Furthermore, in February 2025, new targets were added for FY2035 and FY2040, setting reductions of 60% and 73% from 2013 levels, respectively [9]. As shown in Figure 2.1, these milestones outline a linear trajectory toward the 2050 carbon neutrality goal.

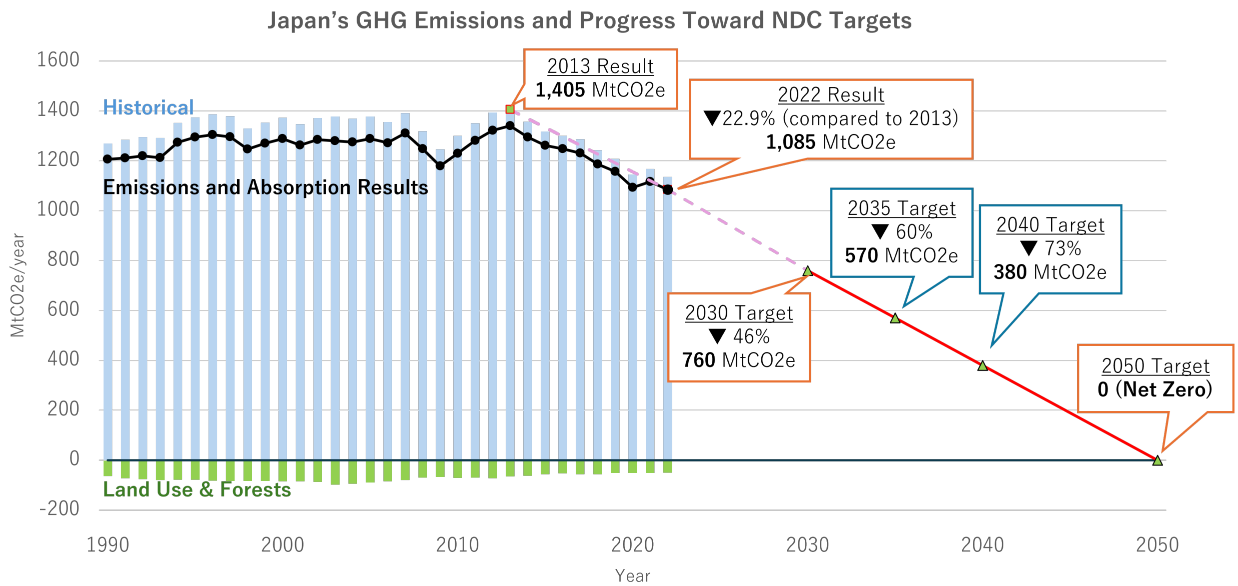


Figure 2.1: Japan's GHG Emissions and Progress Toward NDC Targets [10–12]

Aligned with these targets, Japan revised both its *Plan for Global Warming Countermeasures* and the *7th Strategic Energy Plan* in February 2025 [13]. The revised plans include comprehensive measures to meet the 2030 target, such as:

- Expansion of renewable energy and reinforcement of grid interconnections,
- Promotion of energy efficiency and electrification in industrial and transport sectors,
- Introduction of zero-emission fuels such as hydrogen and ammonia,
- Dissemination of next-generation vehicles (electric vehicles, EVs, and fuel-cell vehicles, FCVs),
- Use of forest carbon sinks and carbon removal technologies to curb net emissions.

In addition, the government emphasized the promotion of Green Transformation (GX) through public-private collaboration. In 2023, a GX Implementation Council presented a policy package aiming to mobilize 150 trillion yen in decarbonization investment over the next decade. This GX strategy also introduced institutional measures such as GX transition bonds and growth-oriented carbon pricing [14].

Despite these initiatives, international assessments suggest that current policies may only achieve a 31 – 37% reduction by 2030, falling short of the 46% NDC target [15]. To address this gap, Japan has pledged in international forums to significantly reduce coal-fired power generation by 2030 and achieve virtually zero emissions in the power sector by 2035 [16]. Achieving these goals will require enhanced institutional frameworks and accelerated implementation, including mobilizing private investment, reforming regulations, and strengthening local-level initiatives.

2.2 Japan's Strategic Energy Policy and the 7th Strategic Energy Plan

Japan's energy policy is guided by the principle of "3E+S"—Energy Security, Economic Efficiency, Environmental Compatibility, and Safety. Under this framework, the government formulates the Strategic Energy Plan based on the Basic Act on Energy Policy.

The 7th Strategic Energy Plan, approved by the Cabinet in February 2025, was designed to address two pressing challenges simultaneously: accelerating decarbonization and enhancing energy security [17]. In the context of rising global energy supply risks and price volatility, the plan emphasizes the establishment of a sustainable and stable energy supply system.

Aligned with the newly established GHG reduction target of 73% below FY2013 levels by FY2040, the plan calls for a fundamental transformation of the energy supply-demand structure. A core component is the accelerated decarbonization of the power sector, with a renewed commitment to treating renewable energy as a "main power source." Notably, the policy on nuclear energy has shifted from "minimizing dependence" to "maximizing utilization." This includes extending the operational lifespan of existing nuclear reactors from 40 to up to 60 years, and promoting the development and construction of next-generation advanced reactors [17].

For FY2030, the targeted power mix remains at 36–38% renewables, 20–22% nuclear, and 41% fossil fuels. By FY2040, the projected mix transitions to 40–50% renewables, around 20% nuclear, and 30–40% fossil fuels, thereby raising the energy self-sufficiency ratio from just over 15% in FY2023 to approximately 30–40% in FY2040 [17].

Despite the stated aim of phasing out inefficient coal-fired power, fossil fuel generation is expected to remain in 2040. This ongoing reliance is considered a key challenge from the perspective of full decarbonization.

Overall, the 7th Strategic Energy Plan presents a vision of securing a diverse and stable energy supply while advancing the energy transition. Its realization requires steady progress on multiple fronts, including:

- Expanding and digitizing transmission infrastructure,
- Deploying large-scale battery storage and flexibility markets,
- Advancing decarbonization technologies such as CCS and ammonia co-firing.

Renewable Energy Expansion

To support the large-scale integration of variable renewable sources such as solar and wind, Japan is transitioning from feed-in tariffs (FIT) to auction systems and feed-in premiums. Measures include grid enhancement, interregional transmission reinforcement, and battery deployment subsidies [17]. Innovation initiatives toward next-generation solar cells and floating offshore wind are also emphasized.

Challenges include land acquisition, local acceptance, grid connection queues, output curtailment, and variability-related balancing. The government aims to address these through digitalized grid infrastructure and a well-functioning flexibility market, aiming for both a higher renewable share and stable electricity supply.

Nuclear Energy Policy

Following the Fukushima Daiichi nuclear accident (2011), Japan's nuclear policy has emphasized safety and public understanding. The 7th Plan designates nuclear as both a "decarbonized and stable power source." While continuing to reduce dependency where possible, the government now promotes proactive utilization [17].

Specific measures include legal revisions to allow operations beyond 60 years if safety requirements are met, and potential replacement of aging reactors with advanced designs. In 2023, the government submitted a bill to amend the Reactor Regulation Act to change operational lifespan rules, aiming to sustain nuclear share at around 20% into the 2030s. However, challenges remain regarding safety of aging reactors, disposal of high-level radioactive waste, and rebuilding public trust.

CCS Policy and Roadmap

Carbon Capture and Storage (CCS) is regarded as essential for hard-to-abate sectors. According to METI's CCS Roadmap (September 2023), Japan aims to launch domestic CCS projects by 2030 and scale up to 120–240 million tons of CO_2 ($MtCO_2$) annually by 2050 [18]. To meet this goal, the government is preparing the necessary business environment by 2030, including:

- Technology development and demonstration to reduce costs,
- Infrastructure development for CO_2 transport,
- Geological surveys for storage capacity,
- Community engagement and legal framework development,

These efforts aim to pave the way for commercial full-scale private-sector deployment in the 2030s.

International Carbon Market Engagement

Japan actively promotes international carbon credit mechanisms. Since 2013, Japan has implemented the Joint Crediting Mechanism (JCM) with developing countries—mainly in Asia—sharing emission reductions as bilateral credits [6]. JCM credits can be counted toward Japan's NDC targets.

Moreover, Japan is deeply involved in shaping rules for new international mechanisms under Article 6 of the Paris Agreement, including both cooperative approaches (6.2) and the global market mechanism (6.4) [7]. Japan is expected to continue combining domestic decarbonization with international cooperation to enhance both its own reductions and global contributions.

2.3 Previous Studies on Japan's Net-Zero Strategy

In parallel with the formulation of long-term climate policy goals, numerous academic studies have analyzed Japan's decarbonization strategies and its target of net-zero emissions by 2050.

One prominent example is the study by Silva Herran and Fujimori [19], which employs a Computable General Equilibrium (CGE) model to assess the impacts of strengthened 2040 and 2050 emission reduction targets on Japan's energy supply and macroeconomic structure. Their analysis simulates an ambitious scenario—assuming net-zero emissions by 2050 and a 63% reduction (relative to 2005 levels) by 2040—and compares energy system transitions and economic outcomes against a reference pathway in which emissions decline at a constant annual rate from 2030 to 2050 to meet the 80% reduction target. The results indicate a substantial increase in the share of low-carbon energy sources in primary energy supply by 2040 and a rapid decline in CO_2 intensity per unit of energy demand. However, the macroeconomic cost—measured in terms of reduced consumption—was found to be 19% to 72% higher compared to the reference scenario, which assumes a linear reduction pathway from 2030 to 2050. The authors conclude that while such costs could be mitigated by technological progress and participation in international carbon markets, achieving more ambitious targets would necessitate an unprecedented rate of structural transformation in Japan's energy system.

Another important contribution is by Oshiro and Fujimori [20], who conduct a comprehensive scenario analysis of net-zero pathways for Japan by 2050. Using Japan's energy system model (AIM/Technology-Mix), they incorporate assumptions about international hydrogen fuel trade and carbon credit pricing. Their findings highlight that, across all scenarios, two key elements are essential: a deep electrification shift on the demand side and the removal of approximately 100 $MtCO_2$ annually through carbon dioxide removal (CDR) technologies such as forest sinks and Direct Air Capture (DAC). This level of removal corresponds to roughly 10% of Japan's current GHG emissions.

The study also finds that Japan may reduce its reliance on CDR if it prioritizes domestic hydrogen production, synthetic fuels, and energy conservation. In contrast, scenarios that depend heavily on imported hydrogen and carbon credits result in over 50% of energy supply being imported, with associated annual import costs surpassing those of current fossil fuel imports. These findings underscore the sharp divergence in energy security outcomes depending on the choice between domestic resource utilization and international dependence. The authors stress the importance of developing national strategies that consider global energy market dynamics. Japan's net-zero strategy, they argue, cannot rely solely on domestic actions; rather, it must integrate energy trade (e.g., hydrogen and ammonia) and international carbon market mechanisms, along with risk assessments related to supply diversification and price volatility.

These studies provide important insights into Japan's potential pathways to net-zero emissions by 2050, emphasizing the roles of electrification, carbon dioxide removal (CDR), and hydrogen-related technologies. However, many prior studies on Japan's climate strategy rely on national-scale models or scenario frameworks that simplify global interdependencies —such as energy trade, international carbon markets, and macroeconomic spillovers—and do not fully capture the implications of international emissions trading or cross-border linkages.

A key contribution of this study is the use of the EPPA model to address these limitations.

The EPPA model enables explicit representation of international emissions credit markets, sectoral interactions, and global feedback mechanisms. By situating Japan's decarbonization scenarios within this international framework, the study provides a more comprehensive and dynamic evaluation of the feasibility, economic impacts, and trade-offs of alternative climate policy options. The following chapter introduces the EPPA model and explains its relevance to the scenario analysis conducted in this thesis.

Chapter 3

Overview of the EPPA Model and Perspectives on Energy-Economic Modeling for Decarbonization Policy

3.1 Structure and Applicability of the EPPA Model

The Economic Projection and Policy Analysis (EPPA) model (version 7) is a global dynamic Computable General Equilibrium (CGE) model designed to analyze the interplay between economic, energy, and environmental systems. Built on the Global Trade Analysis Project (GTAP) database [21]—with extensions to incorporate detailed representation of the electric power sector through GTAP-Power (base year 2014)— the EPPA model provides an integrated platform for policy simulation and scenario evaluation [8].

EPPA adopts a recursive-dynamic structure, solving for a sequence of static global equilibria over time. Each model period updates economic conditions such as capital accumulation and labor force growth, enabling the generation of forward-looking trajectories. The model includes representative agents for households, firms, and governments across multiple regions, all interacting through markets for goods, services, and production factors [8]. A key innovation in EPPA is the explicit modeling of government consumption of energy for the production of public services—an element omitted in earlier versions where governments were treated solely as income-redistributing agents [8].

The energy sector is represented in high detail. Technologies for electricity generation —such as coal, gas, nuclear, oil, hydro, solar, wind, and transmission/distribution—are individually modeled. Fossil fuel power plants are distinguished by vintage (existing versus new), allowing the model to capture technological aging and investment dynamics [8]. Household consumption behavior is governed by heterogeneous preference structures that change with income, reflecting realistic Engel curve dynamics [8].

The EPPA is widely used to evaluate a variety of climate and energy policies, including carbon taxes, emissions trading systems, renewable energy mandates, and technology deployment strategies. It facilitates rigorous cost-benefit analysis and provides critical input for policymaking and international negotiations.

3.2 Applications of the EPPA Model to Japan's Climate Policy Analysis

Several studies have applied the EPPA model to evaluate climate policies specifically for Japan. For example, Kasahara et al. [22] used EPPA to assess the implementation of a carbon tax aimed at meeting Japan's Kyoto Protocol targets. Their study showed that allocating carbon tax revenues from fossil fuels to energy efficiency investments would not be sufficient to achieve the targets unless those investments yielded significantly greater improvements than the historical trend [22]. Furthermore, the analysis revealed that restricting access to international emissions trading would result in substantial economic losses (i.e., welfare declines) for Japan, whereas fully utilizing international carbon markets could significantly alleviate domestic carbon prices and mitigate adverse effects on export-oriented industries [22]. Specifically, the study reported that in scenarios where Japan made full use of emissions trading, both the domestic carbon price and welfare losses were reduced to roughly one-sixth of the levels observed in domestic-only mitigation cases [22]. These findings highlight that the use of international mechanisms is a critical factor influencing the cost of achieving Japan's climate targets.

While numerous studies have employed EPPA to analyze decarbonization policies, the majority focus on global-scale assessments or policy evaluations for countries other than Japan. Detailed scenario evaluations tailored specifically to Japan remain limited. This study contributes a novel approach by applying the latest version, EPPA7, to assess Japan's climate policy scenarios, particularly in the context of achieving its Nationally Determined Contribution (NDC) targets. Building upon insights from previous research—such as the role of technology options and the impact of international credit mechanisms—this study conducts scenario-based analysis that reflects Japan's unique economic structure and energy system. The aim is to comprehensively evaluate the effectiveness and trade-offs of domestic policy strategies.

3.3 Scenario Design and Comparative Framework

The simulation framework begins with the construction of a baseline scenario, which projects the economic and emissions pathway in the absence of additional climate policies. Subsequent policy scenarios are then specified and compared against the baseline. This scenario-based analysis allows for the comprehensive assessment of policy impacts on GDP, consumption, industrial structure, energy mix, emissions trajectories, and even land-use changes.

To evaluate Japan's decarbonization pathways toward 2050, I designed a comprehensive set of policy scenarios based on four key policy dimensions:

1. **Achievement of Nationally Determined Contributions (NDCs):** Alignment with Japan's CO_2 reduction targets for 2030, 2035, and 2040, as outlined in national policy documents.

2. **Attainment of Power Generation Mix Targets:** Implementation of the government' s targets for renewable and nuclear energy shares in 2030 and 2040.

3. **Deployment of Carbon Capture and Storage (CCS):** Integration of carbon capture technologies to enable reductions in sectors with limited abatement options after 2035.[1]

4. **Participation in International Emissions Trading:** Use of credit mechanisms and other global market structures.

Based on these axes, I developed the following scenario categories (see Table 3.1):

- **Baseline Scenario (1a):** Continuation of existing policies without further interventions.
- **Domestic-Only Scenarios (2a to 4b):** Varying levels of ambition in domestic policy without international credit mechanisms.
- **International Cooperation Scenarios (2A to 4B):** Same policy configurations as above, but with emissions trading enabled.
- **Integrated Mitigation Scenarios (5a and 5b):** Realistic reductions between full domestic mitigation and full trading, based on partial extensions of the 3b scenario.

Each scenario was evaluated along a consistent set of indicators.

This study focuses specifically on CO_2-only mitigation policies in order to systematically quantify the major trends, policy impacts, and trade-offs emerging from Japan's transition toward carbon neutrality.[2] In particular, the following indicators were analyzed:

- Total GHG emissions (net of land use),
- Electricity generation mix by technology,
- Macroeconomic impacts (real GDP and consumption),
- Sectoral output indices (e.g., energy-intensive industries, refineries, services),
- Implicit carbon prices.

This structure enables comparisons across scenarios with similar targets but different policy tools—for example, comparing Scenario 4a and 4b highlights the role of CCS, while comparing Scenario 3b and 3B reveals the impact of international emissions trading. In doing so, the framework supports a detailed examination of the trade-offs and synergies among various policy instruments.

[1] While Japan's official roadmap aims to begin domestic CCS deployment around 2030, this study assumes a more conservative implementation timeline starting in 2035, reflecting more realistic considerations regarding technology readiness, regulatory development, and infrastructure build-out.

[2] This focus on CO_2 is justified by its dominant share in Japan's total GHG emissions, as well as the availability of sectoral and policy-relevant data for CO_2-related mitigation measures. While non-CO_2 gases such as methane (CH_4) and nitrous oxide (N_2O) also contribute to climate change, their sources are often diffuse, sector-specific, and subject to different mitigation dynamics. Therefore, to maintain analytical clarity and policy relevance, this study restricts its quantitative analysis to CO_2-only pathways. Previous studies with the EPPA model showed that the major economic impacts are compatible with CO2-only and all-GHG targets.

Table 3.1: Integrated Summary of Scenario Assumptions

Scenario	NDC Targets	Net Zero	Power Mix Targets	CCS Deployment	International Trading
Baseline	×	×	×	×	×
2a (NDC Only)	✓	×	×	×	×
2b (NDC + CCS)	✓	×	×	✓	×
3a (NDC + Power Mix)	✓	×	✓	×	×
3b (NDC + Power Mix + CCS)	✓	×	✓	✓	×
4a (NDC + Net Zero + Power Mix)	✓	✓	✓	×	×
4b (NDC + Net Zero + Power Mix + CCS)	✓	✓	✓	✓	×
2A (NDC) with trade	✓	×	×	×	✓
2B (NDC + CCS) with trade	✓	×	×	✓	✓
3A (NDC + Power Mix) with trade	✓	×	✓	×	✓
3B (NDC + Power Mix + CCS) with trade	✓	×	✓	✓	✓
4A (NDC + Net Zero + Power Mix) with trade	✓	✓	✓	×	✓
4B (NDC + Net Zero + Power Mix + CCS) with trade	✓	✓	✓	✓	✓
5a with limited trade	✓ (60%)	×	✓	✓	×
5b with limited trade	✓ (80%)	×	✓	✓	×

3.4 Key Analytical Indicators

To evaluate the environmental and economic implications of each policy scenario, I employ a set of core quantitative indicators derived from the EPPA model. These indicators are selected to capture the multi-dimensional nature of the decarbonization challenge, including emissions, energy systems, macroeconomic performance, and sectoral transitions.

(1) Greenhouse Gas Emissions

- **Total GHG Emissions (MtCO_2e):** Includes CO_2, CH_4, N_2O, and F-gases, reported net of land use and land-use change.
- **Emissions Reduction (MtCO_2e):** Difference in emissions relative to the baseline scenario (1a).

(2) Power Sector Structure

- **Electricity Generation by Technology (TWh):** Annual electricity output from coal, gas, nuclear, solar, wind, biomass, hydro, and CCS-based generation.
- **Electricity Mix (%):** Share of each technology in total generation, highlighting system composition and decarbonization pathways.

(3) Macroeconomic Indicators

- **Real GDP (billion US$ of 2015):** Gross domestic product in constant 2015 dollars, measuring aggregate economic output.
- **Real Consumption (billion US$ of 2015):** Private consumption expenditures in real terms, indicating household-level economic welfare.
- **Policy Cost (absolute and % GDP):** GDP and consumption losses relative to the baseline scenario, expressed both in billions of US$ and as a percentage.

(4) Sectoral Output Indices

- **Sectoral Indices (2025 = 1.0):** Output indices for key sectors, including electricity (ELEC), refined oil (ROIL), energy-intensive industries (EINT), and services (SERV), allowing comparison of industrial dynamics across sectors and scenarios. A summary of the sectoral classifications and their corresponding indices is provided in Table 4.5.

(5) Carbon Pricing

- **Domestic carbon price (US$/t$CO_2$):** Implicit carbon price under domestic emission quota systems without international trading.

- • **International carbon price (US$/t$CO_2$):** Implied international carbon price under global emissions trading frameworks. If international trading in emissions is permitted, then Japan's carbon price equals to the international carbon price.

These indicators jointly enable a structured analysis of trade-offs between emissions reductions, technological feasibility, economic cost, and sectoral resilience under different policy architectures.

3.5 Analysis Items and Model Outputs

This study uses outputs from the EPPA7 model to assess the environmental, technological, macroeconomic, and sectoral implications of various decarbonization scenarios for Japan. The key analysis items and corresponding model outputs are summarized in Table 3.2.

Table 3.2: Analysis Items and Corresponding EPPA Outputs

Analysis Item	**EPPA Output or Derived Variable**
GHG emissions trajectory	Total GHG emissions net of land use change ($MtCO_2e$)
Emissions reduction from baseline	Difference from baseline scenario 1a ($MtCO_2e$)
Electricity generation structure	Annual electricity output by technology (TWh): coal, gas, nuclear, hydro, solar, wind, biomass, CCS
Power mix composition	Share of each technology in total generation (%)
Real GDP	Aggregate real GDP (billion US$ of 2015)
Real consumption	Aggregate real consumption (billion US$ of 2015)
Policy cost (absolute)	GDP and consumption loss relative to baseline (billion US$ of 2015)
Policy cost (relative)	GDP and consumption loss as percentage of baseline (%)
Sectoral structural change	Output index (2025 = 1.0) by sector: `EINT`, `ROIL`, `ELEC`, `SERV`, `OTHR`, `CROP`, `LIVE`, `FORS`, `NMM`
Carbon pricing (domestic)	Calculated carbon price under domestic carbon budget ($US\$/tCO_2$)
Carbon pricing (international)	Calculated international carbon price under global trading ($US\$/tCO_2$)

These outputs enable a consistent and policy-relevant comparison of scenarios across emissions, technology deployment, economic viability, and industrial transformation. The multi-dimensional structure of EPPA ensures internal consistency across sectors and policy mechanisms, facilitating robust evaluation of Japan's decarbonization pathways.

Chapter 4

Overview of the Baseline Scenario

4.1 Macroeconomic and Demographic Trends

This section outlines Japan's long-term macroeconomic trajectory under the Baseline scenario, focusing on GDP, household consumption, population dynamics, and GDP per capita between 2025 and 2050. As shown in Figure 4.1 and Table 4.1, Japan's real GDP is projected to grow from US$ 4.89 trillion in 2025 to US$ 6.60 trillion in 2050 (in 2015 dollars), corresponding to an average annual growth rate of approximately 1.2%. Growth is particularly stable during the 2030s, maintaining levels slightly above 1.3%. Personal consumption follows a similar trend, increasing from US$ 2.81 trillion to US$ 3.73 trillion over the same period. This stable growth is supported by rising income per capita despite population decline.

Japan's total population is expected to decline from 124 million in 2025 to 106 million in 2050. As a result, per capita GDP increases substantially, from US$ 39,473 to US$ 62,392, as shown in Figure 4.2. This demographic shift underscores the importance of labor productivity and structural reforms in sustaining economic growth.

These trends demonstrate that stable economic growth is possible under a no-additional-policy scenario. However, as discussed in later sections, this growth path fails to achieve substantial GHG reductions and remains heavily reliant on fossil fuels, emphasizing the need for proactive decarbonization strategies.

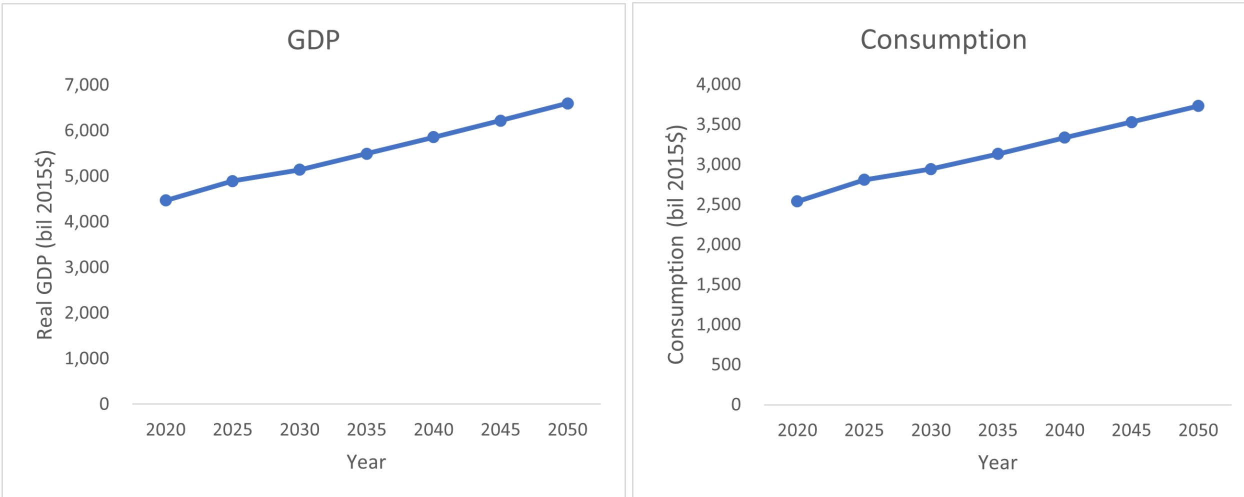


Figure 4.1: Trends in Japan's GDP and Consumption (2020 – 2050)

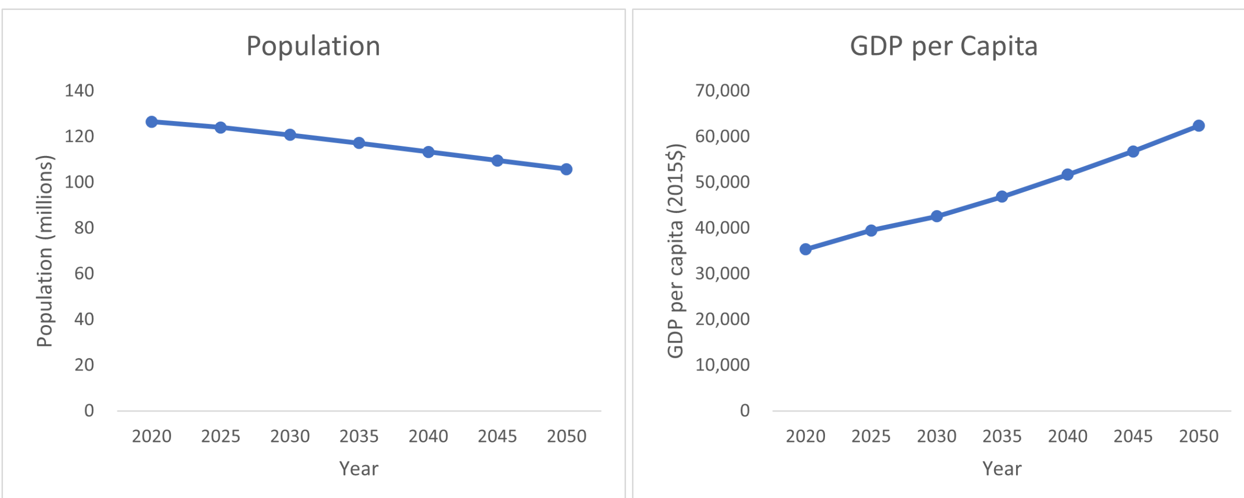


Figure 4.2: Trends in Japan's Population and GDP per Capita (2020 – 2050)

Table 4.1: Japan's Macroeconomic Indicators in the Baseline Scenario

Indicator	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
GDP (Billion US$ of 2015)	4 894	5 140	5 492	5 858	6 218	6 601
Consumption (Billion US$ of 2015)	2 810	2 946	3 133	3 337	3 529	3 731
GDP Growth (% / yr)	0.99	1.31	1.29	1.18	1.19	1.02
Population (millions)	124.0	120.8	117.2	113.4	109.5	105.8
GDP per Capita (US$ of 2015)	39,473	42,567	46,874	51,680	56,773	62,392

4.2 Long-Term Outlook for GHG Emissions

This section analyzes the trends and composition of GHG emissions in Japan from 2025 to 2050 under the Baseline scenario. As shown in Figure 4.3 and Table 4.2, total GHG emissions excluding land use are projected to decline only slightly from 1,188 $MtCO_2e$ in 2025 to 1,066 $MtCO_2e$ in 2050. This corresponds to a mere 10% reduction over 25 years, far from the scale needed to achieve the 2050 net-zero target.

The emissions breakdown indicates that fossil fuel-related CO_2 remains the dominant source, accounting for approximately 76% of total GHG emissions in 2025 and 84% in 2050. Emissions from industrial processes and non-CO_2 gases such as methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (PFCs, SF_6, and HFCs) contribute modestly but persistently. This composition shows little structural change through 2050.

In short, the Baseline scenario reveals a stagnation in emission reduction efforts. Without additional policies or technological transformations, Japan's GHG emissions remain effectively flat, reflecting the continued dominance of fossil energy in the overall system.

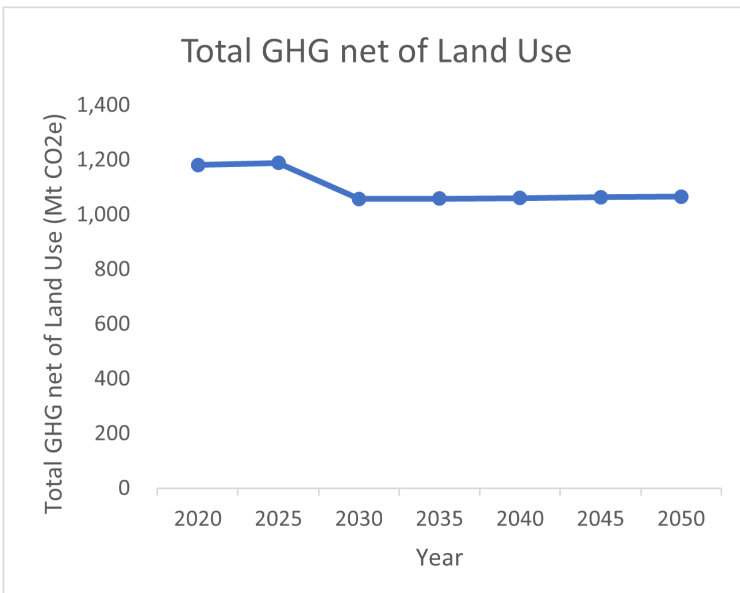


Figure 4.3: Japan's GHG Emissions in the Baseline Scenario

4.3 Current Energy Structure and Future Outlook

Japan remains heavily dependent on fossil fuel imports for its primary energy supply. Under the Baseline scenario, this structure exhibits limited change through 2050, with fossil fuels continuing to dominate the energy mix.

As shown in Figure 4.4 and Table 4.3, primary energy consumption in 2025 is mainly composed of oil (7.1 EJ), coal (4.3 EJ), and natural gas (3.7 EJ), together accounting for about 88% of the total. By 2050, despite a moderate increase in renewable energy which refers specifically to solar and wind power. (from 0.8 EJ in 2025 to 1.2 EJ in 2050), fossil fuels

Table 4.2: Japan's GHG Emissions in the Baseline Scenario ($MtCO_2e$)

Category	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CO_2 (fossil fuel combustion)	1028.5	900.6	900.6	900.6	900.6	900.6
CO_2 (industrial process)	68.4	70.2	73.2	76.2	78.9	81.7
CH_4	0.9	0.8	0.7	0.7	0.6	0.6
N_2O	0.1	0.1	0.1	0.1	0.1	0.1
PFCs (kt CF_4)	0.7	0.6	0.5	0.4	0.4	0.4
SF_6 (kt)	0.1	0.1	0.1	0.1	0.1	0.1
HFCs (kt HFC-134a)	34.7	33.3	34.0	34.9	36.4	37.8
Total GHG (net of land use)	**1188.4**	**1057.2**	**1058.7**	**1060.6**	**1063.1**	**1066.1**

still account for approximately 80% of total supply, indicating that Japan's energy supply structure remains largely carbon-intensive.

Hydropower and nuclear energy provide consistent contributions, with nuclear increasing modestly from 1.0 EJ in 2025 to 1.1 EJ in 2050. However, bioenergy and other renewables remain negligible throughout the period.

In this study, we refer to "bioenergy and other renewables" collectively as Bio/Other RE, which includes biomass, geothermal, and municipal waste-to-energy sources, excluding solar, wind, hydro, and nuclear. While this category is modeled, its contribution remains negligible in Japan throughout the projection period.

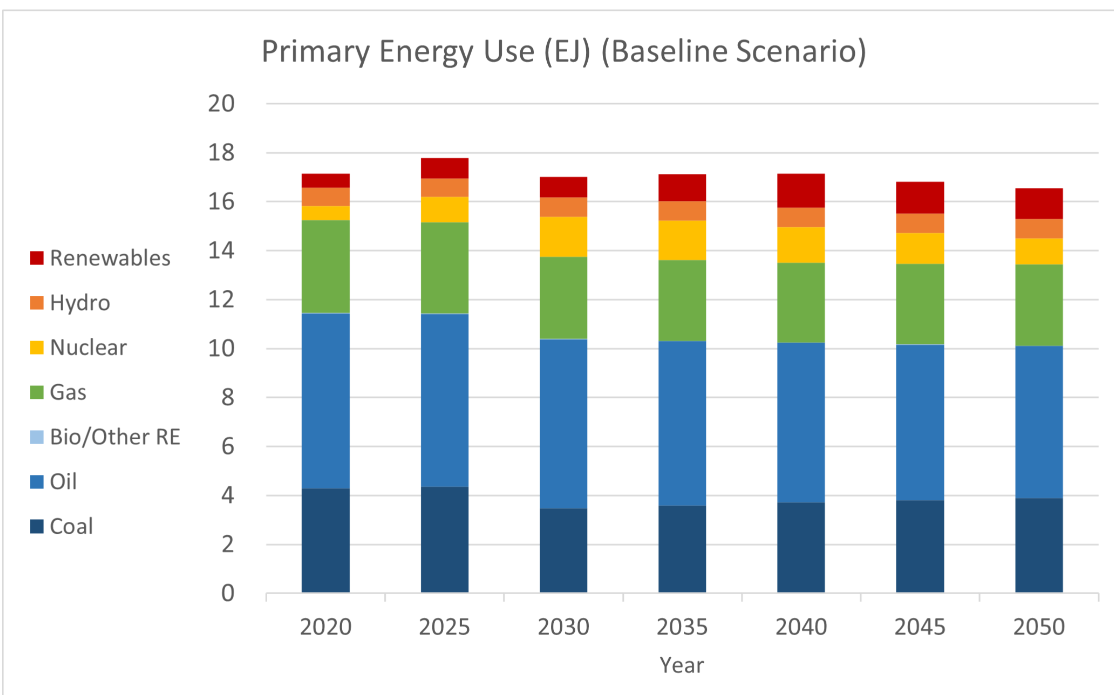


Figure 4.4: Trends in Primary Energy Supply (2020–2050, EJ) in the Baseline Scenario

Table 4.3: Primary Energy Use by Source (2025–2050, EJ) in the Baseline Scenario

Primary Energy Source	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	4.3	3.5	3.6	3.7	3.8	3.9
Oil	7.1	6.9	6.7	6.5	6.4	6.2
Natural Gas	3.7	3.4	3.3	3.3	3.3	3.3
Nuclear	1.0	1.6	1.6	1.5	1.3	1.1
Hydropower	0.8	0.8	0.8	0.8	0.8	0.8
Renewables (Solar/Wind)	0.8	0.9	1.1	1.4	1.3	1.2
Bio/Other RE	0.0	0.0	0.0	0.0	0.0	0.0

A similar pattern is observed in the power sector (Figure 4.5 and Table 4.4). While renewable electricity expands gradually, fossil fuel-based generation remains dominant. In 2025, coal, oil, and natural gas collectively generate about 655 TWh, accounting for roughly 56% of total electricity production. Even by 2050, fossil fuels continue to supply over 500 TWh, indicating persistent reliance.

Nuclear power increases from 118 TWh in 2025 to 131 TWh in 2050, while solar and wind generation rise from 80 TWh and 16 TWh to 121 TWh and 34 TWh, respectively. Hydropower remains stable at around 100 TWh.

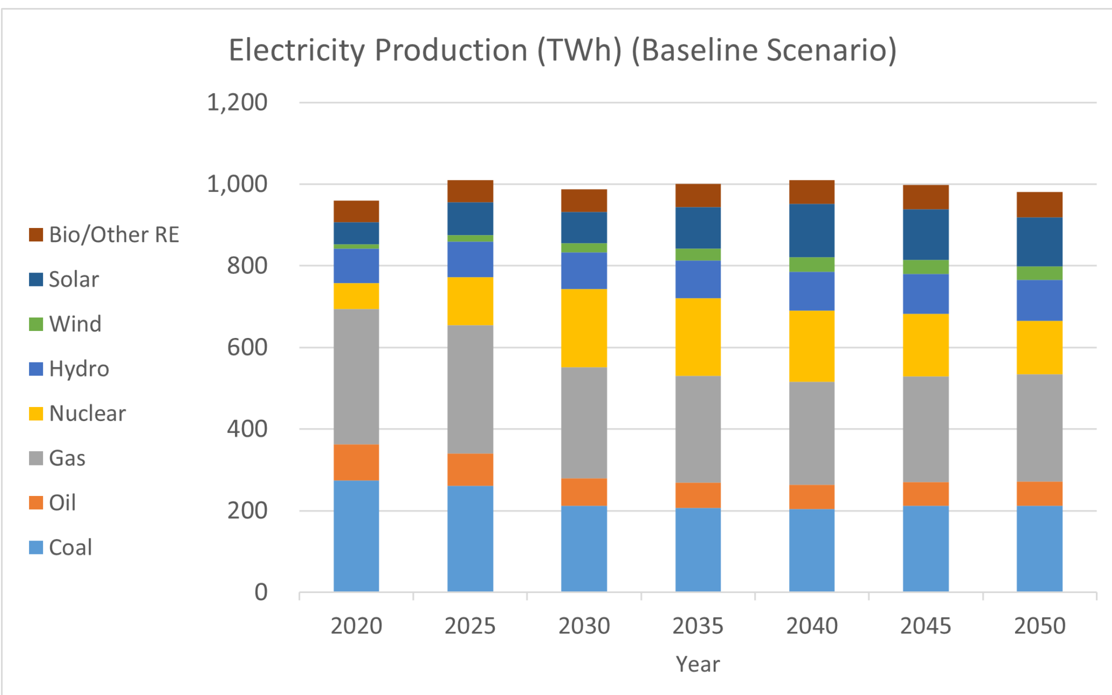


Figure 4.5: Trends in Electricity Generation by Source (2020–2050, TWh) in the Baseline Scenario

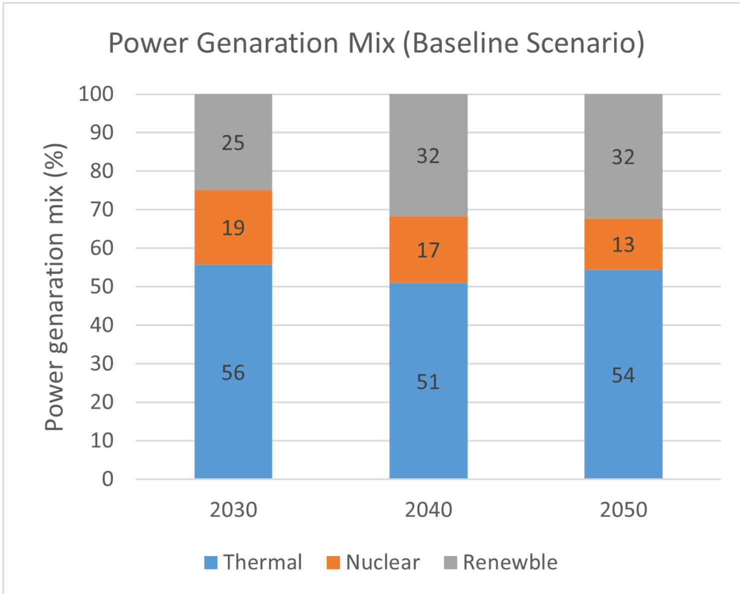


Figure 4.6: Power Generation Mix in the Baseline Scenario (%)

Table 4.4: Electricity Production by Source (2025–2050, TWh) in the Baseline Scenario

Source	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	261	212	206	205	212	213
Coal-CCS	0	0	0	0	0	0
Oil	79	67	62	58	59	59
Gas	315	272	262	252	258	262
Gas-CCS	0	0	0	0	0	0
Nuclear	118	191	190	175	153	131
Hydro	87	90	93	95	98	100
Wind	16	23	29	35	34	34
Solar	80	76	102	131	124	121
Bio/Other RE	54	56	57	59	60	61
Bio-CCS	0	0	0	0	0	0
All Electric Generation	1010	988	1001	1010	998	981

In summary, Japan's energy structure under the Baseline scenario remains dominated by fossil fuels, with only incremental progress in renewable energy deployment. This inertia in the energy system leads to sustained levels of energy-related CO_2 emissions and presents a key challenge for achieving GHG mitigation goals in the long term.

4.4 Sectoral Output Trends

This section analyzes long-term trends in major sectors of the Japanese economy under the Baseline scenario. Using EPPA model simulations, we examine sectoral output indices from 2025 to 2050 to identify growth trajectories and structural vulnerabilities during the transition to a low-carbon economy.

Table 4.5 lists the sectors analyzed in this study, their EPPA notations, and their economic output in 2025 (in 10 billion US$) [8]. These values provide a quantitative basis for interpreting sectoral index trends.

Table 4.5: Sectors Analyzed and Output in 2025 (10 billion US$)

Sector Name	**EPPA Notation**	**Output in 2025**
Services	SERV	444.9
Other Industries	OTHR	204.0
Energy-Intensive Industries	EINT	79.1
Transportation	TRAN	48.7
Ownership of Dwellings	DWE	44.0
Iron and Steel	I_S	38.3
Food Products	FOOD	33.7
Mineral Products	NMM	7.1

Figure 4.7 shows the indexed output trends (2025 = 1.00) in the Baseline scenario. Domestic demand-oriented sectors such as Services and Dwellings exhibit steady growth, reaching indices of 1.30 and 1.40, respectively, by 2050. Transportation and Energy-Intensive Industries also expand moderately, supported by persistent capital and logistics demand.

In contrast, carbon-intensive sectors (Figure 4.8) face stagnation or decline. Refined Oil sector drops to an index of 0.89 by 2050, while Electricity remains nearly flat at 0.96. These trends reflect limited efficiency gains under current policy settings.

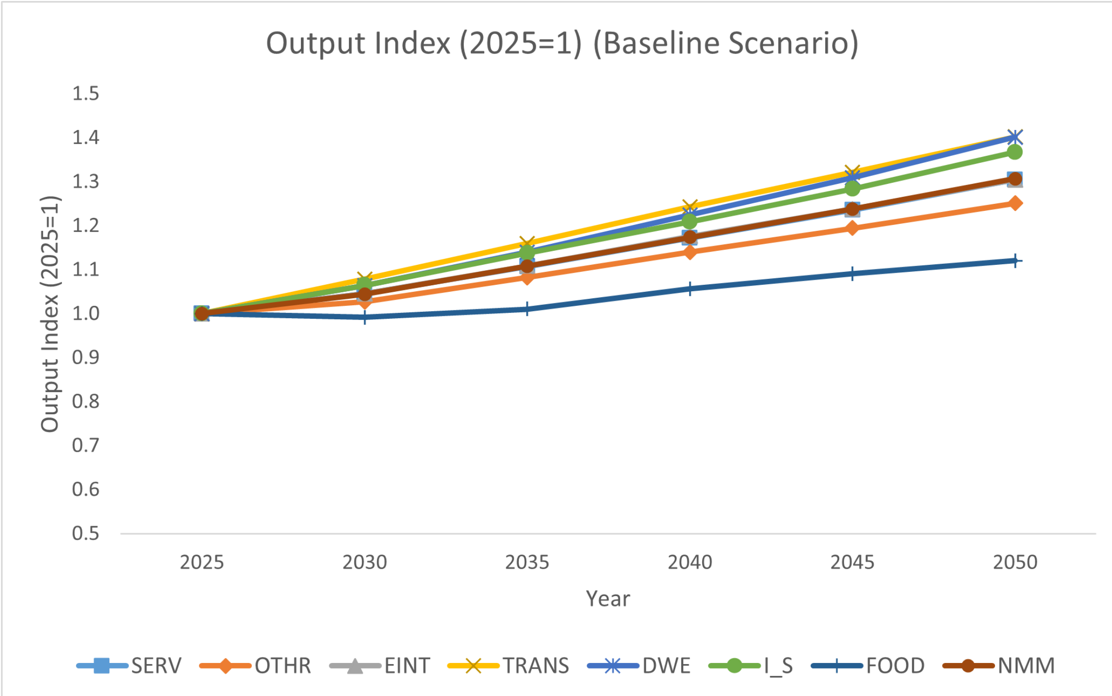


Figure 4.7: Sectoral Output Indices under the Baseline Scenario (2025 = 1)

These disparities are closely tied to Japan's 2025 energy mix, which remains heavily dependent on fossil fuels. Table 4.6 and Figure 4.8 summarize the key inputs: oil (7.1 EJ), coal (4.3 EJ), and gas (3.7 EJ). Electricity generation exceeds 1,000 TWh, yet structural reform remains limited under the Baseline scenario.

Table 4.6: Primary Energy Inputs and Electricity Generation in 2025

Indicator	**Value**
Electric Generation (TWh)	1,009.7
Coal Input (EJ)	4.3
Oil Input (EJ)	7.1
Gas Input (EJ)	3.7

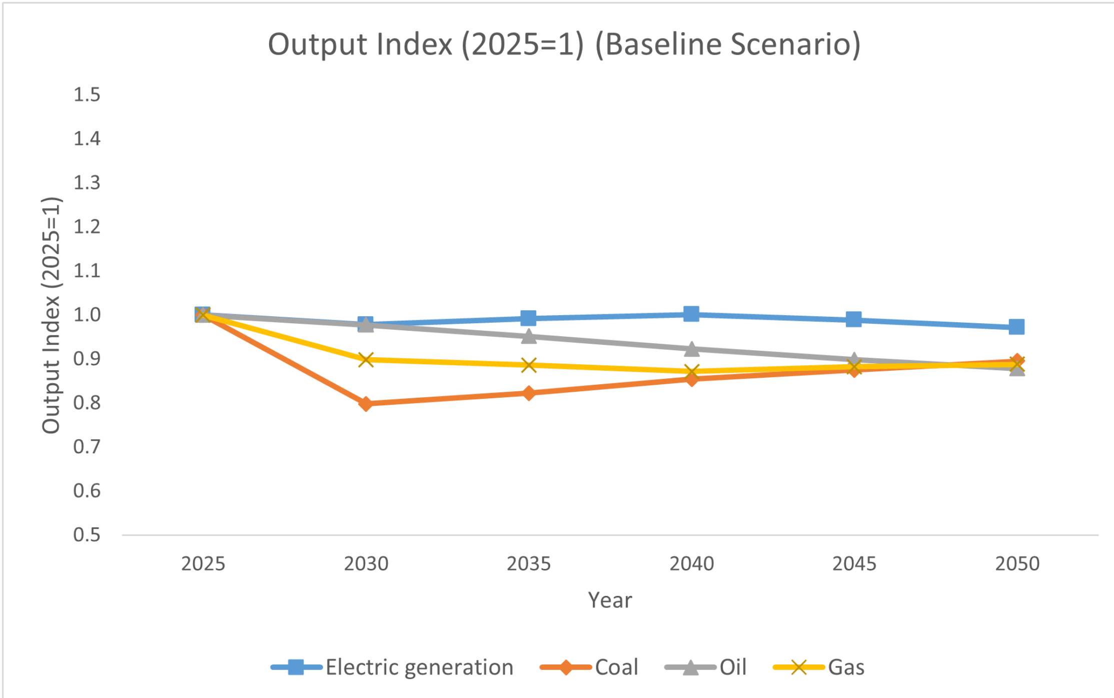


Figure 4.8: Sectoral Output Indices under the Baseline Scenario (2025 = 1)

4.5 Carbon Price

Japan's existing polices and regulations result in an implicit carbon penalty. To keep Japan's GHG emissions constant from 2030 to 2050 (see Figure 4.3), the EPPA model determined an endogenous "shadow price" on emissions that is needed to meet an emissions cap.

Under the Baseline scenario, no additional climate policies are introduced after 2026 and emissions are kept flat up to 2050. As a result, carbon prices remain low throughout the projection period. Figure 4.9 shows the implied carbon price, which declines from $27 per ton of CO_2 in 2030 to just $4 in 2050.

This minimal and declining carbon price reflects the mildness of emissions constraints in the Baseline scenario. Consequently, the scenario involves virtually no economic policy cost. As discussed in earlier sections, GDP and consumption steadily grow, and carbon-intensive activities face no substantial financial penalty.

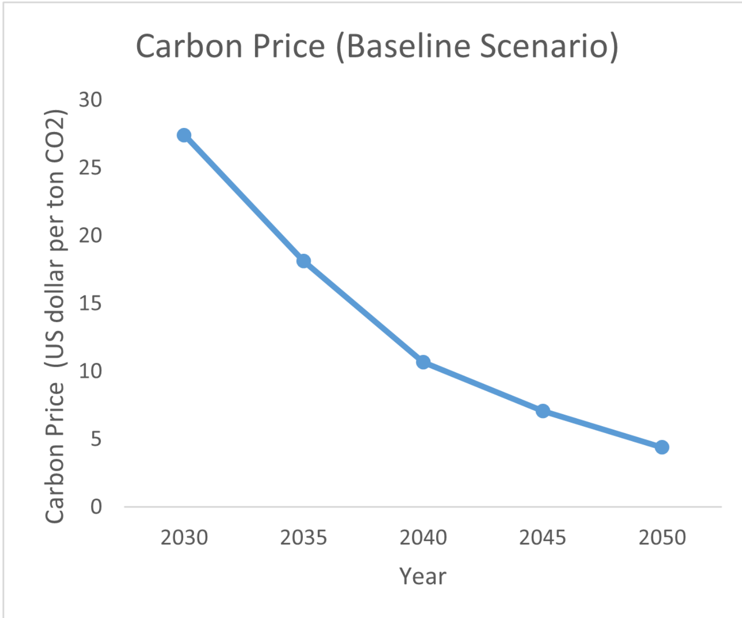


Figure 4.9: Carbon Price in the Baseline Scenario (US\$/tCO_2)

Chapter 5

Policy Scenarios Based on Domestic-Only Emissions Mitigation

5.1 Policy Design and Scenario Overview

This section outlines the structure of the domestic-only mitigation scenarios (without international emission trading). Mitigation is focused solely on CO_2 reduction. The scenarios are constructed by combining four key policy dimensions:

- **Nationally Determined Contributions (NDCs):** GHG reduction targets for 2030, 2035, and 2040 [23],
- **Net-Zero Target:** Achievement of (near) net-zero[1] GHG emissions by 2050,
- **Power Generation Mix Targets:** Shares of renewables, nuclear, and fossil fuels in 2030 and 2040,
- **Carbon Capture and Storage (CCS):** Deployment of CCS technology after 2035.

Based on combinations of these policy elements, six domestic-only scenarios (2a to 4b) are designed. Each scenario sequentially add policy components: first NDCs (2a), then CCS (2b), followed by power mix targets (3a), further CCS (3b), and finally net-zero targets with and without CCS (4a, 4b). This framework enables the evaluation of how incremental policy strengthening affects emissions and economic outcomes.

The targets used in this study are aligned with Japan's NDCs and updated climate strategy as of February 2025, specifically the *Plan for Global Warming Countermeasures* [24] and the *Strategic Energy Plan* [17].

[1] While the model solution gets close to net-zero emissions, they are not exactly zero. To eliminate the remaining emissions, carbon dioxide removal (CDR) can be deployed.

GHG Reduction Targets (NDCs)

Table 5.1: GHG Reduction Targets (NDCs)

Year	Reduction from 2013 Level	Target Emissions ($MtCO_2e$)
2030	−46%	760
2035	−60%	570
2040	−73%	380

Power Generation Mix Targets

Table 5.2: Power Generation Mix Targets

Year	Renewables	Nuclear	Fossil Fuels
2030	36–38%	20–22%	41%
2040	40–50%	20%	30–40%

Structure of Each Scenario

Table 5.3: Composition of Policy Scenarios

Scenario	NDC Targets	Net Zero	Power Mix Targets	CCS (after 2035)
Baseline	×	×	×	×
2a (NDC Only)	✓	×	×	×
2b (NDC + CCS)	✓	×	×	✓
3a (NDC + Power Mix)	✓	×	✓	×
3b (NDC + Power Mix + CCS)	✓	×	✓	✓
4a (NDC + Net Zero + Power Mix)	✓	✓	✓	×
4b (NDC + Net Zero + Power Mix + CCS)	✓	✓	✓	✓

Scenarios 3a and 3b, which align with the government's current climate and energy targets, are particularly important as they serve as realistic benchmarks for future policy pathways.

5.2 Changes in GHG Emissions

This section evaluates the feasibility of achieving Japan's 2050 carbon neutrality target by comparing trends in GHG emissions across scenarios. Figure 5.1 presents time-series emissions from 2030 to 2050, while Table 5.4 summarizes GHG emissions in 2050 and cumulative reductions compared to the baseline.

Under the Baseline scenario, emissions remain nearly flat after 2030, reaching 1,066 $MtCO_2e$ in 2050, with cumulative emissions of 5,306 $MtCO_2e$ from 2030 to 2050. In the scenarios 2a and 3a, where Japan meets its NDC targets, emissions decline to 185 $MtCO_2e$ and 184 $MtCO_2e$ by 2050, respectively—about a 70% reduction relative to the baseline. However, neither scenario achieves net zero, even with deep power sector decarbonization. In the scenarios 2b and 3b, which include CCS deployment, emissions in 2050 are held to 191 $MtCO_2e$, similar to non-CCS scenarios, but with greater energy system flexibility. Scenarios 4a and 4b are the most ambitious, reducing 2050 emissions to 91 $MtCO_2e$ and 117 $MtCO_2e$, respectively. While 4a relies entirely on domestic renewables and nuclear, 4b achieves similar reductions by combining fossil fuels with CCS.

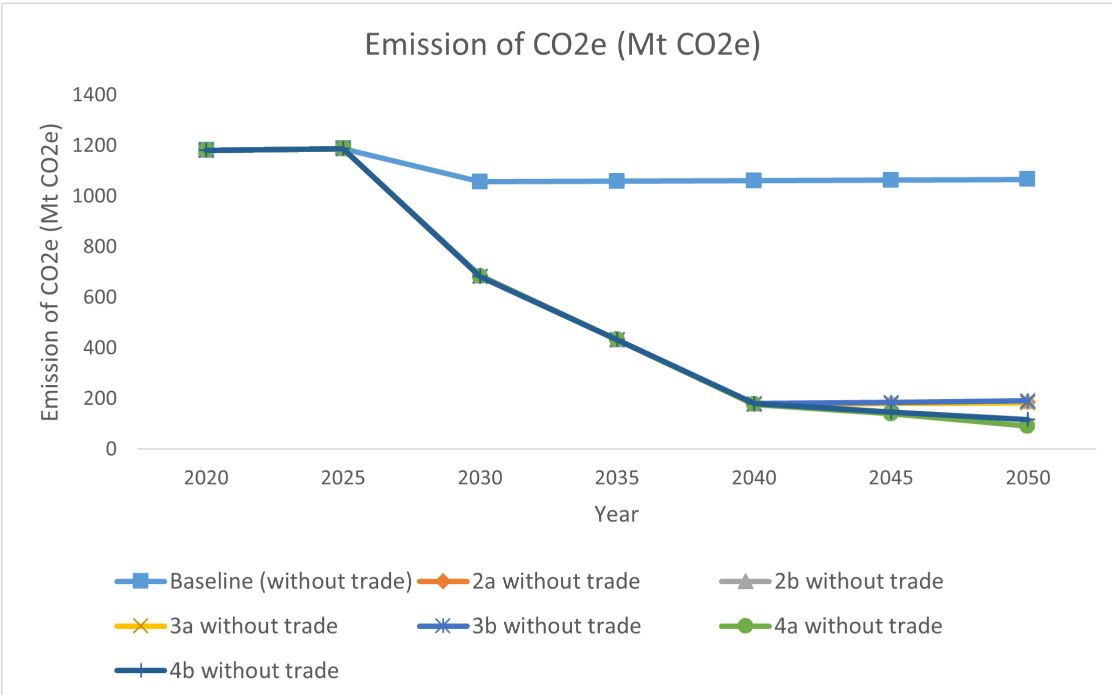


Figure 5.1: Trends in GHG Emissions by Scenario (2020 – 2050, $MtCO_2e$)

Table 5.4: Cumulative GHG Emissions (2030–2050, $MtCO_2e$)

Scenario	2050 Emissions ($MtCO_2e$)	Cumulative Emissions (2030–2050) ($MtCO_2e$)
Baseline without trade (ref)	1066	5,306
2a without trade	185	1,664
2b without trade	191	1,672
3a without trade	184	1,655
3b without trade	191	1,671
4a without trade	91	1,523
4b without trade	117	1,560

5.3 Energy Generation Structure and Low-Carbon Power Technologies

This section analyzes the evolution of Japan's electricity generation structure under domestic-only policy scenarios, focusing on the years 2030, 2040, and 2050. The aim is to identify the implications of technology choices—especially renewables, nuclear, and CCS—on the feasibility and resilience of the power sector transition. Figures 5.2–5.4 present the power generation mix in percentage terms, while Figures 5.5–5.7 show the absolute electricity generation by source in TWh for each scenario.

In 2030, the Baseline scenario shows continued reliance on fossil fuels, with thermal generation accounting for over 55% of electricity supply. In contrast, the scenarios 2a and 3a—featuring NDC and power mix targets—show rapid expansion of solar and wind, with renewables reaching over 43%. This shift sets the stage for deeper decarbonization in later decades.

By 2040, fossil-based generation is nearly phased out in most scenarios except the Baseline. The use of solar power becomes dominant, especially in the scenario 2a, where solar reaches over 670 TWh. Nuclear energy also contributes steadily, with stable output around 175 – 190 TWh across scenarios.

In 2050, the scenarios diverge based on CCS adoption. Scenario 4a, which excludes CCS, relies heavily on nuclear and biomass, resulting in a power mix that is institutionally inflexible. In contrast, the scenario 4b maintains fossil generation via CCS and achieves a balanced mix: 73% renewables, 19% nuclear, and 8% CCS-based generation. This combination offers both environmental performance and technological diversity.

These findings underscore the importance of technology portfolio design. Scenarios relying solely on renewables and nuclear without CCS (2a, 3a, 4a) face structural constraints, while scenarios incorporating CCS (2b, 3b, 4b) demonstrate more balanced, cost-effective, and resilient pathways to decarbonization.

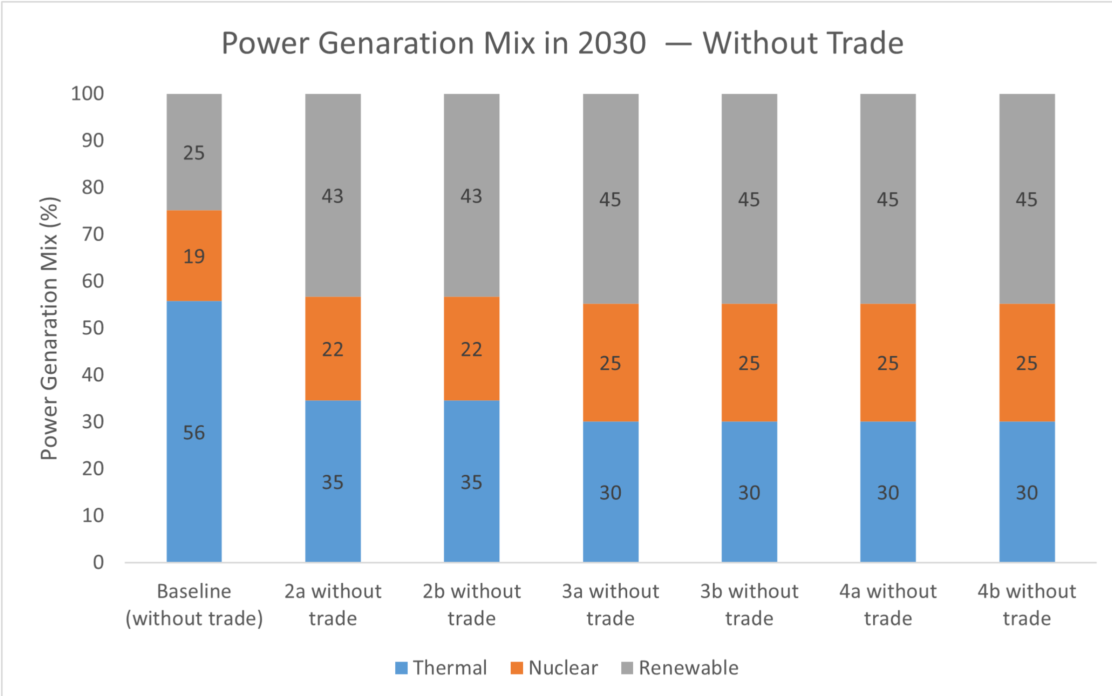


Figure 5.2: Power Generation Mix by Scenario in 2030 (%)

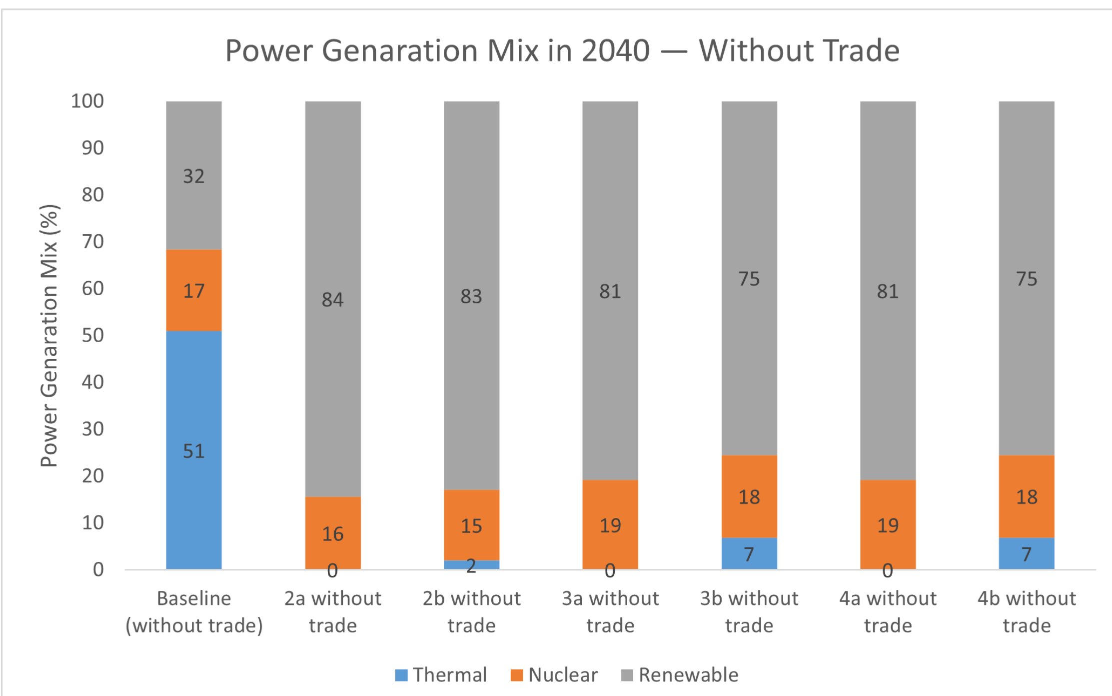


Figure 5.3: Power Generation Mix by Scenario in 2040 (%)

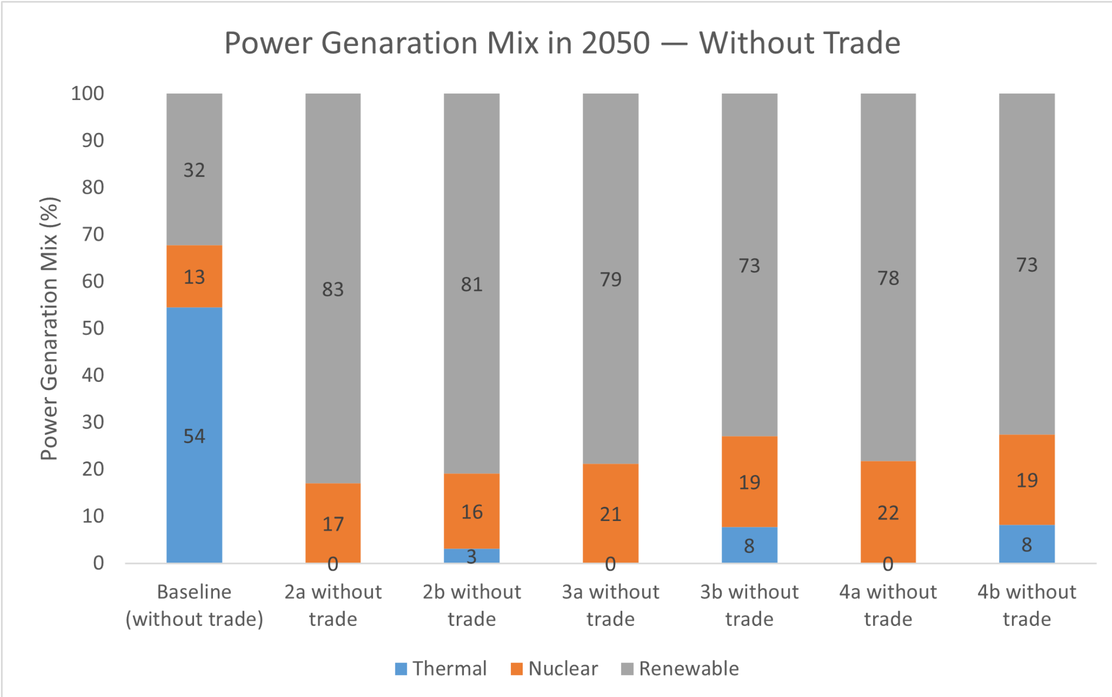


Figure 5.4: Power Generation Mix by Scenario in 2050 (%)

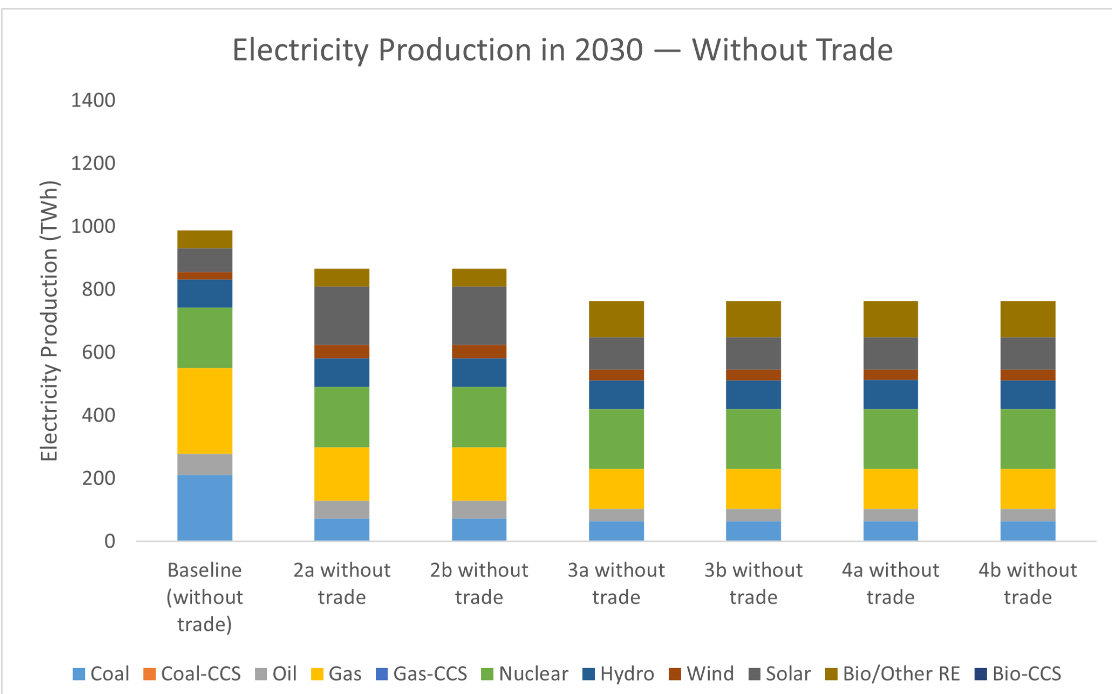


Figure 5.5: Electricity Generation by Source in 2030 (TWh)

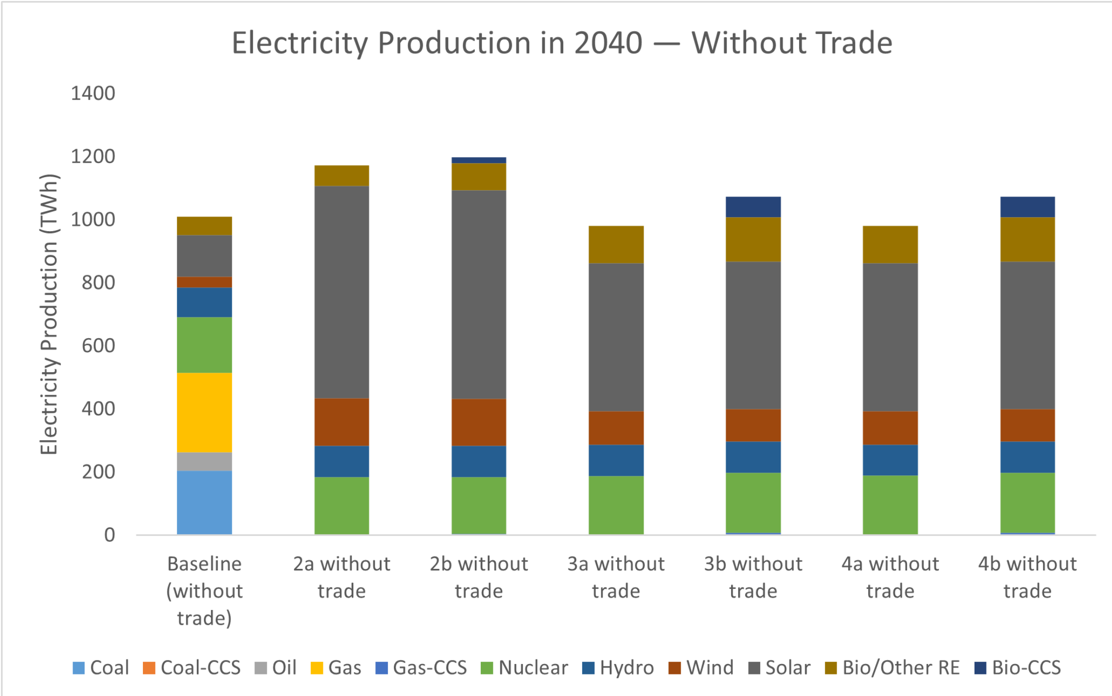


Figure 5.6: Electricity Generation by Source in 2040 (TWh)

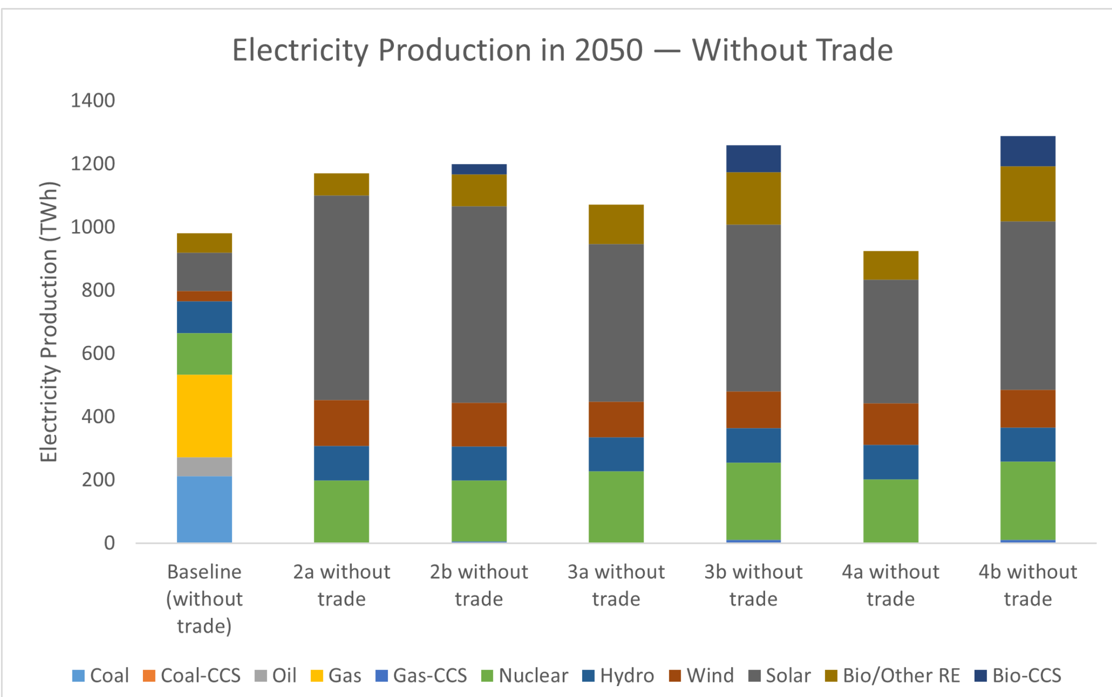


Figure 5.7: Electricity Generation by Source in 2050 (TWh)

5.3.1 Deployment of Low-Carbon Power Technologies

This section examines the deployment of major low-carbon power technologies—renewables, nuclear, and CCS—by 2050 under each policy scenario. It evaluates how these technologies contribute to emission reductions and what trade-offs arise in terms of system flexibility and resource requirements.

Renewable Energy

Across all policy scenarios, the deployment of renewable energy (solar, wind, hydro, and biomass) shows a general trend of expansion. In the Baseline scenario, renewable electricity generation remains at 316 TWh (32%), but in the scenario 4b, it reaches 934 TWh (73%). Solar power in particular increases from 392 TWh to 649 TWh, making it the largest single contributor.

To contextualize this solar expansion, a 649 TWh output corresponds to approximately 329 GW of installed capacity, assuming a 22.5% capacity factor (the ratio of actual to maximum possible generation over a year) and 8,760 operating hours. Based on a land-use coefficient of 0.01 km^2/MW [8], this would require about 3,292 km^2 of land, equivalent to approximately 0.87% of Japan's total area. This highlights the importance of land-use planning and institutional readiness for large-scale renewable deployment.

Nuclear Power

Nuclear power plays a varying role across scenarios depending on policy intensity. In the Baseline scenario, nuclear generation remains at 131 TWh in 2050. However, in more stringent policy cases such as 3a, 3b, and 4a, generation increases to 201 – 248 TWh, contributing 16 – 22% of total power generation.

This steady increase reflects nuclear power's role as a dispatchable, low-carbon energy source. Particularly in the scenarios without CCS (2a, 3a, 4a), nuclear generation compensates for the limitations in renewable deployment, underlining its importance in maintaining both system reliability and emissions reduction.

CCS Technologies

Carbon Capture and Storage (CCS) technologies are deployed in the scenarios 2b, 3b, and 4b, beginning in 2035. By 2050, the total electricity generated from CCS-equipped plants reaches 105 TWh in the scenario 4b. Notably, bio-CCS accounts for 95 TWh of this total, underscoring its dual role in carbon removal and power generation.

The use of bio-CCS enables negative emissions, helping to offset residual emissions in other sectors. The deployment of CCS, particularly in conjunction with biomass, plays a pivotal role in reconciling fossil fuel use with long-term climate goals.

Diversity of the Power Mix and Strategic Implications

The degree of diversity in the 2050 power mix varies significantly across scenarios. In the scenario 4a, which excludes CCS, the energy system relies heavily on nuclear (201 TWh) and biomass-based generation, while the share of solar and wind remains relatively constrained. This results in a power mix that may face risks related to technological concentration and institutional feasibility.

In contrast, the scenario 4b, which incorporates CCS, achieves a more balanced mix: 73% from renewables, 19% from nuclear, and 8% from fossil fuels with CCS. This diversified configuration enhances energy security and institutional resilience while still aligning with the carbon neutrality goal.

These results suggest that a diversified portfolio of power technologies, combining renewables, nuclear, and CCS, provides a more flexible and robust pathway for achieving deep decarbonization.

5.4 Economic Impact Analysis

This section evaluates the macroeconomic impacts of domestic-only mitigation policies by analyzing changes in real GDP and household consumption from 2020 to 2050. I compared GDP losses, consumption declines, and cumulative policy costs across all scenarios using EPPA model outputs.

5.4.1 Trends in Real GDP under Mitigation Scenarios

Figure 5.8 illustrates the trajectory of real GDP from 2030 to 2050 under each mitigation scenario, as projected by the EPPA model. While all scenarios exhibit economic growth over time, the pace and magnitude of this growth vary depending on the policy stringency and technology mix.

Baseline scenario shows steady growth, reaching approximately $6.6 trillion by 2050. In contrast, the scenario 4a, which seeks net-zero emissions without CCS, significantly dampens GDP growth, resulting in a 2050 GDP of around $5.1 trillion. The scenario 4b, which additionally introduces CCS, helps mitigate the economic burden, with GDP recovering to about $5.8 trillion.

Among the scenarios, scenario 3b—which combines NDC targets, power mix goals, and CCS deployment—achieves a balance between environmental ambition and economic performance, reaching a 2050 GDP of roughly $5.9 trillion. These differences underscore the importance of technological strategy design in minimizing adverse macroeconomic impacts.

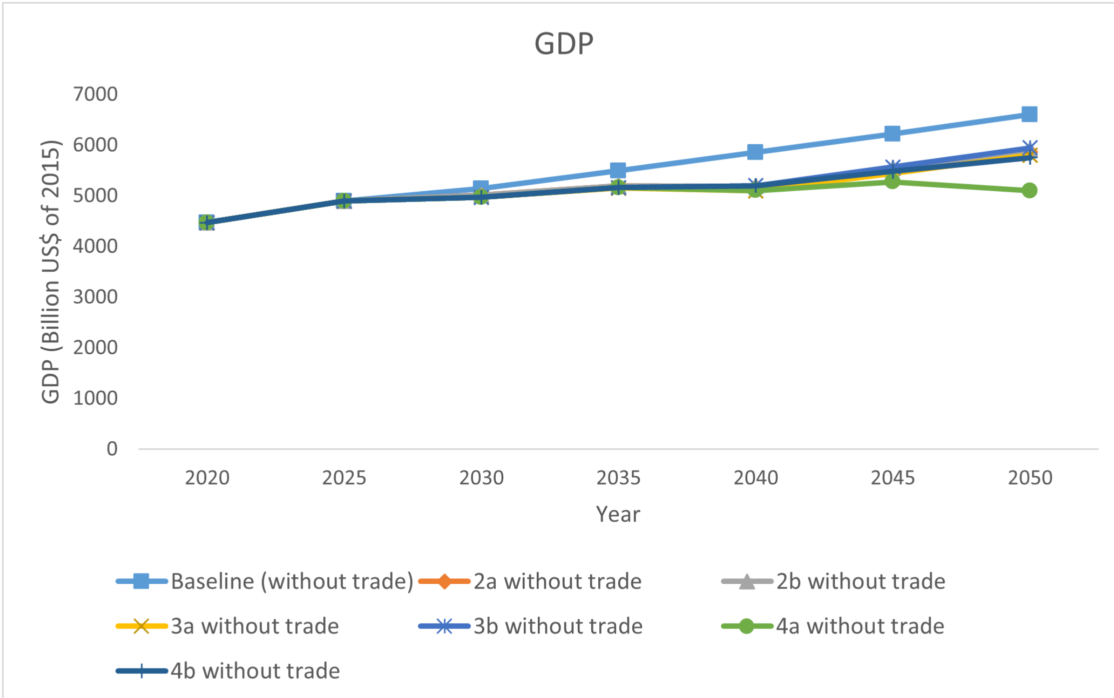


Figure 5.8: Real GDP Trajectory under Each Policy Scenario (Billion US$ of 2015)

5.4.2 Impact on Total Household Consumption

Trends in real household consumption are shown in Figure 5.9. Similar to GDP, consumption increases across all scenarios but at different rates depending on policy design.

In 2050, the scenario 4a exhibits the steepest decline relative to the baseline, with household consumption reduced by $782 billion. The inclusion of CCS in the scenario 4b softens this impact, limiting the reduction to $405 billion. The scenario 3b maintains stable consumption throughout the projection period, highlighting its capacity to balance mitigation goals with economic well-being.

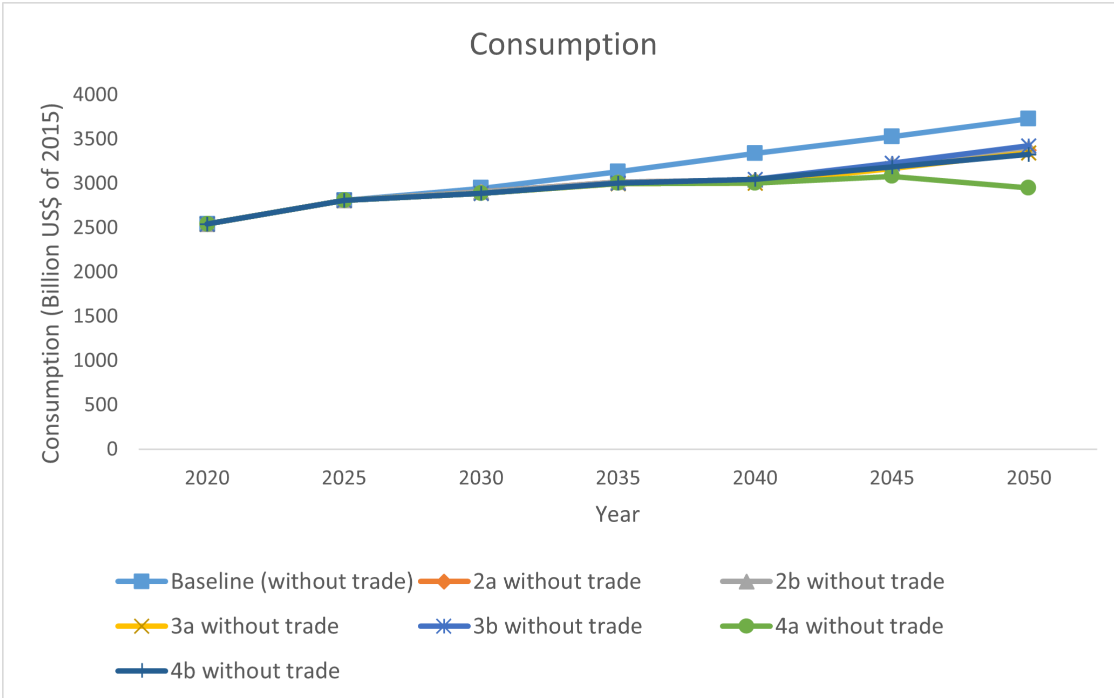


Figure 5.9: Trajectory of Consumption Expenditure under Each Policy Scenario (Billion US$ of 2015)

5.4.3 Cumulative Policy Cost Comparison

To assess the long-term macroeconomic burden of climate policies, I calculated the cumulative undiscounted policy costs as the sum of annual GDP losses from 2030 to 2050 (Figure 5.10).

Scenario 4a incurs the highest policy cost, with cumulative GDP losses reaching $367 billion by 2050. The introduction of CCS in scenario 4b reduces this cost to $261 billion. Among all mitigation scenarios, 3b achieves the lowest cumulative cost—$237 billion—while still delivering substantial emissions reductions.

These results emphasize that policy combinations incorporating CCS are more cost-effective in macroeconomic terms. They also highlight the importance of strategic technology deployment to achieve mitigation goals at manageable economic cost.

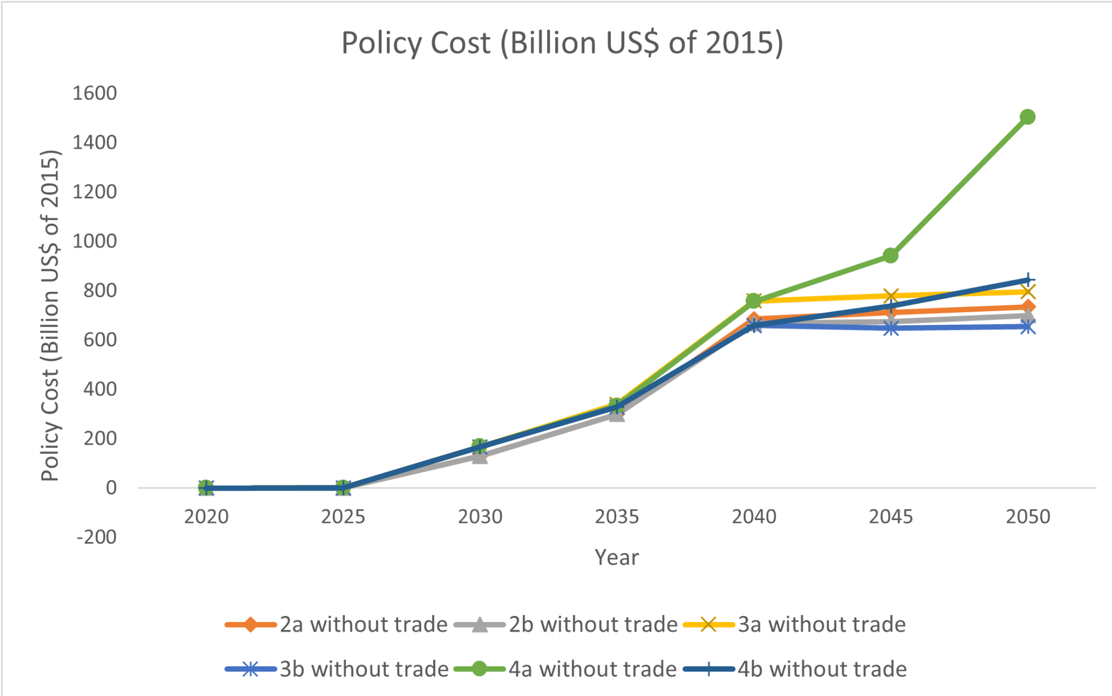


Figure 5.10: Policy Costs under Each Scenario (2030 – 2050) (Billion US$ of 2015)

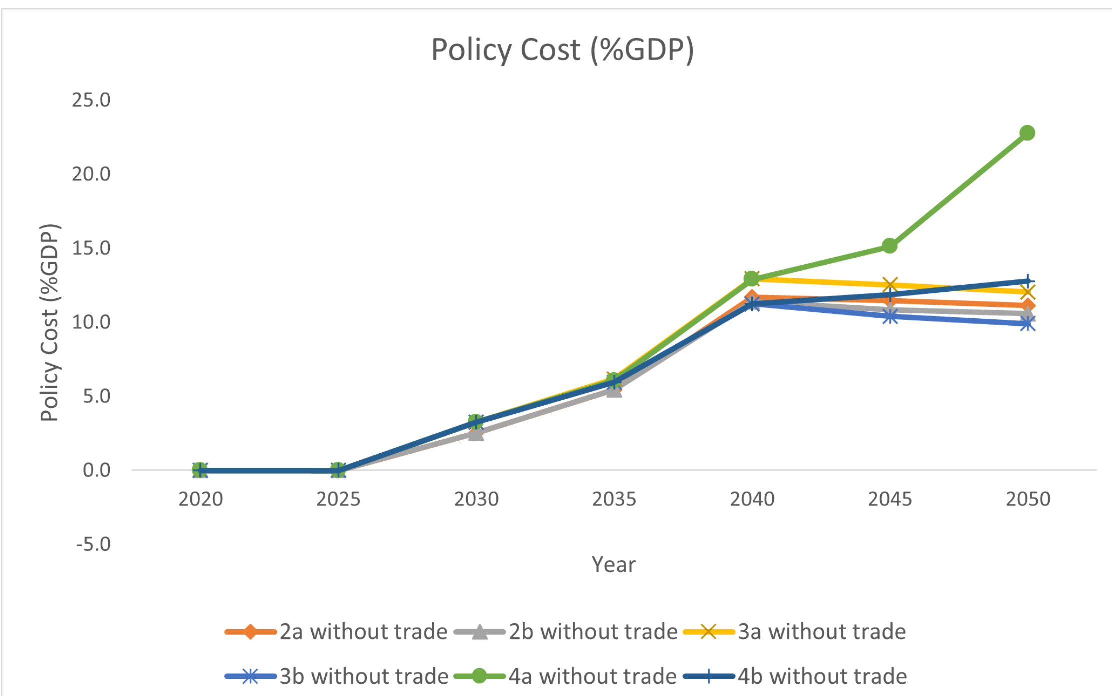


Figure 5.11: Policy Costs under Each Scenario (2030 – 2050) (%GDP)

Table 5.5: Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050)

Scenario	**Reduction vs. Baseline (in 2050) (Billion US$ of 2015)**	**Reduction vs. Baseline (in 2050) (%GDP)**	**Cumulative Policy Cost (2030–2050) (Billion US$ of 2015)**
2a without trade	735	11.1	2,562
2b without trade	699	10.6	2,471
3a without trade	796	12.1	2,841
3b without trade	655	9.9	2,457
4a without trade	1,504	22.8	3,701
4b without trade	844	12.8	2,736

5.5 Sectoral Economic Impacts

This section examines the sector-specific economic impacts of domestic-only decarbonization policies in Japan using the EPPA model. The analysis is based on sectoral output indices measured in real terms and normalized to 2025 levels (2025 = 1). The sector classification follows the EPPA framework, encompassing energy-intensive industries, energy-related sectors, services, and other key segments. All scenarios evaluated in this section—2a through 4b—assume no international emissions trading, focusing instead on the effects of domestic policy tightening.

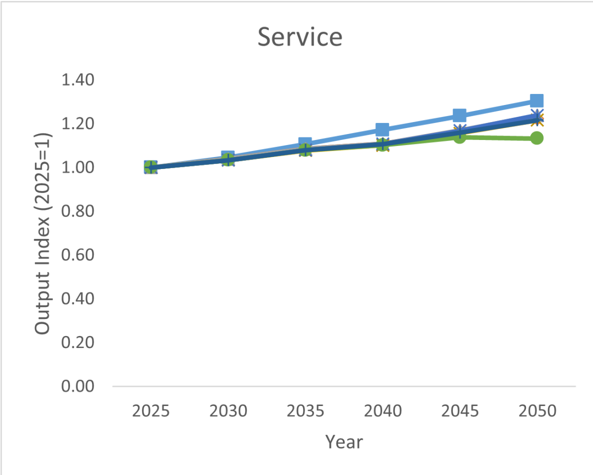
5.5.1 Industrial Sectoral Economic Impacts

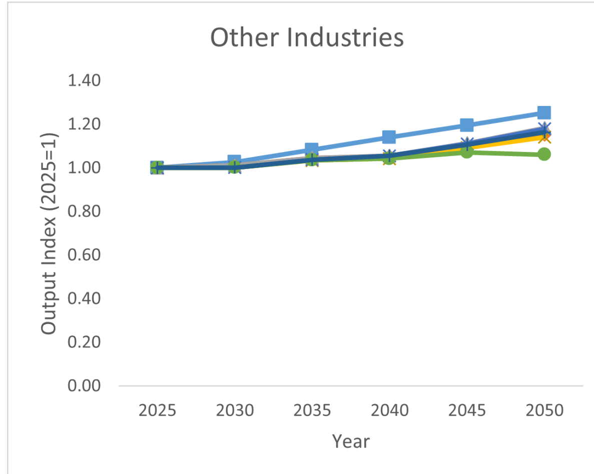
Industrial sectors respond heterogeneously to increasingly stringent mitigation policies. As shown in Figure 5.12, energy-intensive industries (EINT)—including iron and steel, mineral products, and chemicals—experience noticeable declines in output as carbon prices rise and abatement options remain limited.

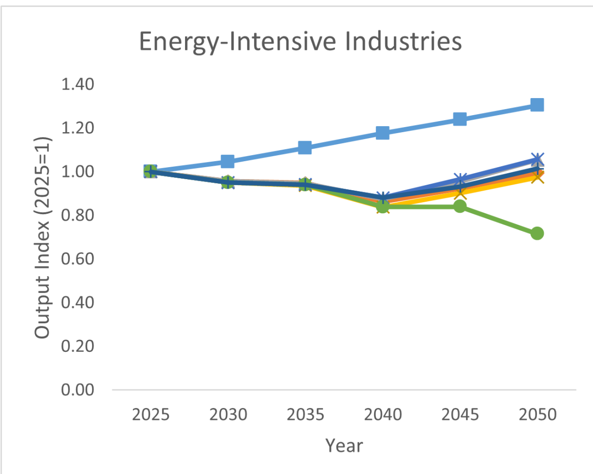
By 2050, the EINT index falls from 1 to 0.72 under the most stringent policy without CCS (Scenario 4a), compared to 1.30 in the Baseline. Similarly, the iron and steel sector (I_S) declines to 0.87 and mineral products (NMM) to 0.87 in the same scenario. These trends reflect the compounded burden of decarbonization on carbon-intensive manufacturing sectors, particularly in the absence of technological flexibility such as CCS or market-based cost relief.

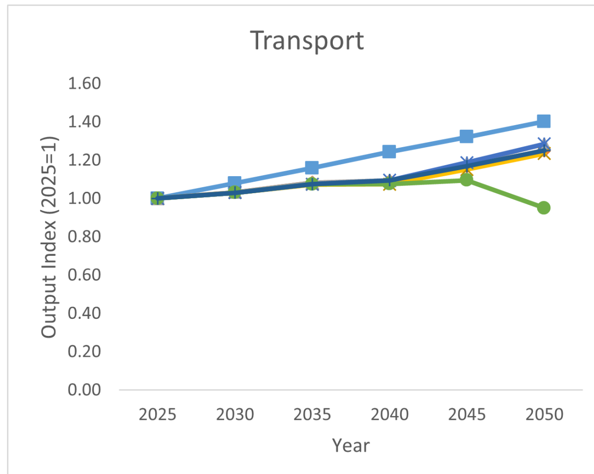
In contrast, less carbon-intensive sectors such as services (SERV) and dwellings (DWE) remain relatively stable. Their indices in the scenario 4a reach 1.13 and 1.14, respectively, by 2050—still growing over time, albeit at slightly reduced rates compared to the baseline. The transportation sector shows a moderate decline, dropping to 0.95 by 2050 in the scenario 4a, indicating input cost pressure under high carbon pricing.

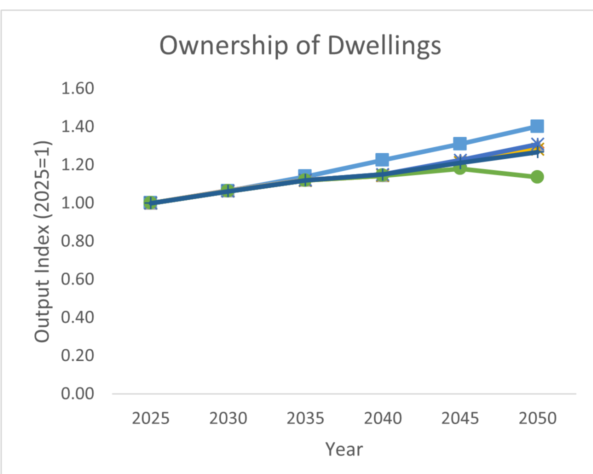
Overall, without international emissions trading, the output divergence between carbon-intensive and low-emissions sectors becomes more pronounced, suggesting limited flexibility in maintaining balanced industrial growth under strict domestic-only mitigation pathways.

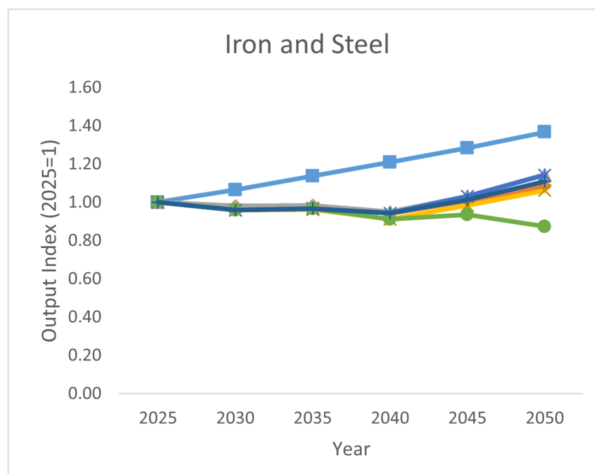

Service
Output Index (2025=1)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Other Industries
Output Index (2025=1)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Energy-Intensive Industries
Output Index (2025=1)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Transport
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Ownership of Dwellings
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Iron and Steel
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year

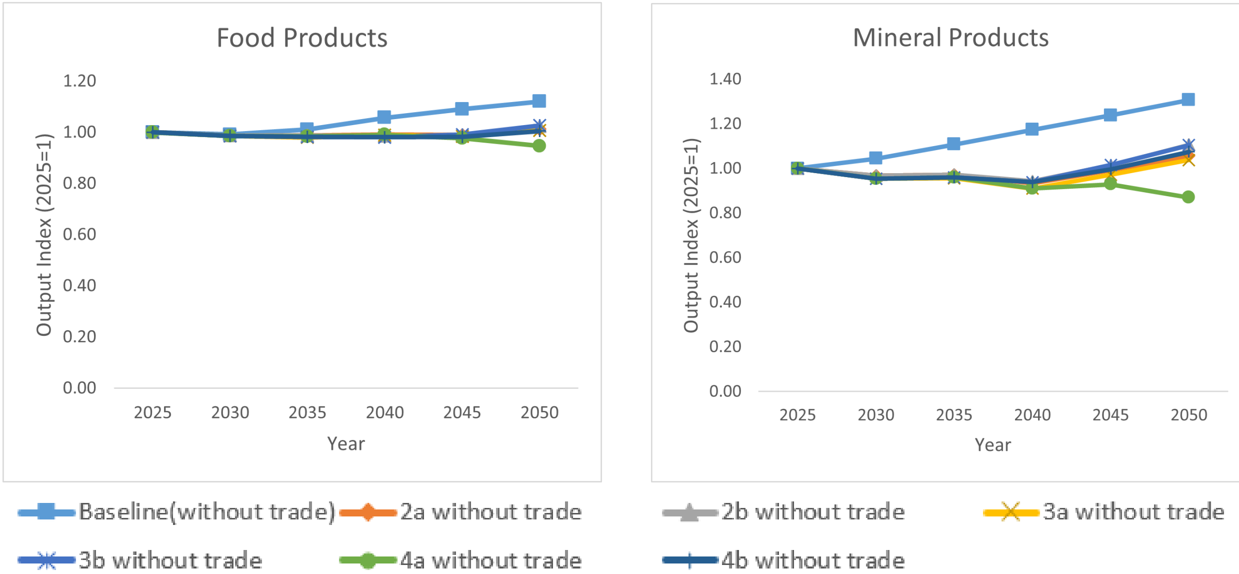


Figure 5.12: Sectoral Output Index (2025 = 1) across Industrial and Service Sectors

5.5.2 Energy-related Sectoral Economic Impacts

Energy supply sectors face the steepest output reductions under domestic-only mitigation scenarios. As shown in Figures 5.13, fossil fuels are gradually phased out in all scenarios, with more rapid declines under more ambitious policy cases.

In the scenario 4a, coal output drops from 1.00 in 2025 to nearly 0.00 by 2050. Oil and gas follow similar paths, falling to 0.01 and below 0.01, respectively. These sharp declines are driven by high domestic carbon prices and the absence of flexible compliance mechanisms.

Electricity generation follows a distinct trend. Under the scenario 4a, output increases through mid-century due to heavy investment in renewables and CCS, peaking at 1.16 in 2040. However, by 2050, the index falls back to 0.92, reflecting rising costs and system saturation.

These results underscore the limitations of relying solely on domestic mitigation. While electricity output is temporarily bolstered, fossil fuel sectors face near collapse, and industrial imbalances intensify.

Figure 5.13: Sectoral Output Index (2025 = 1) in Energy-related Sectors

5.6 Carbon Prices

This section evaluates the cost-effectiveness of domestic mitigation scenarios by examining the trajectories of implicit carbon prices.

In this context, carbon price reflects the marginal cost of reducing one additional tonne of carbon emissions. Higher values indicate that remaining emissions are increasingly costly to abate due to the exhaustion of low-cost mitigation options.

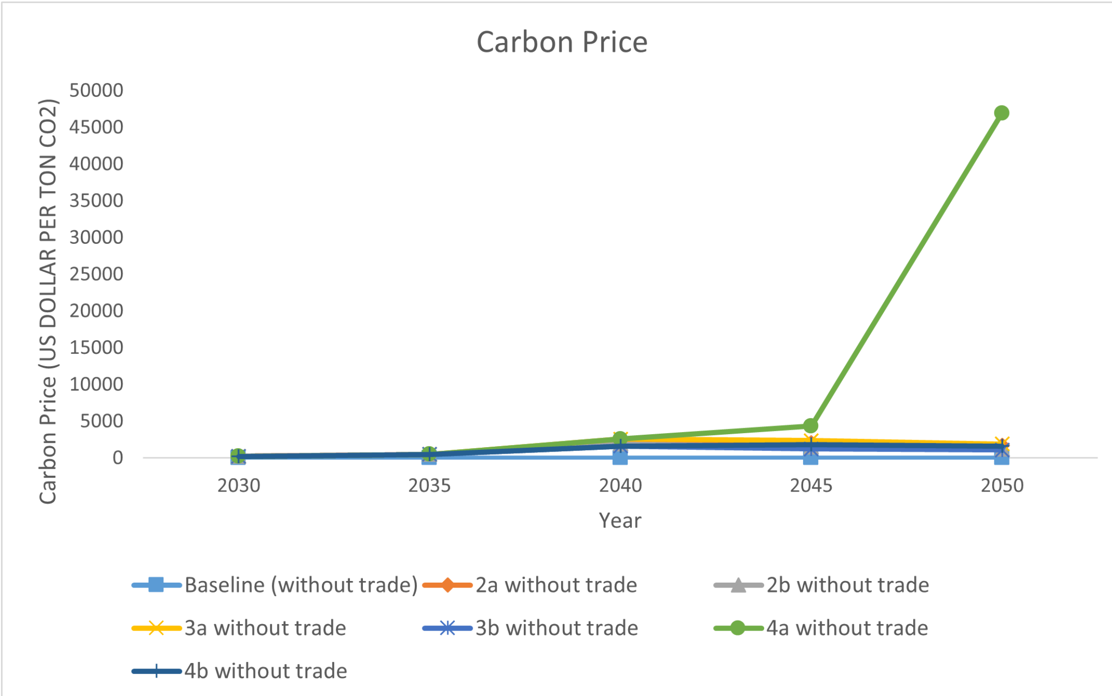
Tabel 5.6 and Figure 5.14 present the evolution of carbon prices from 2030 to 2050 under each scenario. As expected, scenarios without CCS—particularly scenario 4a—exhibit steep rises in carbon prices after 2040, with carbon price exceeding \$46,000 per ton CO_2 in 2050. This extreme figure (\$46,928/tCO_2) reflects the sharply rising cost of mitigating the last portion of emissions when relying solely on domestic, non-technological measures.

In contrast, scenarios that incorporate CCS (2b, 3b, 4b) successfully contain carbon prices at much lower levels. For instance, the scenario 4b—which combines net-zero targets, power mix shifts, and CCS—achieves substantial mitigation at a carbon price of \$1,630/tCO_2 in 2050, nearly 29 times lower than in the scenario 4a. The scenario 3b remains even lower at \$1,101/tCO_2.

These results highlight the critical role of technological flexibility in controlling policy costs. Without CCS, the marginal cost of abatement may increase non-linearly, risking economic disruption. Therefore, integrating technologies like CCS is essential for ensuring that Japan's long-term mitigation goals remain economically viable.

Table 5.6: Carbon Prices in Different Scenario (US\$/tCO_2)

Scenario	**2030**	**2035**	**2040**	**2045**	**2050**
Baseline	27	18	11	7	4
2a without trade	257	505	2213	2037	1729
2b without trade	257	504	1917	1509	1221
3a without trade	214	491	2583	2355	1923
3b without trade	214	486	1625	1226	1101
4a without trade	214	492	2567	4346	46928
4b without trade	214	486	1625	1846	1630



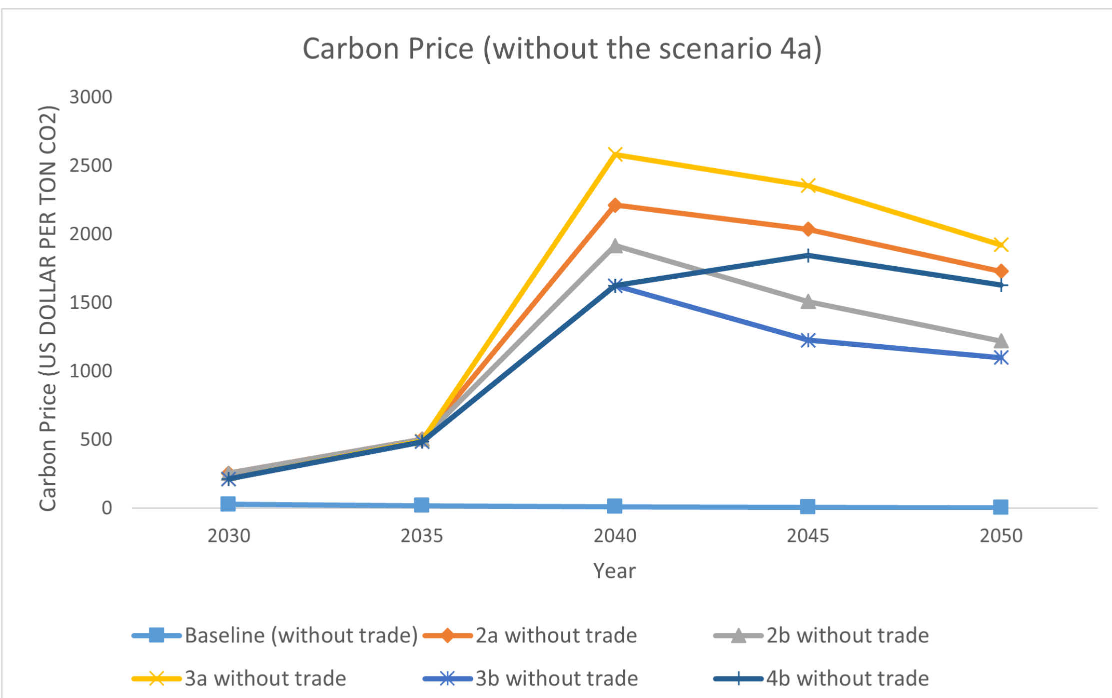


Figure 5.14: Trajectory of Carbon Prices in Different Scenario (US$/t$CO_2$)

5.7 Limitations of Domestic-Only Measures and the Need for International Cooperation

The preceding analysis confirms that Japan can achieve substantial emissions reductions through strengthened domestic mitigation measures, particularly in meeting interim NDC targets for 2030 and 2040. For example, the scenario 2a (NDC only) and the scenario 3a (NDC + power mix) reduce 2050 emissions to 185 $MtCO_2e$ and 184 $MtCO_2e$ respectively—about 70% below the baseline. These scenarios demonstrate that deep decarbonization of the power sector and industrial adjustment can be pursued through domestic action alone.

However, the findings also reveal significant institutional and economic limitations to domestic-only mitigation strategies—especially when aiming for net-zero emissions by 2050 without technological flexibility. The scenario 4a (net-zero without CCS) highlights these constraints. It relies heavily on nuclear (201 TWh) and biomass, raising concerns about energy system rigidity and land/resource constraints. Economically, 4a incurs the highest cumulative GDP loss ($367 billion by 2050) and the largest decline in household consumption ($782 billion in 2050), pointing to substantial welfare impacts.

Moreover, the marginal abatement cost—represented by the carbon price at different levels of emission abatement —escalates dramatically in the scenario 4a, reaching $46,928/$tCO_2$ in 2050. This steep increase reflects the exhaustion of low-cost mitigation options and the difficulty of eliminating residual emissions without international offsets or carbon removal technologies.

By contrast, the scenario 4b, which incorporates CCS, reduces 2050 emissions to a similar level (117 $MtCO_2e$) but at significantly lower cost. The carbon price in the scenario 4b is contained at $1,630/$tCO_2$, and GDP and consumption losses are reduced by 29% and 48% respectively compared to the scenario 4a. These results underscore the vital role of technological options in maintaining economic feasibility.

Nonetheless, even with CCS, the scenario 4b still imposes a considerable macroeconomic burden and fails to fully eliminate emissions. This implies that domestic-only policies—while necessary—may not be sufficient or cost-effective for achieving complete decarbonization.

For a country like Japan, where the marginal abatement cost is high and domestic emissions reduction potential is structurally constrained, international cooperation mechanisms such as emissions trading systems and bilateral crediting frameworks (e.g., the Joint Crediting Mechanism) offer a pragmatic and economically sound path forward. By leveraging cost-effective mitigation opportunities abroad, Japan can meet its climate commitments more efficiently while supporting global decarbonization and technology diffusion.

Building on this recognition, the next chapter investigates scenarios that incorporate international emissions trading. It compares environmental and economic outcomes under global carbon market participation and evaluates the strategic policy implications of enhanced international cooperation.

Chapter 6

Policy Scenarios with International Emissions Trading

6.1 Policy Design and Scenario Overview

This chapter evaluates the environmental and economic impacts of policy scenarios that incorporate international emissions trading (scenarios 2A to 4B). These scenarios build upon the domestic-only policy cases analyzed in Chapter 5 by introducing the possibility of using international carbon credits. The goal of this analysis is to assess how international cooperation can reduce the economic burden of decarbonization while maintaining equivalent environmental outcomes. Mitigation and trading are focused solely on CO_2 reduction.

In this study, international emissions trading is modeled as a system in which countries can purchase emissions reductions from abroad to meet their own mitigation targets. In the EPPA model, this is operationalized using the `tco2cf` setting, which enables a globally integrated carbon market. When activated, this option equalizes carbon prices across regions, allowing mitigation efforts to be allocated to regions with the lowest marginal abatement costs.

Figure 6.1 summarizes the policy composition of the six international trading scenarios (2A to 4B). Each of these scenarios mirrors its domestic counterpart (2a to 4b) in terms of policy design—namely, the inclusion of NDC targets, power mix constraints, net-zero goals, and CCS deployment—but adds the option to use international emissions trading after 2030. The comparison of these matched pairs isolates the policy effects of trading and highlights the role of global cooperation in achieving decarbonization targets.

Table 6.1: Composition of International Emissions Trading Scenarios (2A – 4B)

Scenario	**NDC Targets**	**Power Mix Targets**	**CCS Deployment**	**International Trading**
2A (NDC)with trade	✓	×	×	✓
2B (NDC + CCS) with trade	✓	×	✓	✓
3A (NDC + Power Mix) with trade	✓	✓	×	✓
3B (NDC + Power Mix + CCS) with trade	✓	✓	✓	✓
4A (NDC + Net Zero + Power Mix) with trade	✓	✓	×	✓
4B (NDC + Net Zero + Power Mix + CCS) with trade	✓	✓	✓	✓

6.2 Changes in GHG Emissions

This section analyzes the effect of international emissions trading on Japan's GHG emissions trajectory, comparing scenarios 2A to 4B with their domestic-only counterparts (2a to 4b). The key question is how the use of international credits alters the level and composition of domestic emissions while maintaining the overall emission reduction (domestic and purchased from abroad) consistent with the Japan's targets.

Figure 6.1 presents the GHG emissions trends under scenarios 2A to 4B. Compared with the domestic-only scenarios, the overall reduction in Japan's effective emissions is preserved, while the burden of domestic abatement is significantly reduced. For instance, in 2050, the scenario 4A achieves net emissions of 91 $MtCO_2e$ domestically, while the scenario 4B achieves 117 $MtCO_2e$. However, with the addition of international credits, both scenarios effectively meet the net-zero goal.

Table 6.3 summarizes the cumulative GHG emissions from 2030 to 2050 for each scenario. While domestic-only cases such as 4a and 4b show cumulative emissions of 1,524 and 1,560 $MtCO_2e$, their international counterparts (4A and 4B) achieve similar cumulative values despite reduced domestic efforts. This demonstrates that international emissions trading can preserve environmental outcomes while improving implementation flexibility.

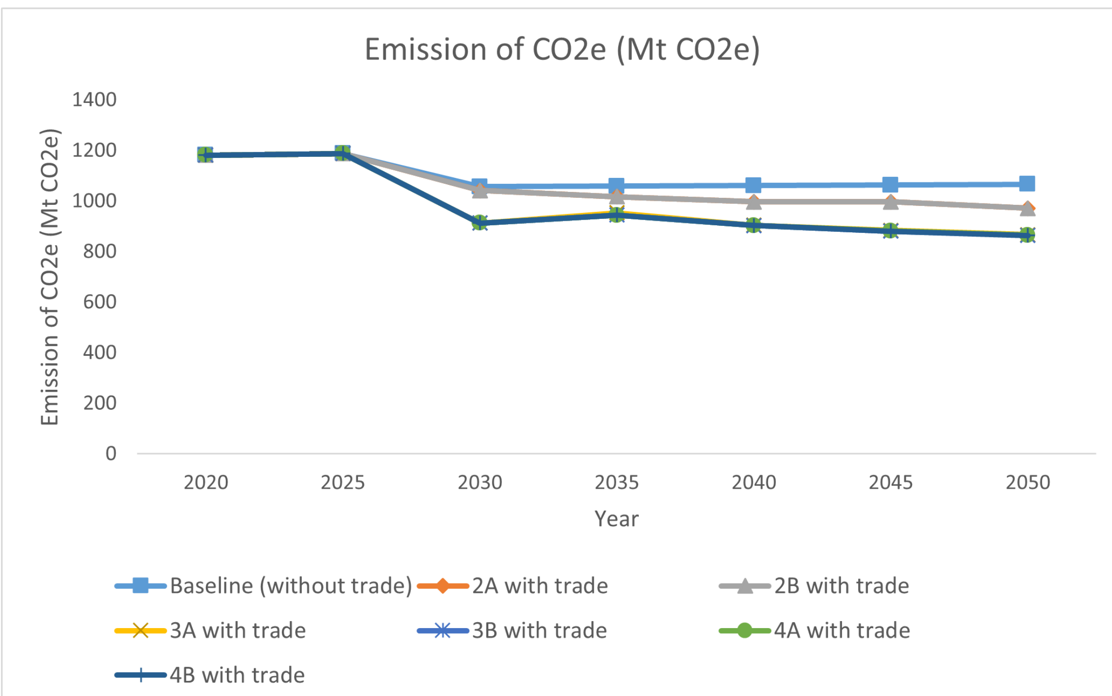


Figure 6.1: GHG Emissions Trajectory under Scenarios with International Trading ($MtCO_2e$)

Table 6.2: Cumulative GHG Emissions (2030–2050, $MtCO_2e$)

Scenario	2050 Emissions ($MtCO_2e$)	Cumulative Emissions (2030–2050) ($MtCO_2e$)
Baseline without trade (ref)	1066	5,306
2a without trade (ref)	185	1,664
2b without trade (ref)	191	1,672
3a without trade (ref)	184	1,655
3b without trade (ref)	191	1,671
4a without trade (ref)	91	1,523
4b without trade (ref)	117	1,560
2A with trade	971	5,025
2B with trade	972	5,026
3A with trade	867	4,521
3B with trade	865	4,506
4A with trade	864	4,506
4B with trade	867	4,505

6.3 Electricity Generation Structure

This section analyzes Japan's electricity generation mix under the international emissions trading scenarios (2A through 4B), focusing on the years 2030, 2040, and 2050. While all scenarios meet emissions targets through the global carbon market, they vary in domestic technological configurations and fossil phase-out pathways.

Figures 6.2–6.4 illustrate the power generation mix in percentage terms, and Figures 6.5–6.7 provide absolute generation levels (TWh) by technology.

By 2030, coal power is still present in all international trading scenarios (2A – 4B) at 212 TWh in the scenarios 2A and 2B, and approximately 106 TWh in the scenarios 3A – 4B. This reflects a slower phase-out compared to domestic-only scenarios, enabled by the cost-offset flexibility of trading. Despite this, renewables—including solar, wind, hydro, and bioenergy—expand significantly, particularly in the scenarios 3A to 4B, where total renewable output exceeds 260 TWh. Nuclear power remains stable at 191 TWh across all scenarios, contributing roughly 19 – 22% of the mix.

In 2040, fossil fuel generation declines notably. Coal falls to 182 – 183 TWh in the scenarios 2A – 2B, and to around 113 – 114 TWh in the scenarios 3A – 4B. Gas-fired generation drops to 223 – 236 TWh, with no deployment of gas-CCS. Nuclear output holds steady at 175 TWh, while renewables such as solar and wind continue to grow. Solar generation reaches 152 TWh in the scenarios 2A – 2B and over 220 TWh in the scenarios 3A – 4B. Bioenergy and hydro contribute modest but stable amounts. The total share of non-fossil sources surpasses 60% in most cases.

By 2050, the power mix in all trading scenarios becomes significantly cleaner. Coal power remains at 177 TWh in the scenarios 2A – 2B, but drops below 100 TWh in the scenarios 3A – 4B. Gas power continues at about 119 – 124 TWh in the scenarios 3A – 4B, with no

CCS deployment, indicating a reliance on international credits to offset residual emissions. Renewable generation exceeds 440 TWh in all scenarios, with solar alone reaching up to 211 TWh in the scenarios 3A and 206 TWh in the scenario 4B. Nuclear energy ranges from 131 TWh (scenarios 2A – 2B) to 180 – 174 TWh (scenarios 3A – 4B), playing a key role in ensuring baseload stability.

The data reveal that international emissions trading allows Japan to maintain a flexible, economically efficient power system transition while meeting carbon constraints. Unlike domestic-only scenarios that necessitate deep fossil phase-out and expensive abatement technologies (e.g., CCS), trading scenarios retain moderate levels of coal and gas through credit purchases, reducing pressure on domestic innovation and infrastructure shifts.

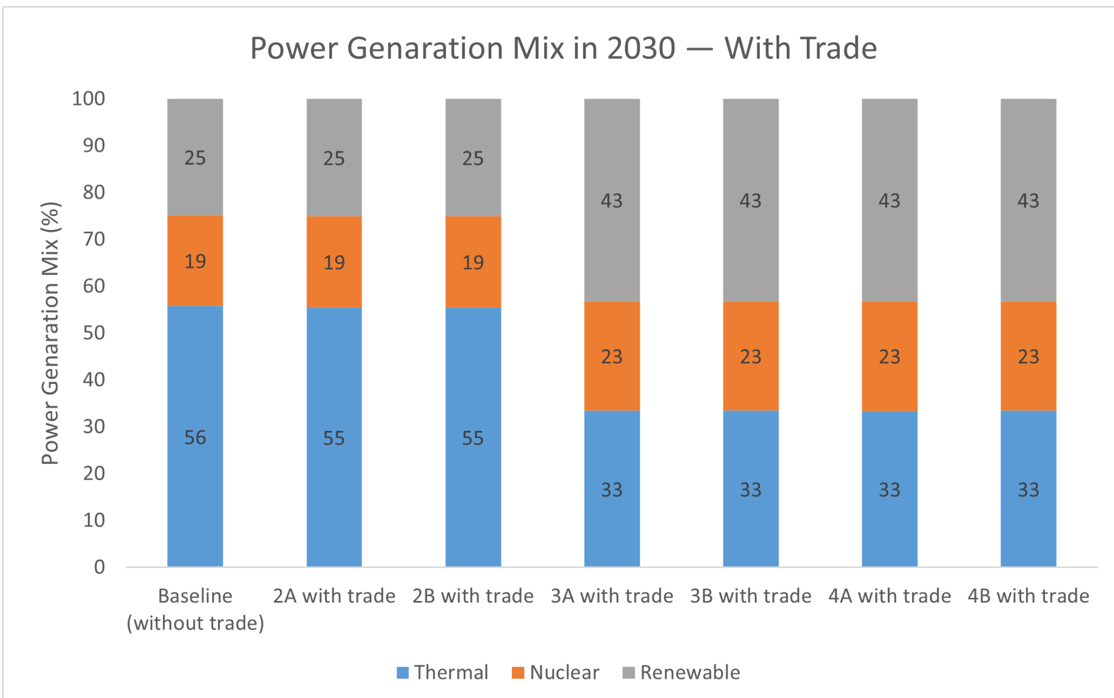


Figure 6.2: Power Generation Mix by Scenario in 2030 (%)

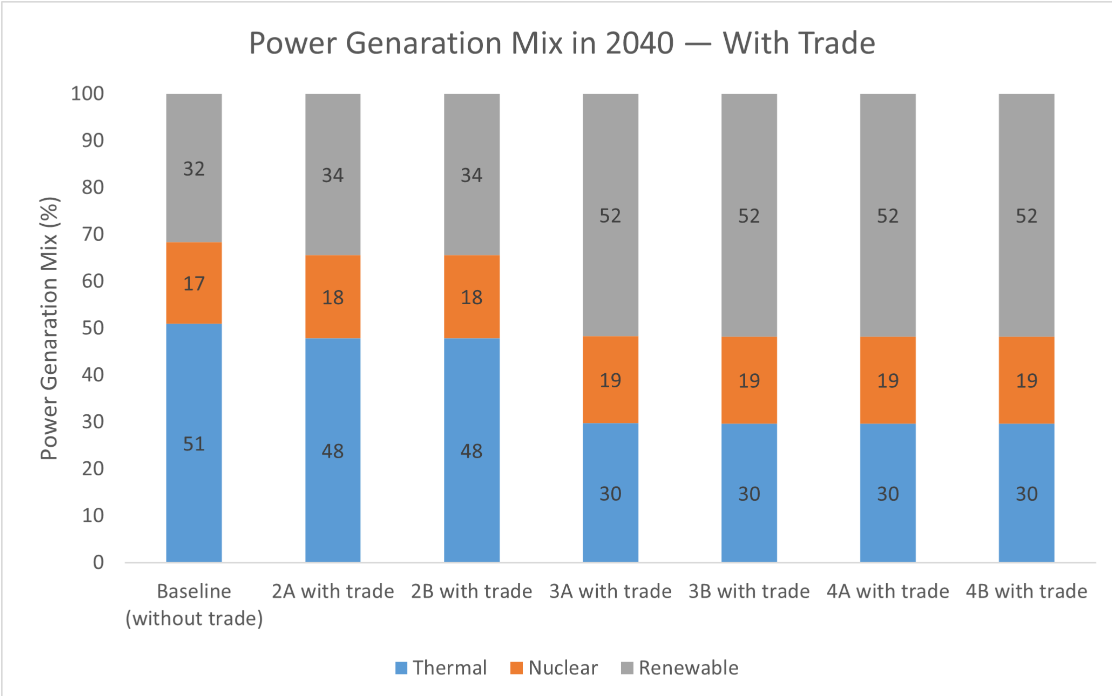


Figure 6.3: Power Generation Mix by Scenario in 2040 (%)

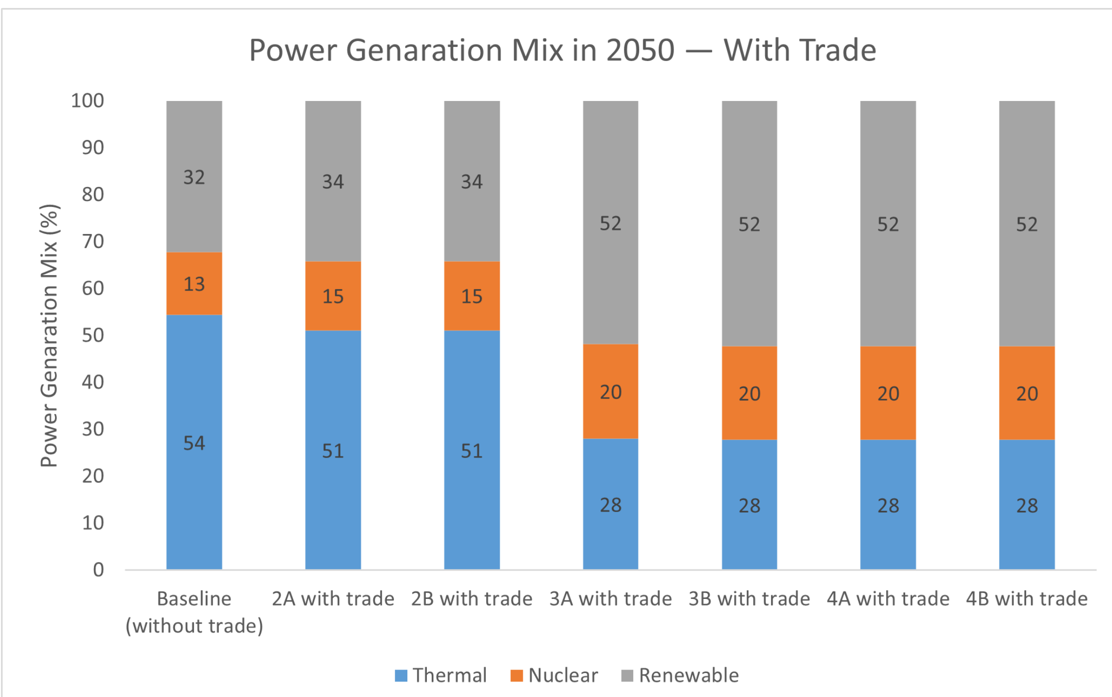


Figure 6.4: Power Generation Mix by Scenario in 2050 (%)

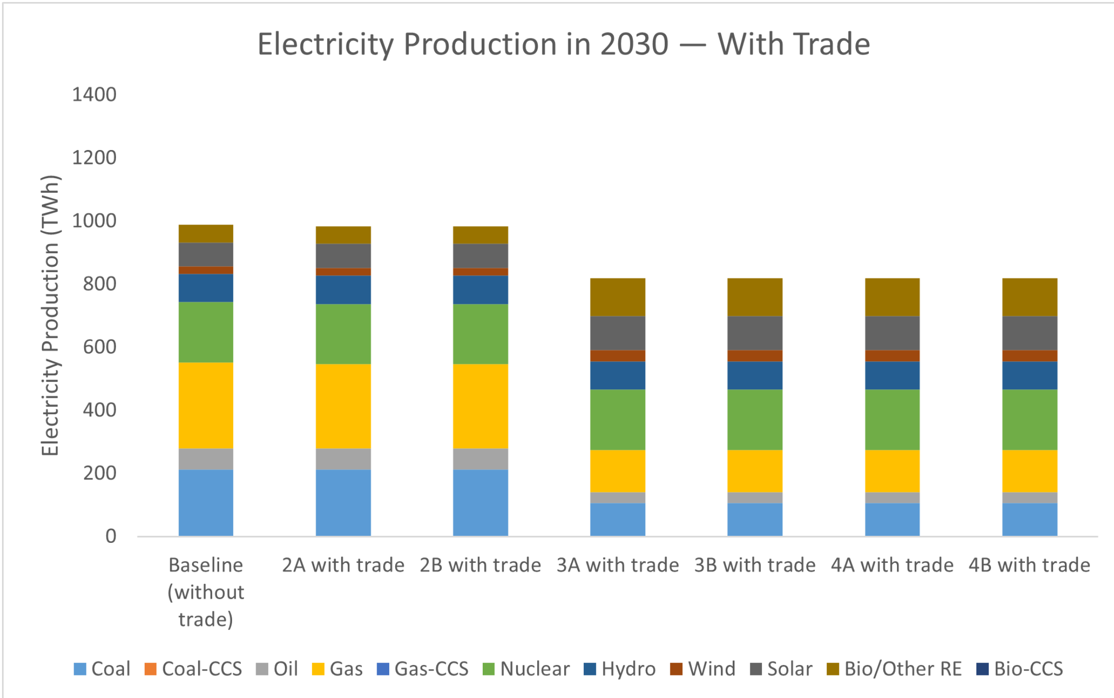


Figure 6.5: Electricity Generation by Source in 2030 (TWh)

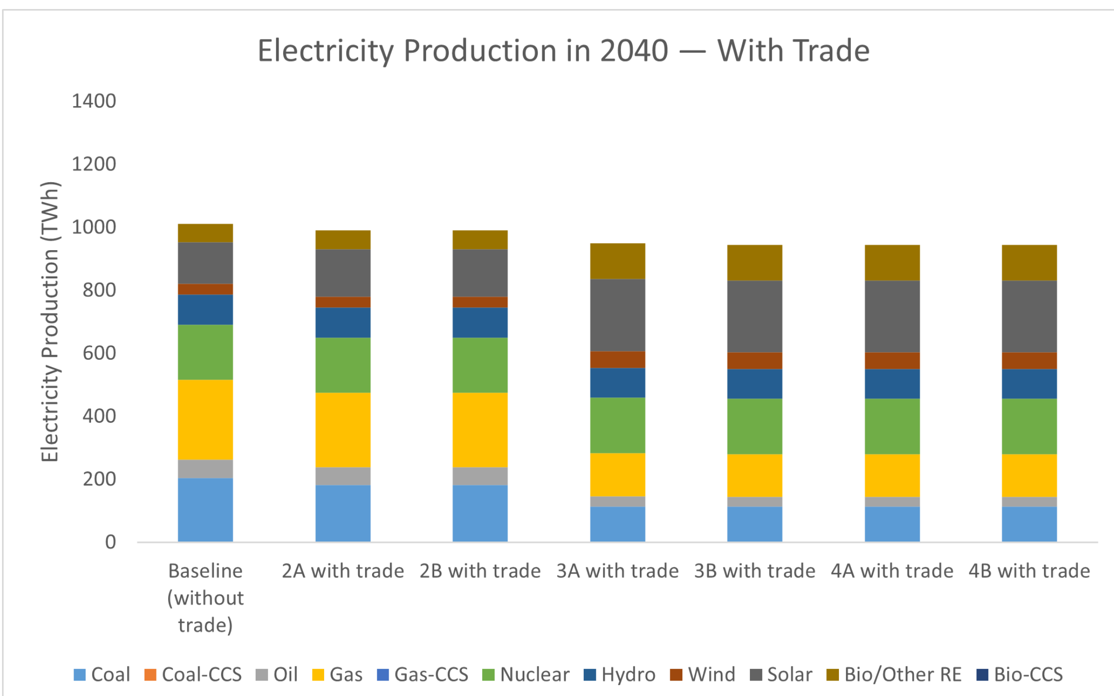


Figure 6.6: Electricity Generation by Source in 2040 (TWh)

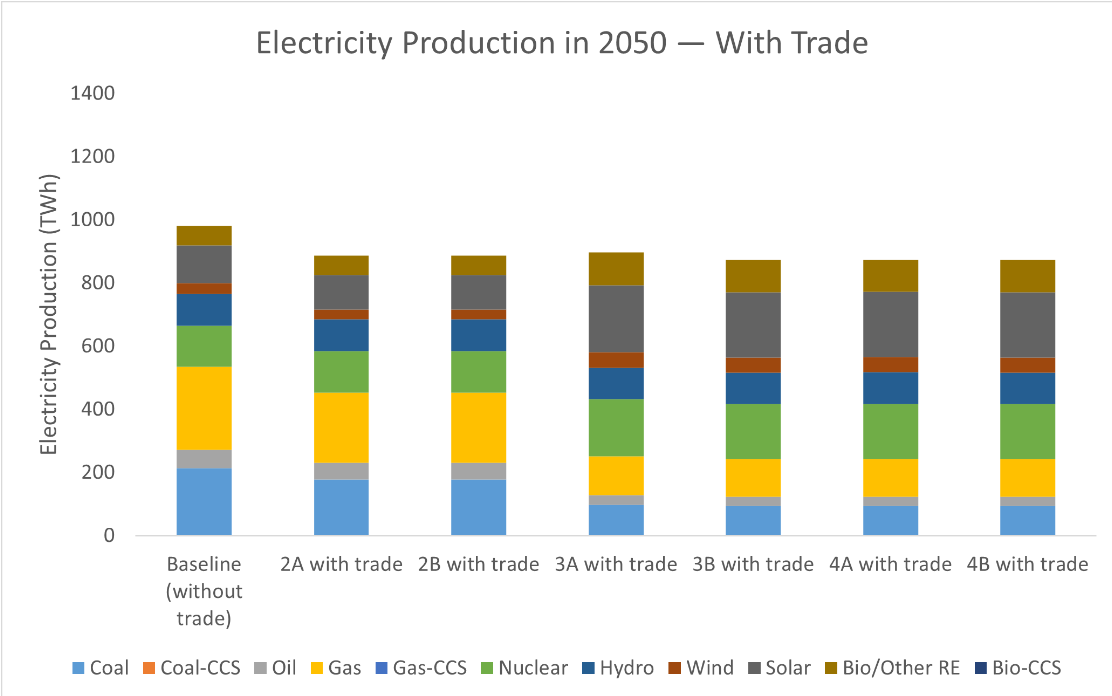


Figure 6.7: Electricity Generation by Source in 2050 (TWh)

6.4 Economic Impact Analysis

The introduction of international emissions trading provides greater flexibility in achieving climate targets and serves as an effective mechanism to alleviate the economic burden on the domestic economy. This section evaluates the economic implications of scenarios 2A through 4B by comparing them with their domestic-only counterparts (scenarios 2a – 4b), focusing on the evolution of real GDP and household consumption between 2030 and 2050.

As shown in Figures 6.8 and 6.9, both GDP and consumption steadily increase in all international trading scenarios. However, the pace and scale of growth vary depending on policy stringency and the availability of trading mechanisms.

For instance, under Scenario 4B, real GDP reaches $6.495 trillion and real household consumption reaches $3.682 trillion in 2050 (both in 2015 USD). Compared to the corresponding domestic-only scenario 4b (GDP: $5.757 trillion, consumption: $3.326 trillion), this represents an increase of $738 billion in GDP and $356 billion in consumption. Furthermore, the policy cost in terms of GDP is reduced from 12.8% in the Scenario 4b to 1.6% in the Scenario 4B, and the consumption loss decreases from 10.9% to 1.3%.

A similar trend is observed when comparing scenarios 3B and 3b. In 2050, the scenario 3B achieves a GDP of $6.495 trillion and consumption of $3.683 trillion, compared to $5.947 trillion and $3.424 trillion in the scenario 3b. This corresponds to improvements of $548 billion and $259 billion, respectively. The GDP loss rate drops from 9.9% to 1.6%, and the consumption loss rate from 8.2% to 1.3%.

In terms of emissions reduction, international trading scenarios tend to achieve smaller domestic reductions. For example, the 2050 net GHG emissions under the scenario 4b are reduced to 117 $MtCO_2e$, whereas under the scenario 4B they remain at 864 $MtCO_2e$. This reflects the substitution of domestic efforts with internationally acquired emissions credits.

As summarized in Figures 6.10 and 6.11 and Table 6.3, cumulative GDP losses from 2030 to 2050 are also significantly lower in all scenarios that incorporate international trading. In particular, the scenario 4a incurs a cumulative loss of \$367 billion, while the scenarios 4A reduces this to \$307.9 billion, saving approximately \$59 billion. These results clearly demonstrate that international trading substantially mitigates macroeconomic policy costs.

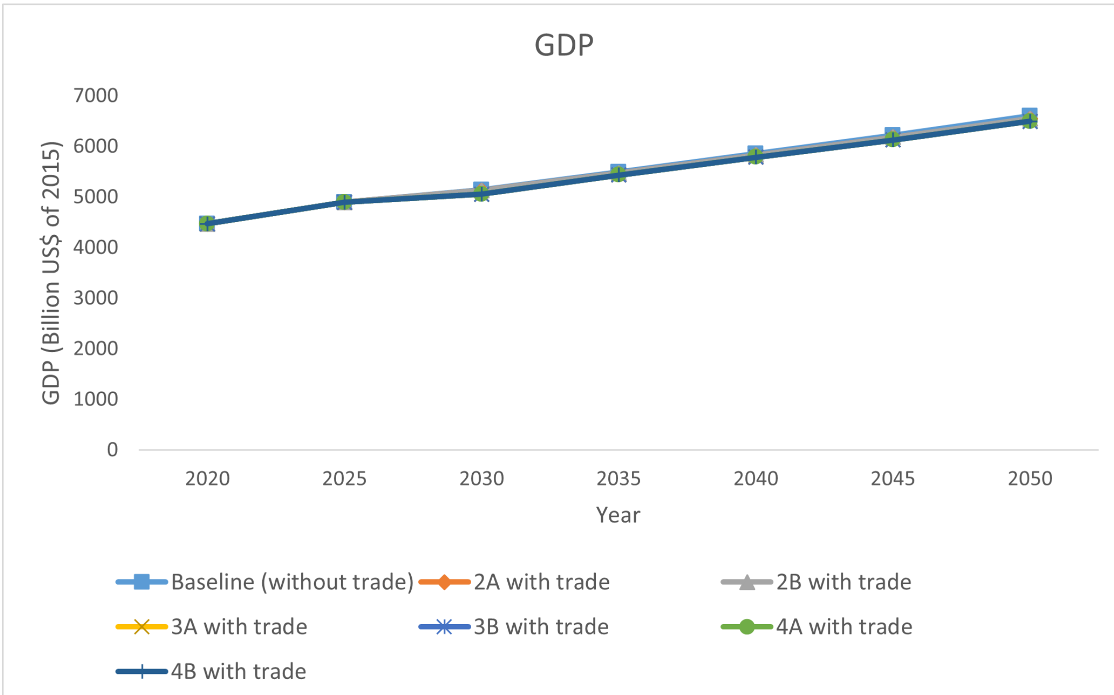


Figure 6.8: Real GDP (Billion US$ of 2015)

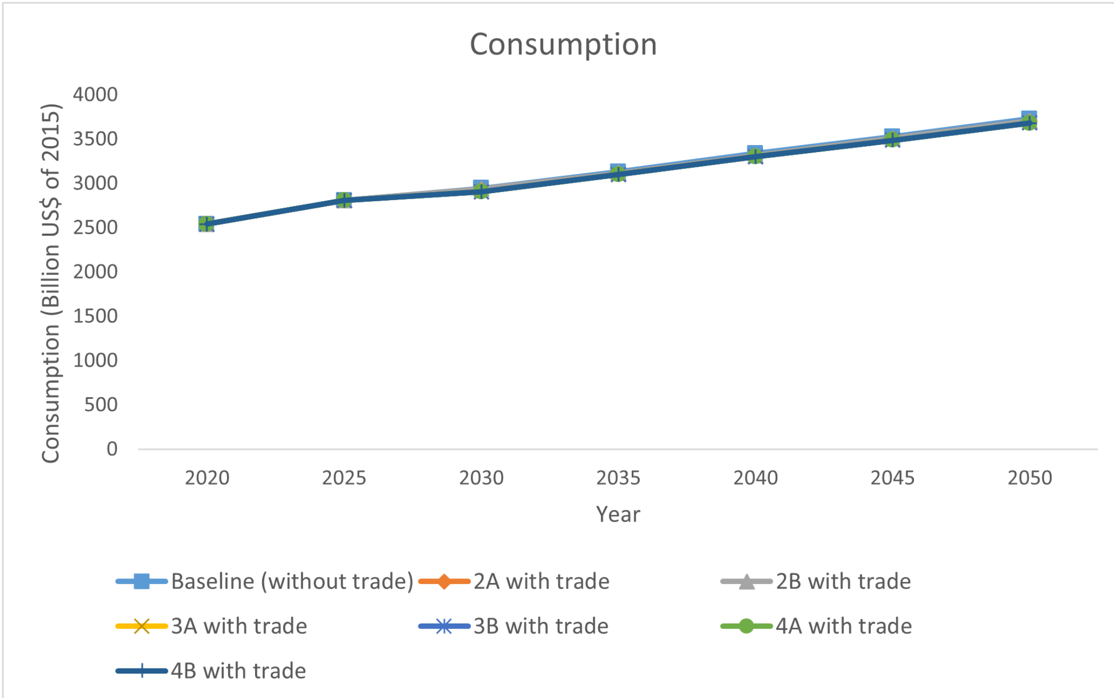


Figure 6.9: Real Household Consumption (Billion US$ of 2015)

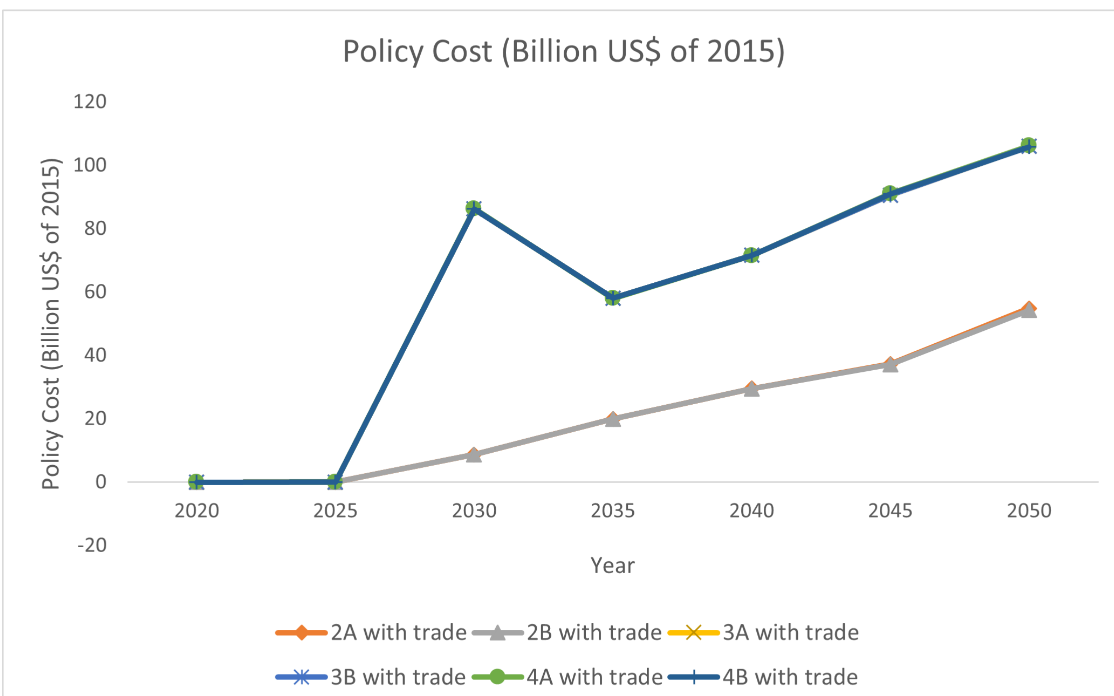


Figure 6.10: Policy Cost (2030 – 2050) (Billion US$ of 2015)

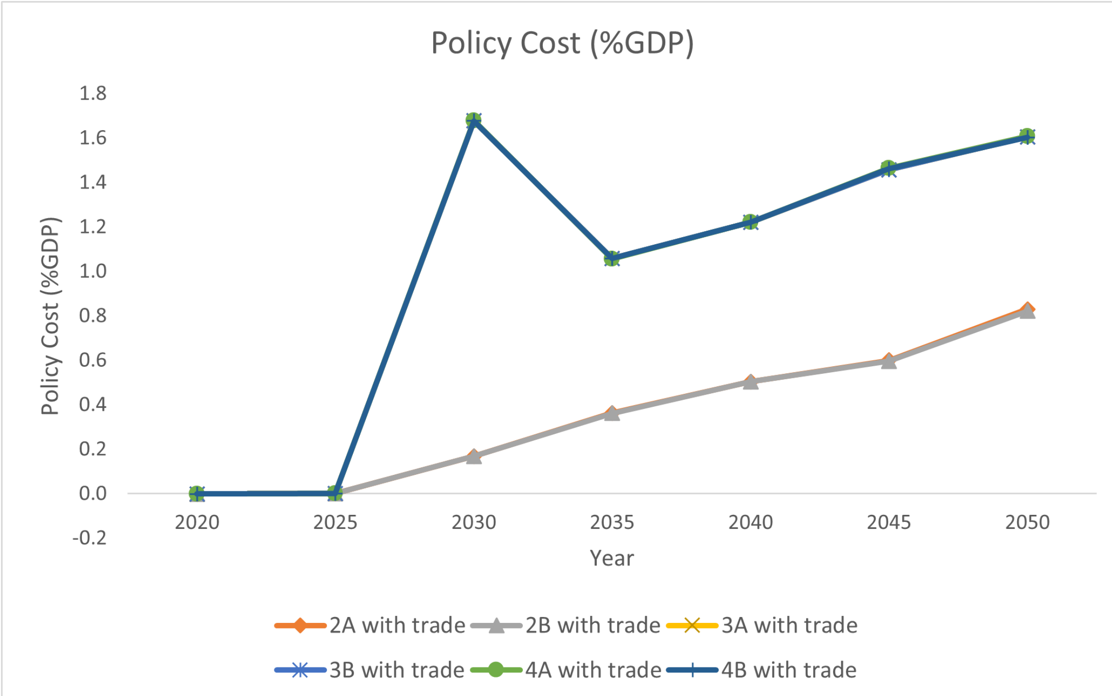


Figure 6.11: Policy Cost (2030 – 2050) (%GDP)

Table 6.3: Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050)

Scenario	**Reduction vs. Baseline (in 2050) (Billion US$ of 2015)**	**Reduction vs. Baseline (in 2050) (%GDP)**	**Cumulative Policy Cost (2030–2050) (Billion US$ of 2015)**
2A with trade	55	0.8	150
2B with trade	54	0.8	149
3A with trade	106	1.6	412
3B with trade	106	1.6	412
4A with trade	106	1.6	413
4B with trade	106	1.6	413

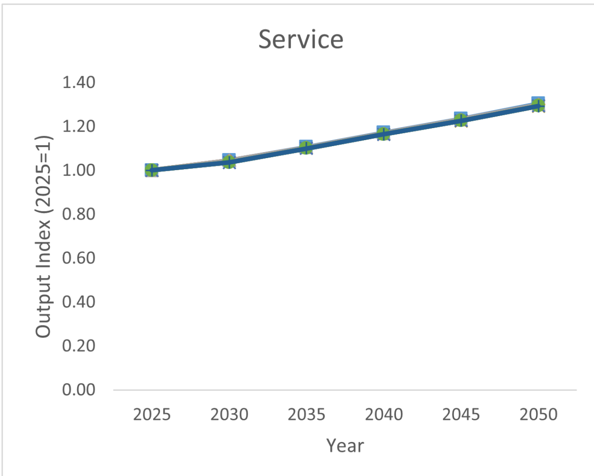
6.5 Sectoral Economic Impacts

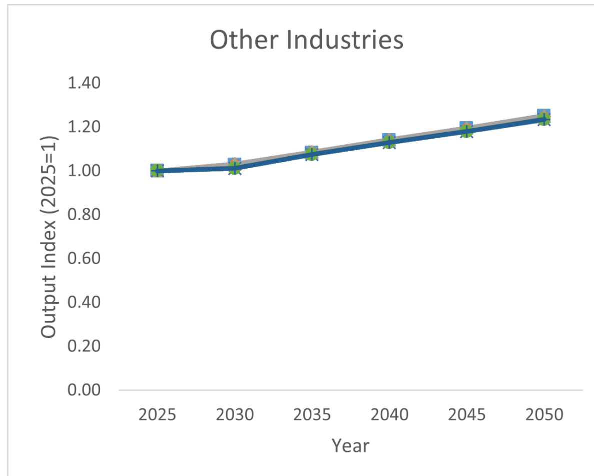
This section evaluates the sector-specific implications of introducing international emissions trading under deep decarbonization scenarios.

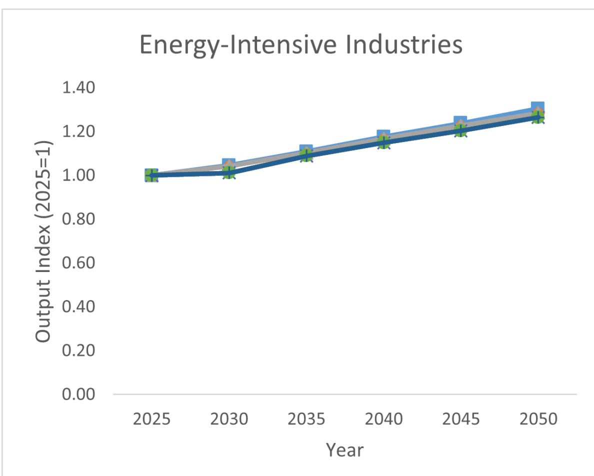
6.5.1 Industrial Sectoral Economic Impacts

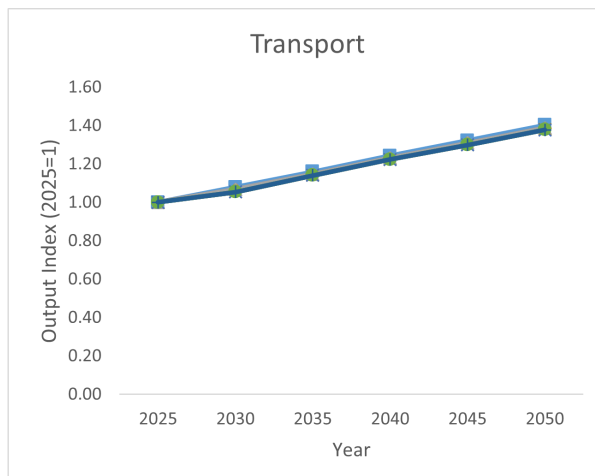
As shown in Figure 6.12, international emissions trading contributes to greater convergence in output trends across industrial sectors. In contrast to domestic-only mitigation—where carbon-intensive sectors face sharp declines while others remain stable or grow, leading to significant divergence—trading mechanisms reduce such disparities by reallocating mitigation burdens more efficiently across the economy.

As a result, the overall industrial structure becomes more stable, with output indices clustering more closely around the baseline trajectory. This outcome highlights the role of emissions trading in enhancing structural resilience, allowing industrial activities to proceed with less disruption even under ambitious decarbonization goals.









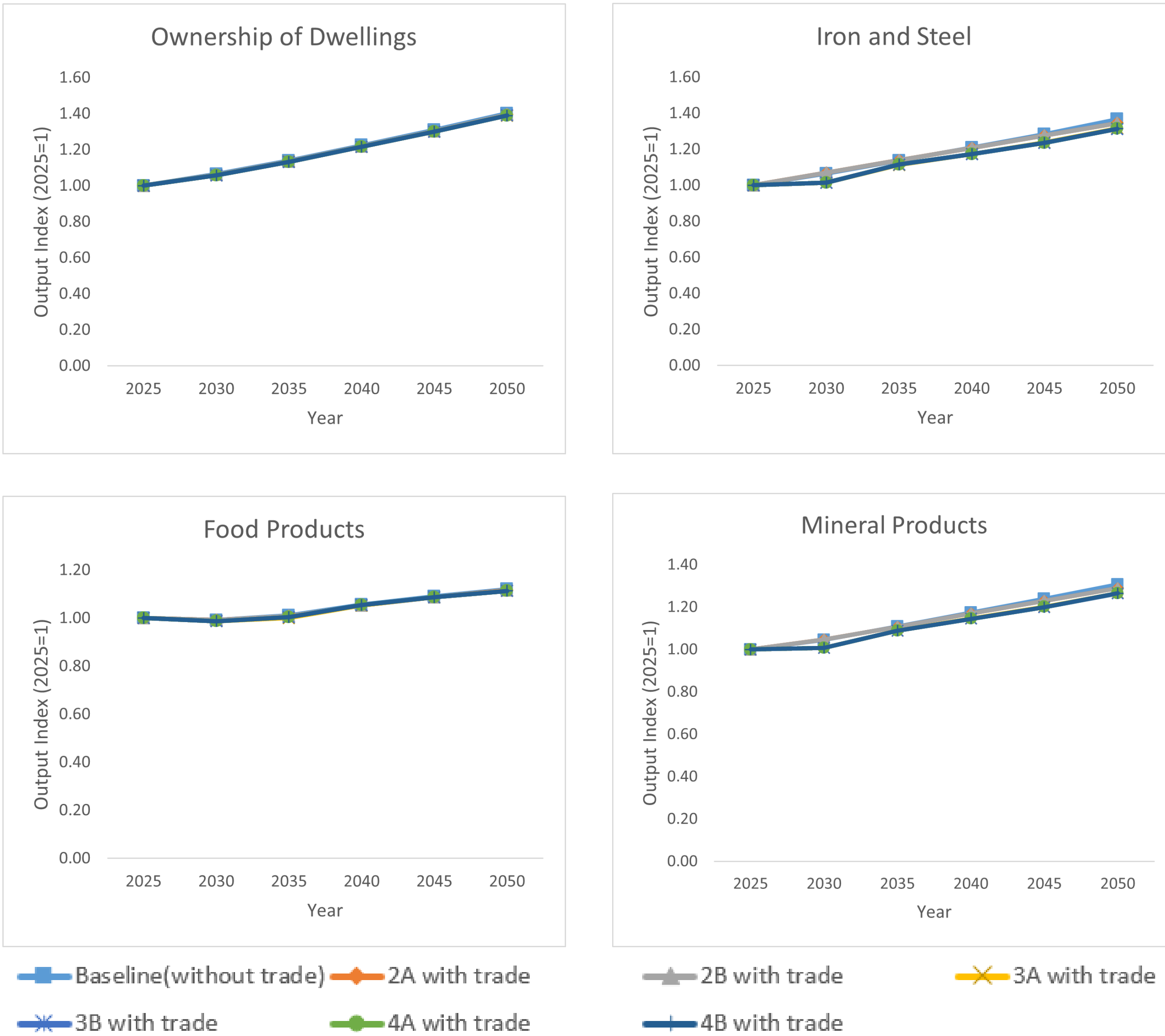


Figure 6.12: Sectoral Output Index (2025 = 1) across Industrial and Service Sectors

6.5.2 Energy-related Sectoral Economic Impacts

As shown in Figure 6.13, energy-related sectors exhibit the greatest variation in output trajectories depending on policy design. In domestic-only mitigation scenarios, fossil fuel supply sectors—such as coal, oil, and natural gas—experience steep declines, in some cases approaching near-total phaseout. By contrast, the introduction of international emissions trading significantly mitigates this contraction, enabling these sectors to retain a portion of their output.

Electricity generation shows a more complex pattern. Under domestic-only policies, high carbon prices drive large-scale investments in CCS and renewable technologies, temporarily boosting electricity output. In contrast, scenarios with international trading shift part of the mitigation burden abroad, which reduces the need for aggressive domestic capacity expansion and moderates output growth.

In summary, international emissions trading plays a balancing role in the energy transition by slowing the decline of fossil fuel sectors and avoiding excessive expansion in the power sector. For fossil fuel-dependent economies in particular, this mechanism serves as a critical policy tool to enable a more realistic and cost-effective path to decarbonization.

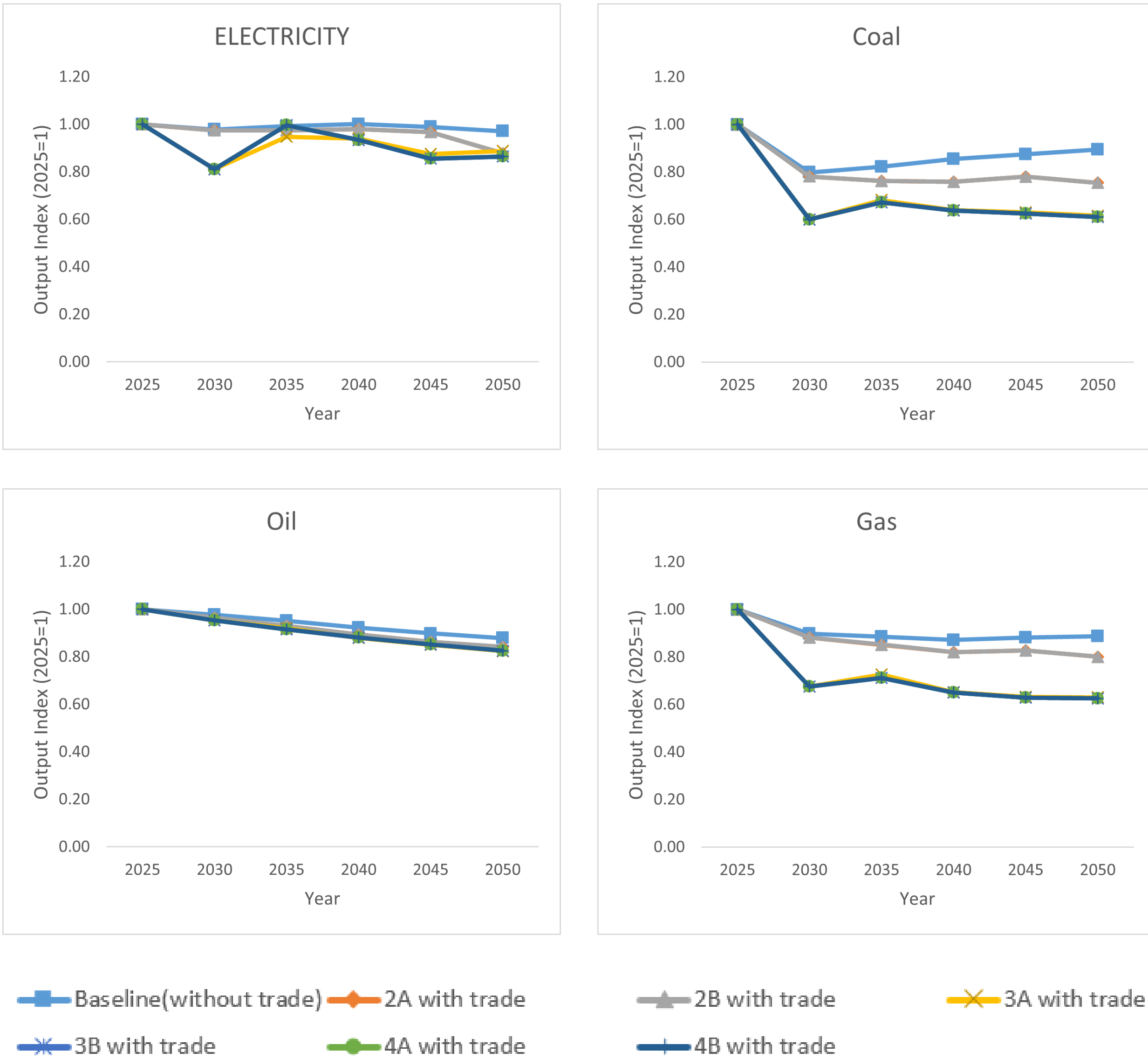


Figure 6.13: Sectoral Output Index (2025 = 1) in Energy-related Sectors

6.6 Carbon Prices

This section evaluates the cost-effectiveness of international emissions trading scenarios. As shown in Figures 6.15 and 6.14, the level and trajectory of carbon prices differ significantly depending on the presence of international trading. In the scenario 4a, where Japan aims to achieve net-zero emissions solely through domestic measures, the carbon price reaches an extreme level of $46,928 per ton of CO_2 by 2050, illustrating the severe economic burden in the absence of flexible mitigation options. Even in the scenario 4b, where CCS is introduced, the carbon price still rises to \$1,630/tCO_2 in 2050.

In contrast, scenarios with international emissions trading (scenarios 2A through 4B) exhibit a markedly different trend. The carbon price peaks at \$32/tCO_2 in 2030 and gradually declines to around \$17 by 2050. This represents a reduction of more than 99% compared to the scenario 4a, and even relative to moderate domestic scenarios such as scenarios 3b, the cost remains significantly lower.

These results clearly demonstrate that the introduction of international emissions trading substantially reduces the marginal cost of abatement.

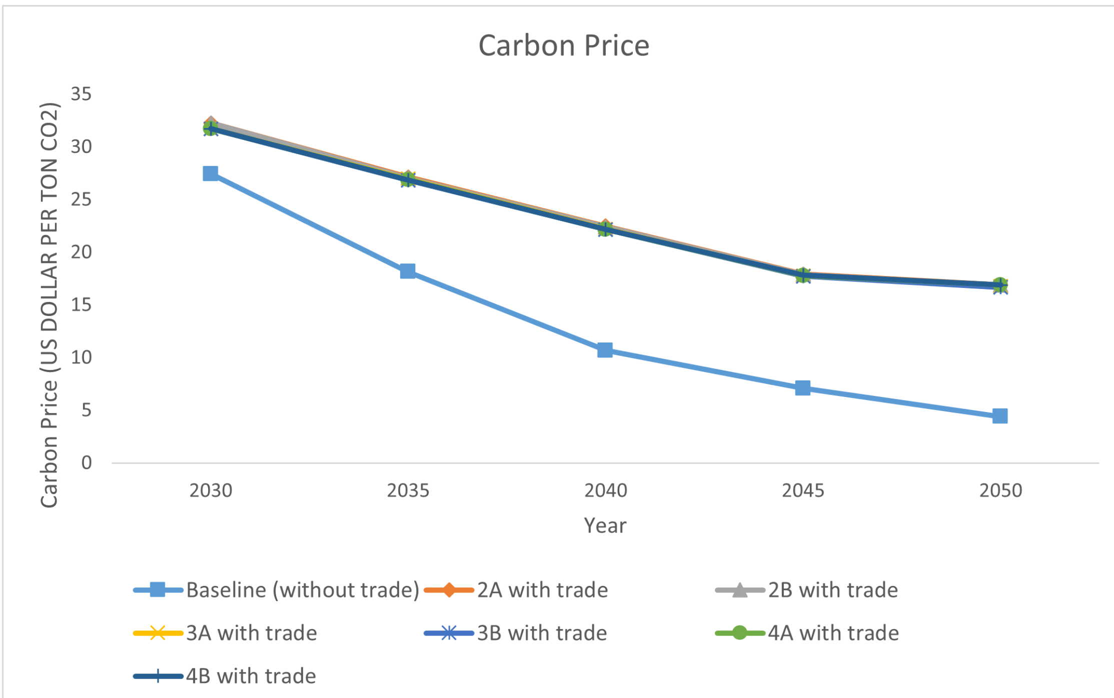


Figure 6.14: Carbon Price With International Emissions Trading (US\$/tCO_2)

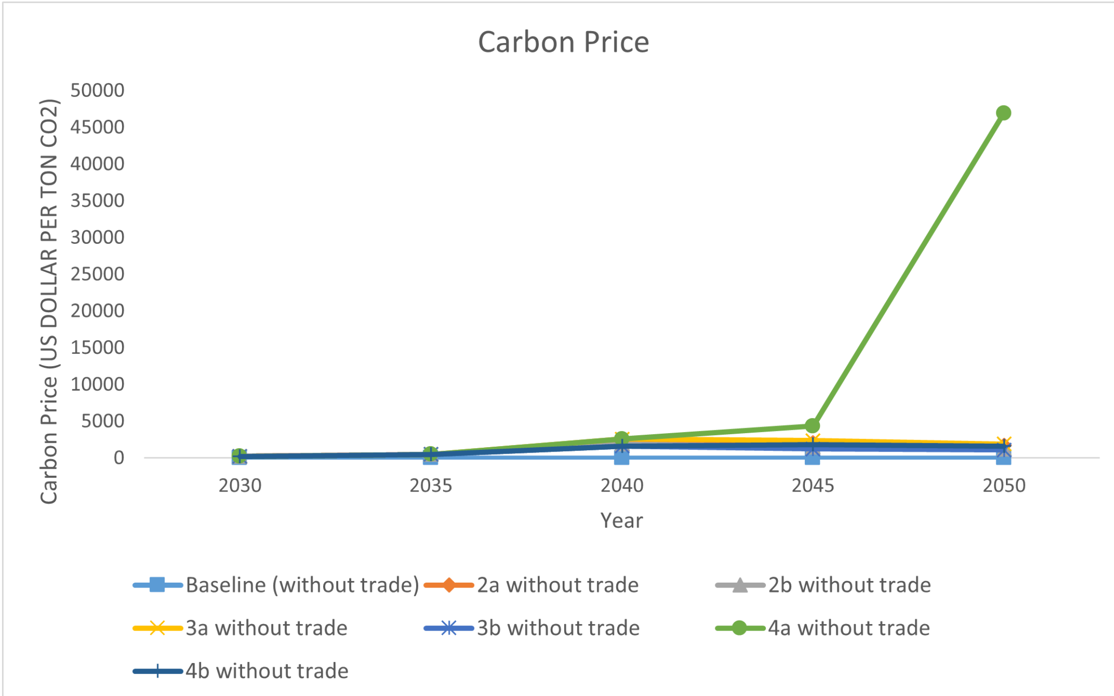


Figure 6.15: Carbon Price Without International Emissions Trading (US\$/tCO_2) *(Reproduced from Chapter 5)*

6.7 Policy Implications of International Emissions Trading

The analysis in this chapter has demonstrated that international emissions trading plays a crucial role in supporting Japan's decarbonization strategy, both environmentally and economically. This section summarizes the key policy implications in four major areas.

1. Enhanced Economic Sustainability

First, international trading significantly reduces the marginal abatement cost for Japan, thereby enhancing economic sustainability. As shown in Section 6.6, the carbon price in 2050 reaches nearly \$47,000/tCO_2 under the domestic-only Scenario 4a, whereas scenarios 4A and 4B, which incorporate trading, maintain prices below \$20/tCO_2. This stark contrast illustrates the critical importance of flexible international mechanisms in containing economic burden and ensuring long-term feasibility.

2. Industrial Competitiveness and Sectoral Resilience

Second, international trading mitigates adverse impacts on energy- and emissions-intensive sectors. Section 6.5 showed that output indices in sectors such as electricity, refined oil, and basic materials remain significantly higher in scenarios 4A and 4B than in scenario 4a, indicating that international credit mechanisms preserve industrial competitiveness. This is particularly relevant for Japan, whose industrial base is heavily exposed to carbon price volatility.

3. Strategic Leverage through International Cooperation

Third, international trading offers a strategic opportunity to expand Japan's influence in global climate action. Mechanisms such as the Joint Crediting Mechanism (JCM) enable Japan to partner with developing countries in implementing cost-effective mitigation projects. These partnerships not only reduce Japan's compliance costs but also promote low-carbon development, technology transfer, and diplomatic engagement.

In conclusion, international emissions trading is not merely a cost-containment measure but a structural enabler of realistic and resilient decarbonization. To fully leverage its benefits, Japan should proactively promote the development of transparent, credible, and inclusive international market mechanisms, while integrating these tools into its national carbon neutrality roadmap.

Chapter 7

Integrated Policy Scenarios

7.1 Policy Design and Scenario Overview

This chapter evaluates the feasibility of integrated decarbonization scenarios (5a and 5b) that combine robust domestic mitigation with partial use of international emissions trading. While global carbon markets offer a potentially efficient tool for achieving emissions reductions, it is neither realistic nor institutionally guaranteed that they will always function perfectly. Therefore, sustained domestic efforts remain essential for ensuring the credibility and resilience of national decarbonization strategies.

Scenarios that rely too heavily on external credits may face political, technical, or diplomatic barriers. To address these concerns, this chapter explores scenarios that preserve a significant level of domestic abatement while utilizing international cooperation as a complementary mechanism. Specifically, the scenarios 5a and 5b assume that 60% and 80% of the required reductions by 2050 are achieved domestically, with the remaining portion fulfilled through carbon credit purchases. This framework allows for a comprehensive assessment of how deep emission cuts can be achieved under more realistic and institutionally sustainable conditions.

This section outlines the policy framework and scenario settings for integrated mitigation pathways (scenarios 5a and 5b), which balance substantial domestic reductions with partial use of international emissions trading. These scenarios are designed to evaluate the feasibility of achieving deep emission cuts while maintaining economic stability and institutional realism.

The scenario 5a assumes that 60% of the required emission reductions by 2050 are achieved through domestic measures, with the remaining 40% covered by international carbon credits. The scenario 5b raises the domestic mitigation share to 80%, allowing only 20% of reductions to be achieved via trading. Both scenarios incorporate the full achievement of the 2030 and 2040 power mix targets and assume active deployment of carbon capture and storage (CCS) technologies. Mitigation is focused on solely on CO_2 reduction.

Table 7.1 summarizes the policy elements of scenarios 5a and 5b.

Table 7.1: Composition of Intermediate Domestic Mitigation Scenarios (5a – 5b)

Scenario	NDC Targets	Power Mix Targets	CCS Deployment	International Trading
Baseline without trade (ref)	×	×	×	×
3b without trade (ref)	✓	×	✓	✓
5a with limited trade	✓(60%)	✓	✓	×
5b with limited trade	✓(80%)	✓	✓	×
3B with trade (ref)	✓	✓	✓	✓

7.2 Changes in Greenhouse Gas Emissions

This section evaluates the emissions trajectories and mitigation effects of the scenarios 5a and 5b. For comparison, the analysis includes the Baseline scenario and the scenario 3b, which achieves full implementation of Japan's 2030 and 2040 NDC and power mix targets as well as the deployment of carbon capture and storage (CCS) technologies without international emissions trading. For illustrative purposes, I also include the scenario 3B, which achieves the same targets through the use of international carbon trading.

As shown in Figure 7.1, The scenario 5a achieves a moderate reduction trajectory, with emissions declining to 645 MtCO_2e in 2040 and 651 MtCO_2e in 2050. This corresponds to an approximately 51% reduction relative to 2015 levels. The scenario 5b, representing a more ambitious pathway, reduces emissions further to 410 MtCO_2e in 2040 and 418 MtCO_2e in 2050—about 68.5% below 2015 levels.

Table 7.2 summarizes GHG emissions in 2050 and cumulative reductions compared to the baseline. Cumulative emissions over the period 2030 – 2050 are 3,679 MtCO_2e in the scenario 5a and 2,667 MtCO_2e in the scenario 5b, implying an additional reduction of approximately 1,012 MtCO_2e in the scenario 5b (about 30% lower than 5a).

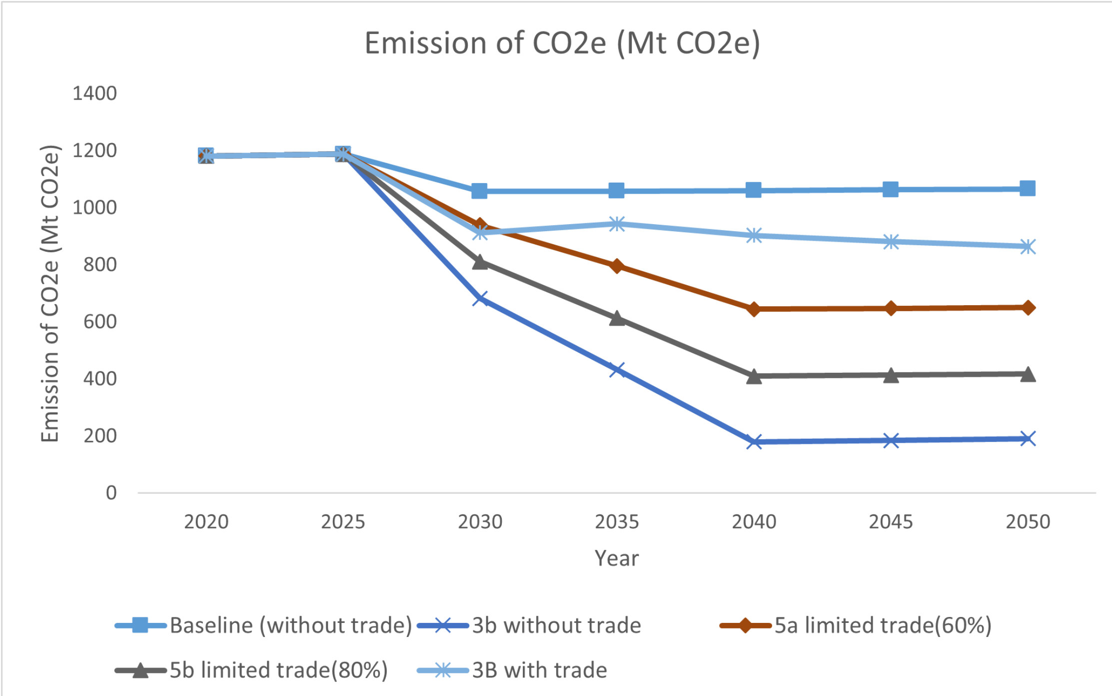


Figure 7.1: CO_2 Emissions Trajectory in Scenarios 5a and 5b

Table 7.2: Cumulative GHG Emissions (2030–2050, $MtCO_2e$)

Scenario	2050 Emissions ($MtCO_2e$)	Cumulative Emissions (2030–2050) ($MtCO_2e$)
Baseline without trade (ref)	1066	5,306
3a without trade (ref)	184	1,655
5a with limited trade	651	3,679
5b with limited trade	418	2,667
3b without trade (ref)	191	1,671

7.3 Energy Generation Structure

This section examines the structure of electricity generation in scenarios 5a and 5b, which represent intermediate mitigation pathways combining domestic efforts with limited international emissions trading. Figures 7.2–7.4 present the power generation mix in percentage terms, while Figures 7.5–7.7 display total electricity generation in TWh by energy source for 2030, 2040, and 2050.

In 2030, both scenarios achieve the renewable and nuclear targets set in the power mix policy, with renewables accounting for approximately 43% of generation. Solar and wind play an increasingly central role, while fossil-based generation is reduced.

By 2040, fossil fuels are further phased out, and CCS becomes more prominent. In the scenario 5a, CCS accounts for about 7% of generation, while in the scenario 5b, it increases to 11%. Nuclear power remains stable at around 175–180 TWh in both cases.

In 2050, the scenario 5a achieves a generation mix of 75% renewables, 18% nuclear, and 7% CCS-based fossil generation. The scenario 5b shows a slightly higher CCS contribution and a corresponding decrease in renewables. This diversification reflects a pragmatic balance between technological feasibility, cost control, and emissions mitigation.

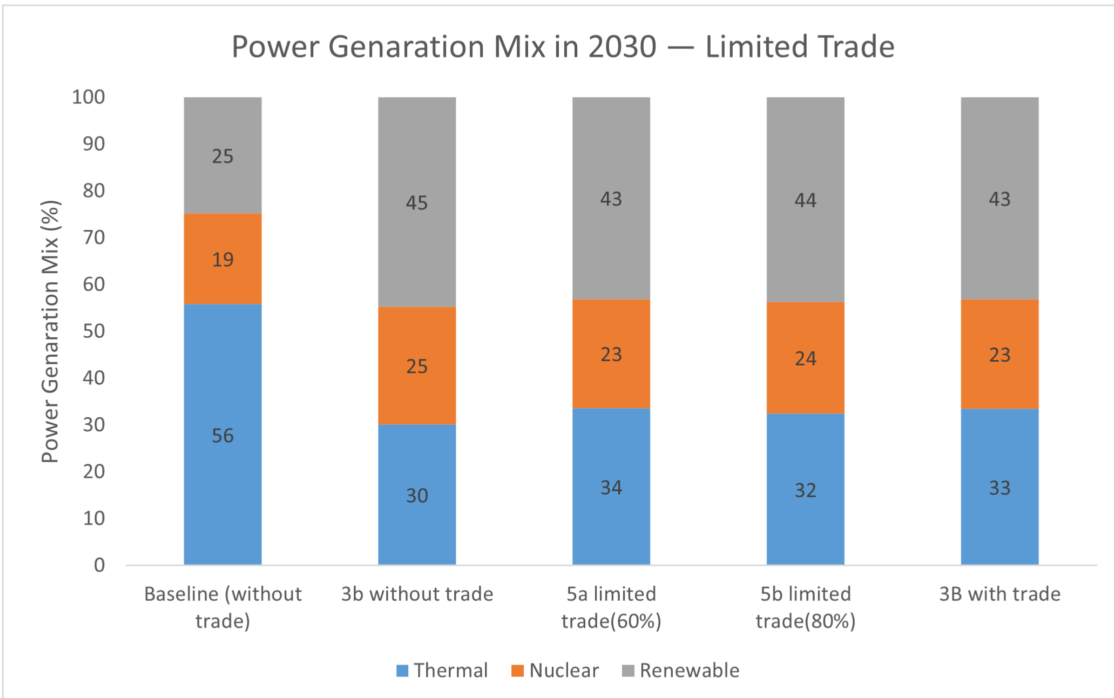


Figure 7.2: Power Generation Mix by Scenario in 2030 (%)

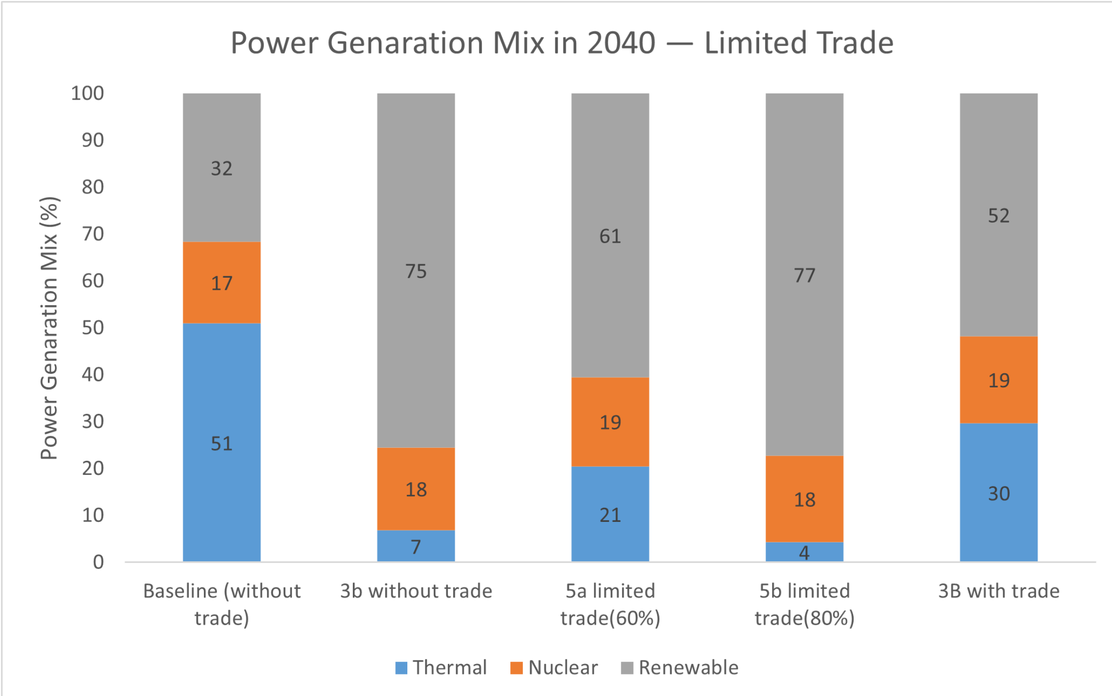


Figure 7.3: Power Generation Mix by Scenario in 2040 (%)

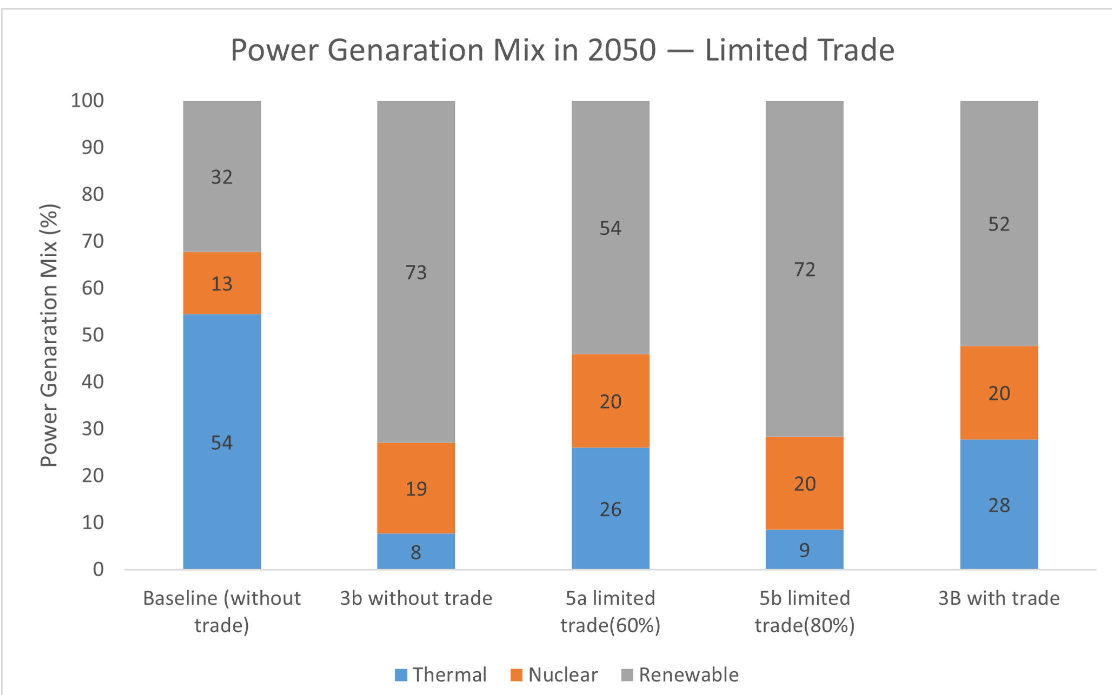


Figure 7.4: Power Generation Mix by Scenario in 2050 (%)

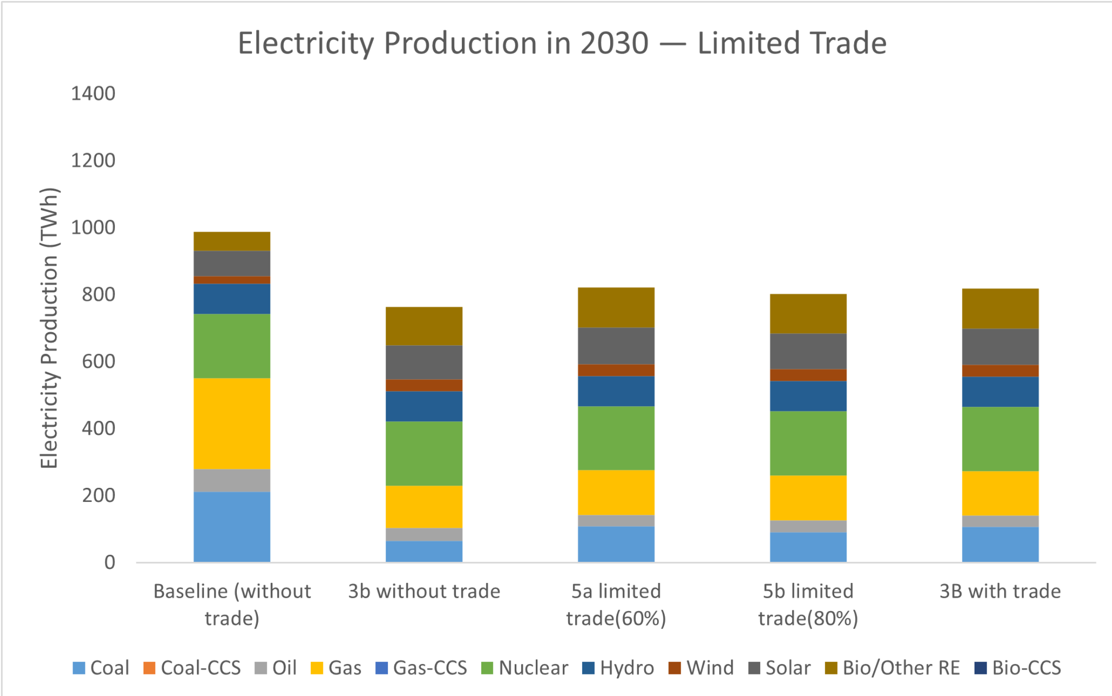


Figure 7.5: Electricity Generation by Source in 2030 (TWh)

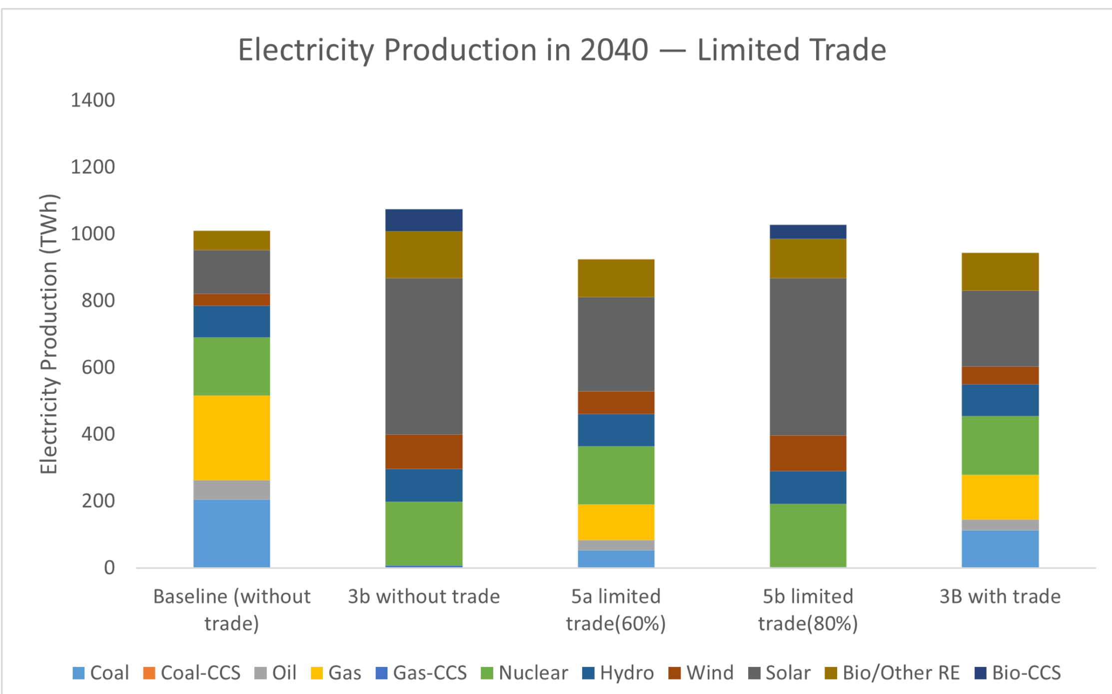


Figure 7.6: Electricity Generation by Source in 2040 (TWh)

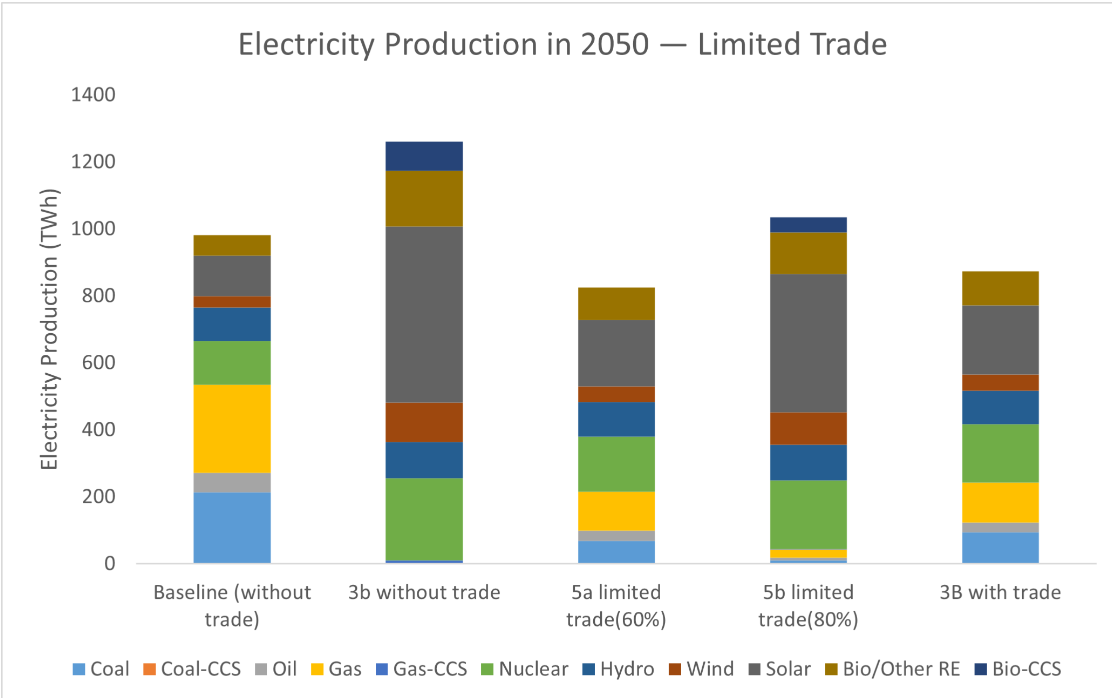


Figure 7.7: Electricity Generation by Source in 2050 (TWh)

7.4 Economic Impact Analysis

This section evaluates the macroeconomic effects and policy costs of the scenarios 5a and 5b.

As shown in Figures 7.8 and 7.9, both scenarios maintain a trajectory of real GDP and consumption growth, though with varying degrees of mitigation-induced slowdown. In 2050, real GDP reaches \$6.47 trillion in the scenario 5a and \$6.26 trillion in the scenario 5b, compared to \$6.60 trillion in the baseline. Household consumption in 2050 follows a similar pattern: \$3.65 trillion in the scenario 5a and \$3.54 trillion in the scenario 5b.

Policy costs are evaluated in terms of GDP loss relative to the baseline. As summarized in Table 7.3 and visualized in Figure 7.10, The scenario 5a incurs a cumulative GDP loss of \$196 billion (US\$ of 2015) from 2030 to 2050, equivalent to about 1.4% of baseline GDP in 2050. The scenario 5b, with more stringent reduction targets, results in a cumulative GDP loss of \$422 billion, or approximately 3.1%.

Despite higher costs, the scenario 5b remains more cost-effective than high-ambition scenarios like scenario 4a, which incur GDP losses exceeding \$1.5 trillion. Both scenarios 5a and 5b deliver substantial mitigation at moderate economic cost, highlighting their feasibility as transitional options.

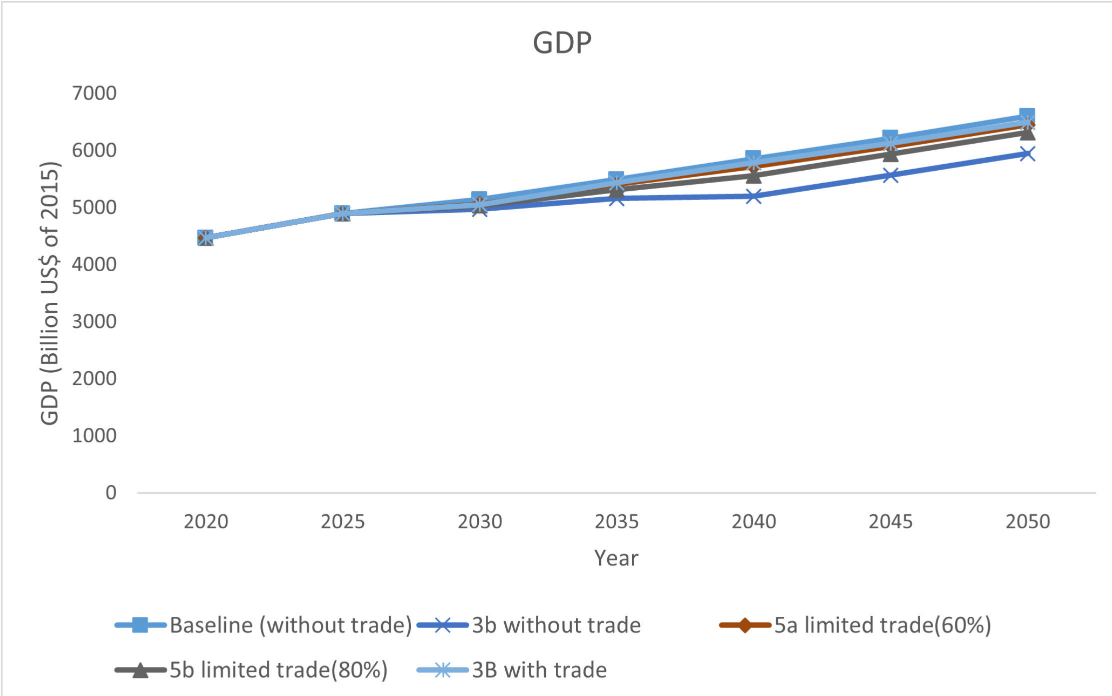


Figure 7.8: Real GDP (Billion US$ of 2015)

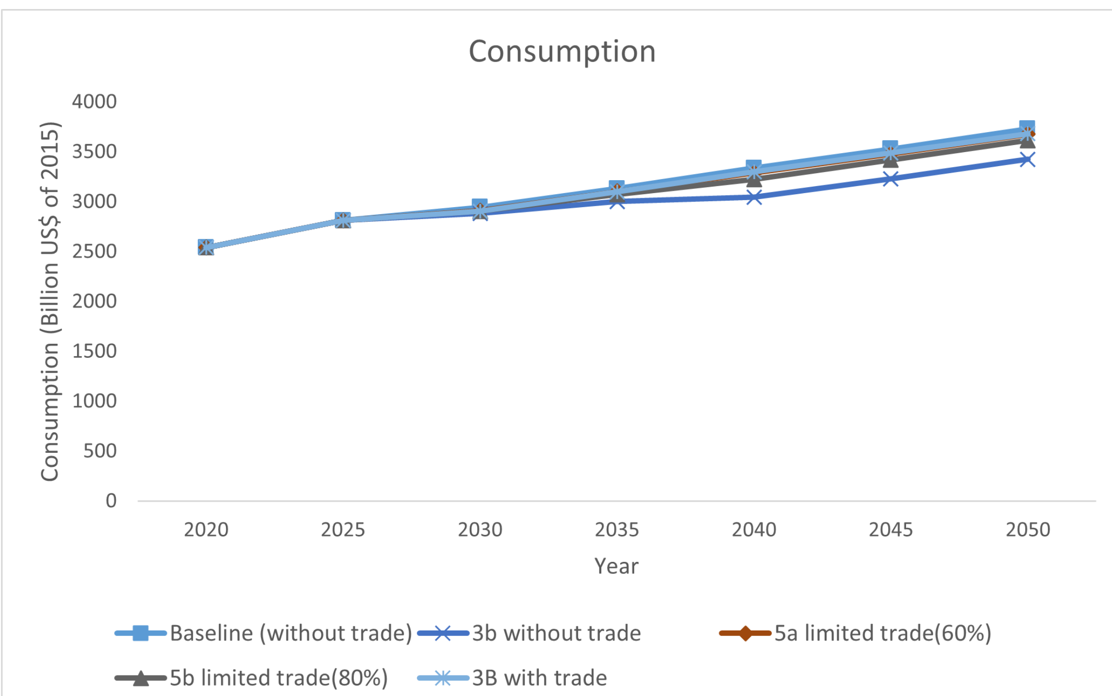


Figure 7.9: Real Consumption (Billion US$ of 2015)

Table 7.3: Policy Costs (GDP Loss) in 2050 and Cumulative Policy Costs (2030–2050)

Scenario	**Reduction vs. Baseline (in 2050) (Billion US$ of 2015)**	**Reduction vs. Baseline (in 2050) (%GDP)**	**Cumulative Policy Cost (2030–2050) (Billion US$ of 2015)**
3b without trade	655	9.9	2,457
5a limited trade (60%)	152	2.3	599
5b limited trade (80%)	286	4.3	1,152
3B with trade	106	1.6	412

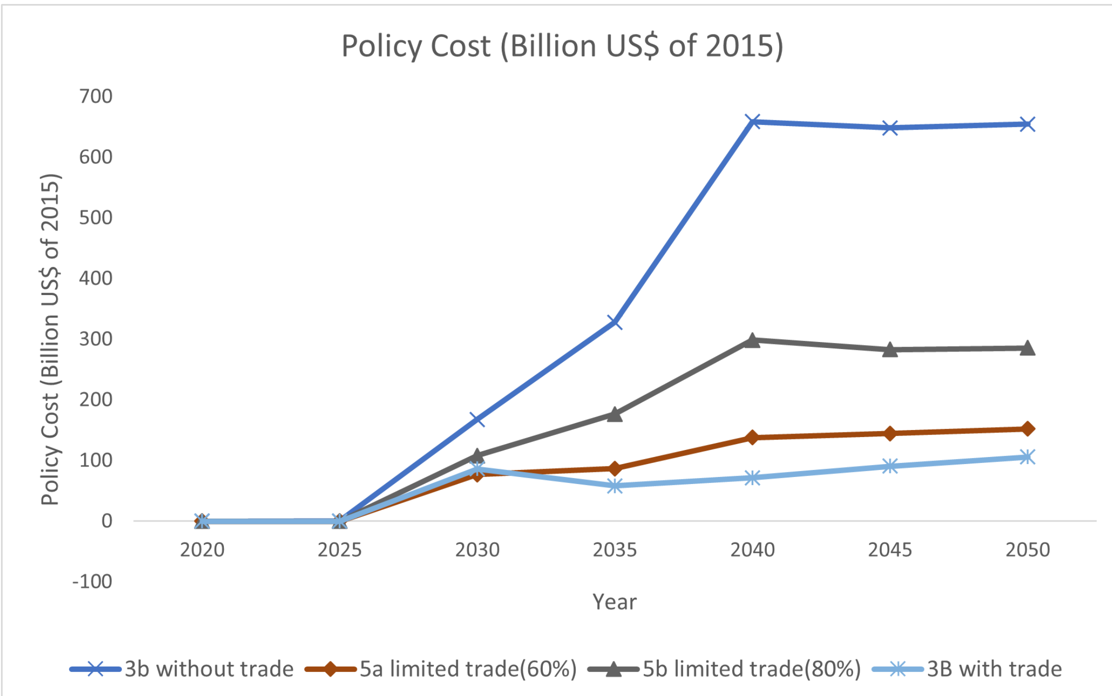


Figure 7.10: Policy Cost (2030 – 2050) (Billion US$ of 2015)

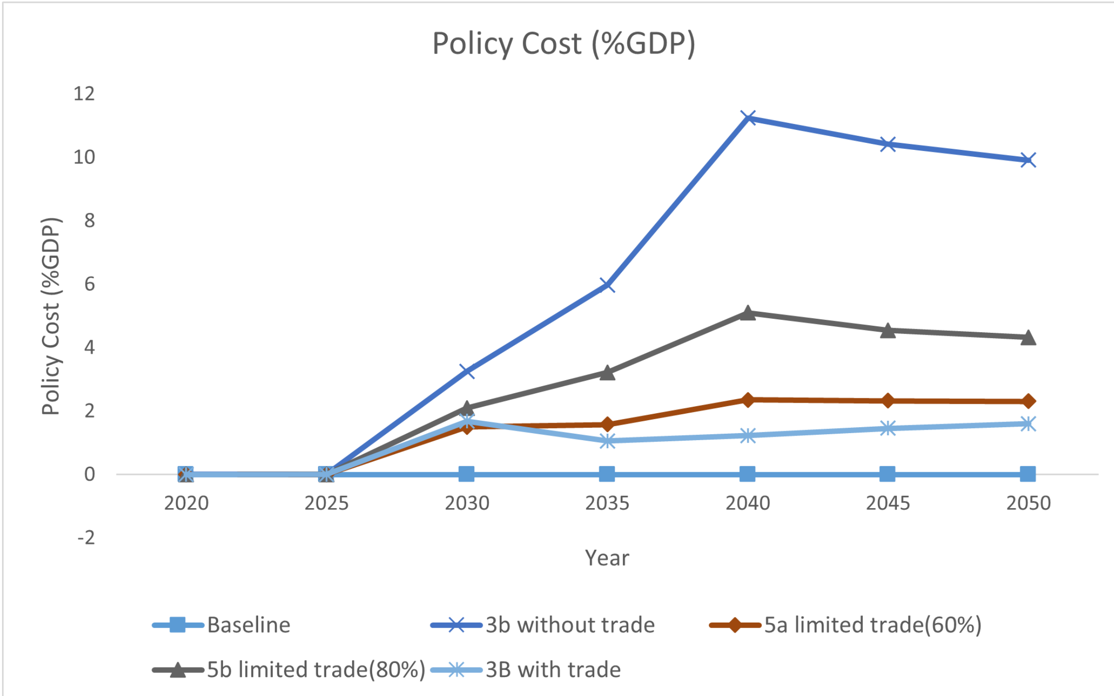


Figure 7.11: Policy Cost (2030 – 2050) (%GDP)

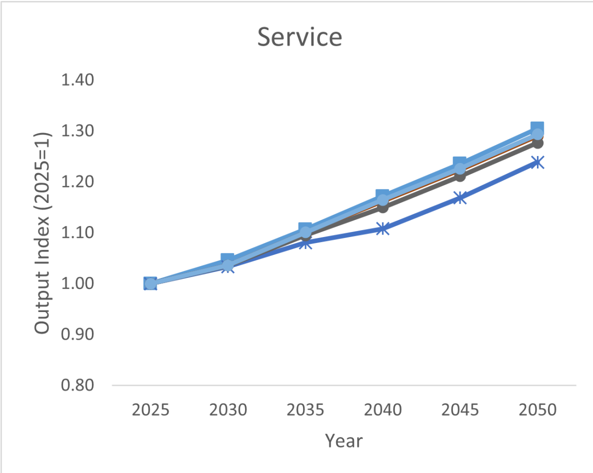
7.5 Sectoral Economic Impacts

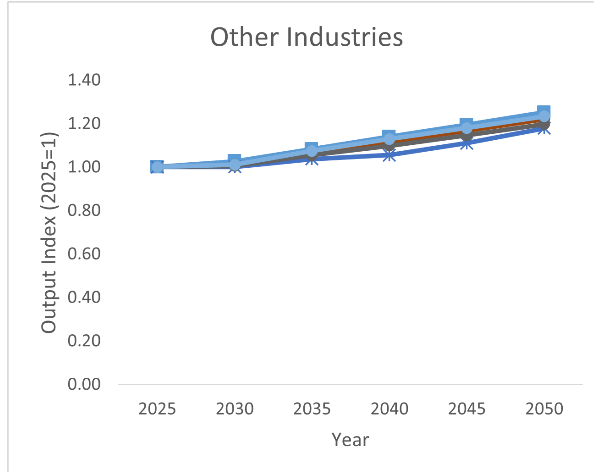
7.5.1 Industrial Sectoral Economic Impacts

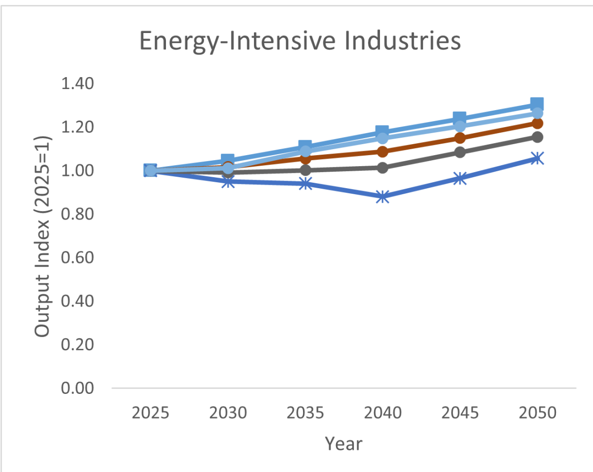
As shown in Figure 7.12, sectors primarily driven by domestic demand—such as Services (SERV), Ownership of Dwellings (DWE), and Transportation (TRAN)—continue to expand steadily under both scenarios. By 2050, the output index for Services reaches 1.29 in 5a and 1.28 in 5b, while Dwellings reaches 1.39 and 1.38, respectively. Transportation grows to 1.37 in 5a and 1.34 in 5b, approaching the baseline trend (1.40).

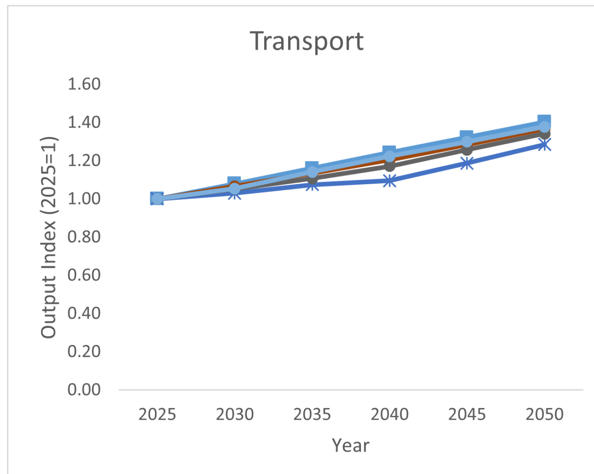
Energy-intensive industries (EINT) also perform relatively well, reaching 1.22 in 5a and 1.16 in 5b. These levels are substantially higher than in domestic-only scenarios such as 4a (0.72) and align closely with the baseline trajectory (1.30), indicating that moderate decarbonization combined with limited trading preserves industrial competitiveness.

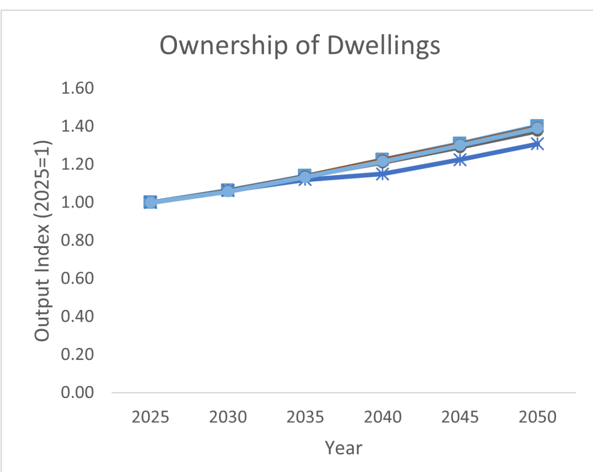
Subsectoral trends confirm this pattern. The Iron and Steel (I_S) index climbs to 1.27 in 5a and 1.21 in 5b, while Mineral Products (NMM) reach 1.22 and 1.17, respectively. These results demonstrate that scenarios 5a and 5b strike a balance between emissions reduction and industrial output retention.

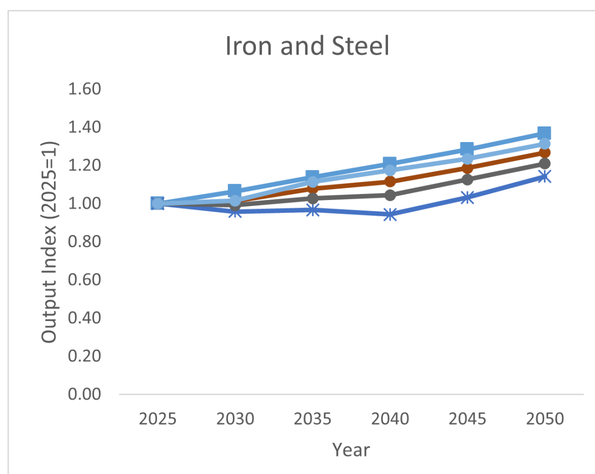

Service
Output Index (2025=1)
1.40
1.30
1.20
1.10
1.00
0.90
0.80
2025
2030
2035
2040
2045
2050
Year


Other Industries
Output Index (2025=1)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Energy-Intensive Industries
Output Index (2025=1)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Transport
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Ownership of Dwellings
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year


Iron and Steel
Output Index (2025=1)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
2025
2030
2035
2040
2045
2050
Year

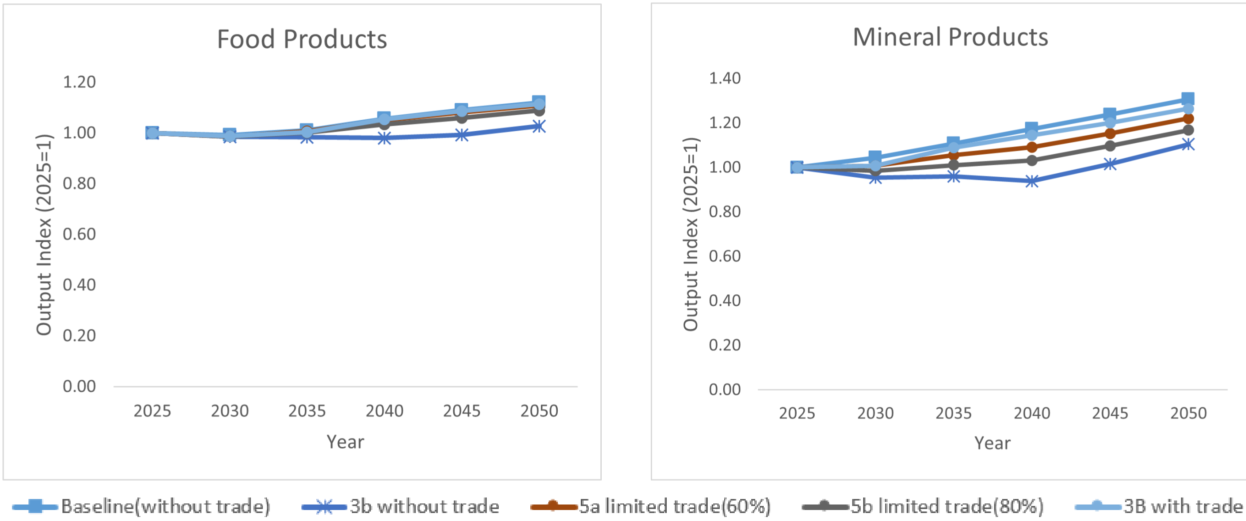


Figure 7.12: Sectoral Output Index (2025 = 1) across Industrial and Service Sectors

7.5.2 Energy-related Sectoral Economic Impacts

As shown in Figure 7.13, The fossil fuel supply sectors show continued contraction, but less abrupt than in stricter domestic-only scenarios. By 2050, the output index for Coal declines to 0.29 in the scenario 5a and 0.10 in the scenario 5b, while Oil falls to 0.78 and 0.65, and Gas to 0.51 and 0.24, respectively. These values suggest a managed decline consistent with partial international trading, avoiding sudden disruptions in energy supply chains.

Electricity production follows a more moderate path compared to full domestic mitigation. The output index reaches 0.82 in the scenario 5a and 1.02 in the scenario 5b by 2050. This reflects a shift toward non-fossil generation while mitigating the overshooting observed in some stricter policy scenarios (e.g., 4b = 1.28). The relatively lower electricity index in the scenario 5a indicates cost-sensitive optimization under carbon pricing and technological constraints.

Overall, scenarios 5a and 5b demonstrate a feasible middle-ground pathway: industrial sectors retain growth, energy-related sectors undergo gradual transitions, and emissions reduction is achieved with less economic distortion.

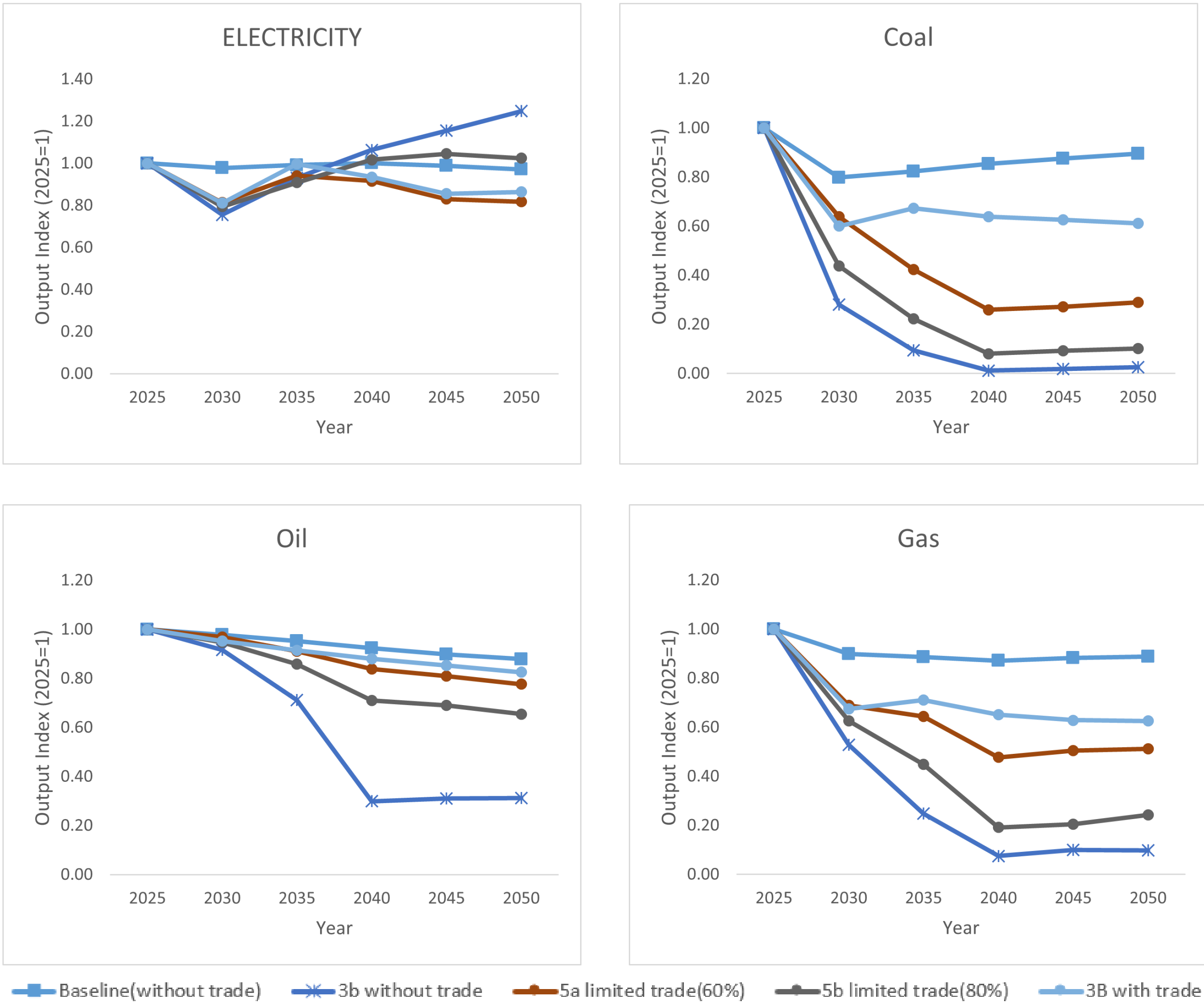


Figure 7.13: Sectoral Output Index (2025 = 1) in Energy-related Sectors

7.6 Carbon Prices

This section evaluates the carbon prices in the scenarios 5a and 5b and discusses their implications for policy flexibility and mitigation incentives.

As shown in Figure 7.14, the scenario 5a maintains relatively moderate carbon prices throughout the modeling horizon. The price reaches 178 US\$/tCO_2 in 2040 and declines to 134 US\$/tCO_2 by 2050. This trajectory reflects the scenario's moderate ambition and the availability of relatively low-cost abatement options within the scope of its domestic efforts.

In contrast, the scenario 5b—which targets more aggressive emissions reductions—exhibits higher carbon prices, reaching 458 US\$/tCO_2 in 2040 and 333 US\$/tCO_2 in 2050. These levels indicate an increased reliance on high-cost abatement technologies, including bioenergy with carbon capture and storage (bio-CCS) and deep structural changes in energy and industrial systems.

Despite the increase, the carbon prices in 5b remain far below those observed in extreme domestic-only mitigation scenarios such as scenario 4a, where carbon price exceeds 46,000 US$/t$CO_2$ by 2050. This outcome confirms that the use of international emissions trading substantially reduces marginal abatement costs and improves policy feasibility.

Overall, the scenarios 5a and 5b demonstrate that ambitious emissions reductions can be achieved within a manageable carbon pricing range by combining domestic mitigation with international credit mechanisms. The flexibility in policy design afforded by emissions trading ensures that carbon prices remain within realistic economic thresholds, even under strengthened climate targets.

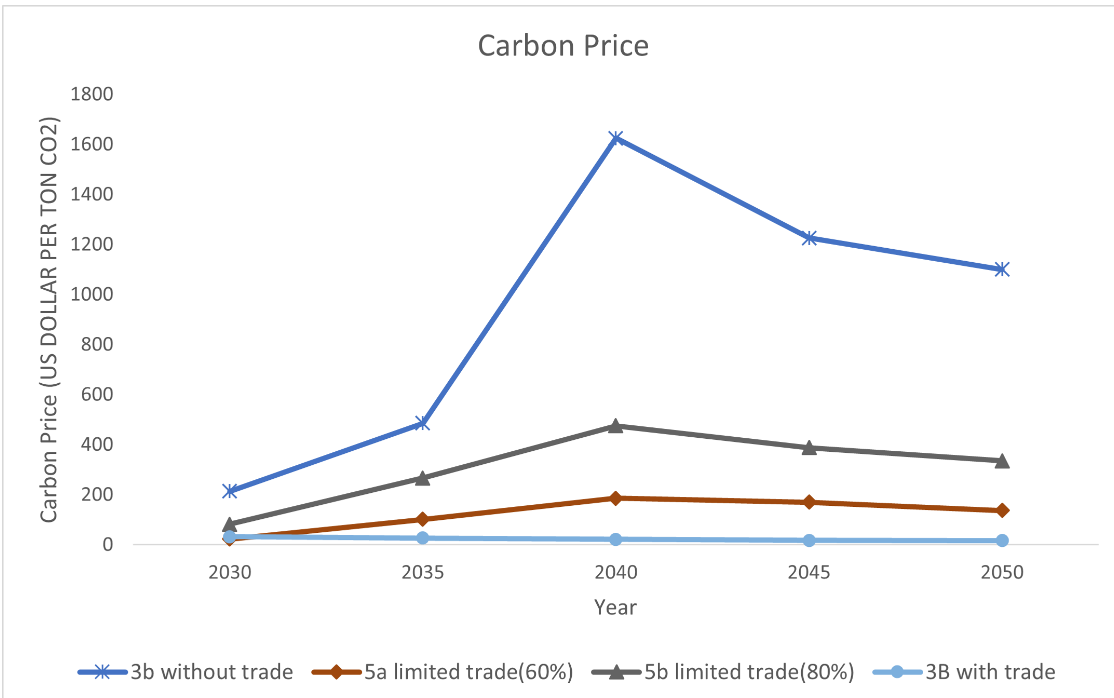


Figure 7.14: Carbon Price Trends in Scenarios 5a and 5b (US$/t$CO_2$)

7.7 Summary

This chapter evaluated two intermediate mitigation scenarios (5a and 5b) that emphasize domestic emission reduction efforts while leveraging the flexibility of international emissions trading.

In terms of emissions performance, the scenario 5a achieves approximately a 51% reduction in CO_2 emissions by 2050 compared to 2015 levels, while the scenario 5b achieves about a 68.5% reduction. Cumulative emissions over 2030 – 2050 total 3,679 MtCO_2e in 5a and 2,667 MtCO_2e in 5b—an additional 1,100 MtCO_2e in abatement for 5b. These reductions exceed those achieved under the current policy scenario (3b), though still fall short of the full net-zero trajectory defined in the scenario 4b.

Economically, both scenarios maintain moderate policy costs. The scenario 5a incurs a peak cost of about 2% of GDP, with carbon prices stabilizing below 180 US$/t$CO_2$. The scenario 5b entails a higher burden—around 4% of GDP and carbon prices reaching

458 US$/$tCO_2$ in 2040—but remains far more cost-effective than the extreme domestic-only pathway in the scenario 4a.

Sectoral analysis reveals that services, residential, and transportation sectors maintain growth under both scenarios. Energy-intensive industries also avoid contraction, especially under the scenario 5a. Meanwhile, sectors like electricity and refined oil undergo structural transformations, reflecting progress toward a low-carbon economy.

Lastly, carbon pricing under both scenarios remains within manageable thresholds. The scenario 5b shows that even ambitious targets can be met without triggering excessive economic burden, provided that international trading and technological diversification are leveraged.

Together, these findings position scenarios 5a and 5b as realistic and strategically valuable options for Japan. They demonstrate that a combination of strengthened domestic action and flexible international cooperation can enable deep emissions reductions without undermining economic stability.

Chapter 8

Conclusion

8.1 Research Objective and Analytical Framework

In this study, I enhanced the EPPA model for the latest data for Japan and quantitatively evaluated the environmental and economic impacts of multiple policy scenarios using the EPPA model, to assess the feasibility of Japan achieving carbon neutrality by 2050. The central objective was to analyze how policy configurations aligned with existing greenhouse gas reduction targets, the NDC goals for 2030 and 2040, and the net-zero goal for 2050, affect emissions, the power generation mix, macroeconomic indicators, and industrial structure. Through this, I aimed to identify the key conditions for effective decarbonization policy.

The policy scenarios were designed along four dimensions:

1. Achievement of Nationally Determined Contributions (NDCs),
2. Attainment of power generation mix targets (e.g., shares of renewables and nuclear),
3. Deployment of carbon capture and storage (CCS),
4. Participation in international emissions trading schemes.

Based on these axes, I constructed a set of scenarios with varying policy intensities—from isolated domestic measures to integrated strategies—including scenarios 2a to 4b, 2A to 4B, and supplementary scenarios 5a and 5b. These were then evaluated against the baseline scenario (1a).

The evaluation was conducted along the following dimensions:

- Alignment with emissions reduction targets,
- Technology-specific composition of power generation,
- Macroeconomic impacts (real GDP and consumption),
- Sectoral output indices,
- Quantification of policy costs through implicit carbon pricing.

Additionally, to realistically assess the balance of domestic mitigation efforts, I introduced intermediate scenarios (5a and 5b) that aim to achieve 60% and 80% of the 2040 NDC target, respectively, while attaining the power generation mix targets in both 2030 and 2040, and deploying carbon capture and storage.

Key numerical findings are as follows:

- Under the baseline scenario, Japan's GHG emissions in 2050 reach approximately 1,066 $MtCO_2e$, far above the net-zero target.
- Scenario 4a, which excludes international trading and CCS, achieves significant emissions reduction but still results in 91 $MtCO_2e$ of residual emissions in 2050.
- In the absence of CCS and trading, carbon prices can rise steeply, reaching up to \$46,928/tCO_2 in 2050 under scenario 4a.
- Scenario 4b, which includes CCS but not international trading, reduces residual emissions to 117 $MtCO_2e$ and limits cumulative GDP loss over 2025–2050 to about 6.2% (equivalent to \$2,736 billion).
- International emissions trading significantly lowers the policy cost. In scenario 4B, the carbon price in 2050 falls to \$17/tCO_2, and the cumulative GDP loss is reduced to \$413 billion, or approximately 1.4%.
- Integrated scenarios (5a and 5b) provide a balanced approach: carbon prices in 2050 are \$137 and \$336/tCO_2, respectively, with GDP losses of \$599 billion (1.6%) and \$1,152 billion (3.1%) over the 2025–2050 period.

The following sections present key quantitative findings from the analysis and offer insights into how environmental effectiveness, economic cost, and institutional flexibility can be balanced in decarbonization policy design.

8.2 Feasibility of Energy Policies and Emissions Reduction Targets

By analyzing GHG emissions and the evolution of Japan's power generation mix under various policy scenarios, I found that achieving net-zero emissions by 2050 will require the stepwise implementation of additional policy measures beyond current efforts.

In the baseline scenario, 1a, which assumes a continuation of existing policies, GHG emissions in 2050 reach 1,066 $MtCO_2e$. This result clearly indicates that current measures alone are insufficient to achieve Japan's 2050 net-zero target.

In contrast, scenarios 2a and 2b, which incorporate the 2030, 2035, and 2040 NDC targets, and scenarios 3a and 3b, which add power generation mix targets in 2030 and 2040, result in emissions of approximately 683–686 $MtCO_2e$ by 2030, confirming a certain level of progress. In particular, scenarios 3a and 3b explicitly incorporate the 2030 and 2040 power mix goals, which include higher shares of renewables and nuclear energy, and thus demonstrate measurable emissions reductions through energy system transformation.

Scenarios 4a and 4b, which are designed to meet the 2050 net-zero target in addition to the 2030, 2035, and 2040 NDC targets and power generation mix targets in 2030 and 2040, achieve more significant reductions, reaching 91 $MtCO_2e$ in 4a and 117 $MtCO_2e$ in 4b by 2050. These results confirm that substantial domestic reductions are possible. However, scenario 4a, which eliminates all fossil fuels, results in extremely high dependence on renewables and nuclear power, raising concerns over the system' s flexibility and reliability. In contrast, scenario 4b incorporates CCS and allows for the retention of a modest share of fossil-fueled power generation, about 8%, enabling a more realistic and balanced power mix.

Additionally, in scenarios 5a and 5b, which achieve 50% and 70% reductions, respectively, from the 3b scenario' s emissions trajectory by 2050, relying solely on domestic mitigation efforts. These scenarios aim for emissions levels of 651 $MtCO_2e$ in 5a and 418 $MtCO_2e$ in 5b. Both maintain alignment with the 2030 and 2040 power mix targets while balancing diversity and cost-effectiveness in electricity supply.

8.3 Comparison of Economic and Industrial Impacts

To assess the feasibility of emissions reduction under each policy scenario, I compared and evaluated the economic and structural impacts of decarbonization policies by examining macroeconomic indicators, such as real GDP and consumption, as well as the output indices of major sectors. I also analyzed how carbon price dynamics reflect the relationship between institutional feasibility and economic burden.

First, GDP and consumption exhibited significant variation depending on the stringency of emission constraints and the technologies adopted in each scenario. The most severe economic impact in 2050 was observed in scenario 4a, which eliminates fossil fuels entirely and relies solely on renewables and nuclear energy. Under this scenario, GDP falls by 22.8% and consumption by 21.0% compared to the baseline. This sharp decline is driven by extremely high carbon prices, reaching \$46,928 per ton of CO_2 in 2050, which in turn raises energy costs and production expenses.

On the other hand, scenarios 3b and 4b, both of which incorporate CCS technology, show much more moderate economic impacts, with GDP and consumption losses limited to 9.9–12.8% and 10.9% respectively. These results confirm that technological choices can significantly alleviate economic burdens. In particular, scenario 4b achieves its emissions reduction target with a diversified power mix—66% renewables, 22% nuclear, and 12% fossil fuels in 2050—ensuring both economic stability and energy security.

From a sectoral perspective, carbon-intensive sectors such as energy-intensive industries (EINT), refined oil (ROIL), and electric power (ELECTRIC) were most sensitive to policy stringency. In scenario 4a, the output indices for EINT, ROIL, and ELECTRIC fell to 0.72, 0.00, and 0.57, respectively, showing significant contraction. In contrast, in scenario 4b, which includes CCS, these indices improve to 1.01, 0.07, and 0.66, indicating that economic activity in these sectors can be maintained to some extent. Moreover, in key non-energy sectors such as services (SERV) and other industries (OTHR), the output indices in scenario 4b reach 1.22 and 1.16, respectively, remaining close to the baseline levels.

In terms of carbon pricing, the policy structure also has a significant influence. The renewable-heavy scenario 4a suffers from extreme carbon price escalation, undermining institutional feasibility. In contrast, scenario 4b benefits from the mitigation capacity provided by CCS, which keeps the carbon price in 2050 to a more manageable $1,630 per ton. This demonstrates that the inclusion of technological options not only reduces economic costs but also enhances the flexibility of institutional design.

8.4 The Role of International Cooperation and Credit Mechanisms

In this study, I also examined the role of international emissions trading in reconciling emissions reduction targets with economic stability. Compared to scenarios relying solely on domestic mitigation efforts, namely scenarios 2a through 4b, scenarios that incorporated international trading, 2A through 4B, demonstrated greater flexibility and cost smoothing across emissions, economic outcomes, industrial performance, and carbon prices.

Regarding emissions levels, scenario 4B reduced domestic emissions to around 864 $MtCO_2e$ by 2050. Through the purchase of international credits, it became possible to achieve effective net-zero emissions. Compared to scenario 4b, which achieved 117 $MtCO_2e$ through domestic action alone, scenario 4B provided a more balanced path that reduced the burden on domestic mitigation while still contributing to global reductions.

The introduction of international trading also had a clear moderating effect on economic impacts. For example, in scenario 4a, which did not involve trading, GDP and consumption fell by 22.8% and 21.0%, respectively, from the baseline by 2050. In contrast, scenario 4A, which achieved the same emissions constraint through international credits, limited GDP and consumption losses to just 1.6% and 1.3%, respectively. Carbon prices also differed dramatically: while the scenario 4a saw prices surge to $46,928 per ton of CO_2, the scenario 4A maintained a much lower price of $17 per ton. These results illustrate how international flexibility can support the institutional sustainability of emissions policies.

From an industrial perspective, international trading also contributed to maintaining competitiveness. In energy-intensive industries, the output index in scenario 4b remained at 1.01, while scenario 4B, which utilized international trading, improved it to 1.26. This demonstrated that industrial activity could remain viable even under stringent emissions constraints if international mechanisms were employed.

In addition, international emissions trading directly enables Japan to expand the global deployment of its decarbonization technologies. Through the JCM, Japan can disseminate technologies such as renewable energy, energy storage, high-efficiency thermal power, CCS, and DAC to developing countries. This approach allows Japan to leverage its technological advantage while contributing meaningfully to global emissions reduction.

In sum, active participation in international carbon markets serves as a powerful strategy to simultaneously achieve multiple policy goals: flexible emissions reductions, cost containment, industrial competitiveness, and international credibility. Future policy design must adopt an integrated approach that combines domestic measures with international cooperation.

8.5 Policy Significance of Intermediate Reduction Strategies (Scenarios 5a and 5b)

In the preceding scenario analyses, I confirmed the effectiveness of emissions reduction under scenarios 2a through 4b and 2A through 4B. However, I also found that these scenarios entailed significant economic and institutional burdens, including sharp increases in carbon prices and substantial declines in GDP and industrial output. Moreover, in scenarios involving international emissions trading, there was a tendency for the system to rely heavily on foreign credit for cost-effectiveness, resulting in limited domestic mitigation efforts.

To address these challenges, I designed and analyzed two supplementary intermediate strategy scenarios, 5a and 5b, to more realistically assess the scope and impact of domestic emissions reductions. These scenarios were constructed as gradual extensions of scenario 3b, which implements domestic policies through 2040. Specifically, scenario 5a targeted a 50% reduction in total emissions by 2050, reaching 651 MtCO_2e, while scenario 5b aimed for a 70% reduction, reaching 418 MtCO_2e.

In terms of economic impact, scenario 5a limited GDP loss to 2.3% and held the carbon price to $137 per ton of CO_2, suggesting that it falls within a socially and institutionally acceptable range. Even in scenario 5b, where deeper reductions were achieved, GDP loss was contained at around 4.3%, and the carbon price remained moderate at $336 per ton. These results indicated the possibility of balancing emissions mitigation with economic viability.

Sectoral analysis showed that both scenarios maintained a reasonable level of industrial activity. For energy-intensive industries (EINT), the output index ranged from 1.22 to 1.16; for refined oil (ROIL), from 0.68 to 0.51; and for electric power (ELECTRIC), from 0.69 to 0.64. These figures suggested that the overall industrial structure remained resilient. In addition, major non-carbon-intensive sectors, such as services (SERV) and other industries (OTHR), continued to exhibit stable growth, with output indices in 2050 reaching 1.29 and 1.20 respectively in scenario 5b.

8.6 Policy Implications

Based on the results of my quantitative analysis, I conclude that three key policy strategies are essential for Japan to realistically and economically achieve carbon neutrality by 2050.

(1) Phased Policy Strengthening and a Clear Long-Term Roadmap

Achieving the NDC targets and renewable energy goals by 2030 is a critical first step toward carbon neutrality. Beyond 2030, Japan must advance a set of long-term measures, including renewable energy expansion, infrastructure development, and the phased phase-out of coal-fired power. By clearly presenting a long-term roadmap, the government can provide predictability for industry and civil society, thereby facilitating an orderly transition.

(2) Institutional Support for CCS and Negative Emission Technologies

My analysis confirmed that the deployment of CCS can play a vital role in controlling carbon price escalation, preserving industrial output, and diversifying the power mix. Therefore, the government should expand its support for the implementation of CCS and other negative emission technologies (NETs), such as DAC (Direct Air Capture) and biochar. This support should include regulatory frameworks, infrastructure investment, and incentive mechanisms.

(3) Active Use of International Emissions Trading and Strengthened Technology Transfer

Given Japan's high marginal abatement cost, leveraging international emissions trading is economically rational. To do so, Japan must design a robust and credible crediting system and actively participate in international rule-making, such as linking schemes and multilateral market mechanisms. Moreover, through international frameworks such as the Joint Crediting Mechanism (JCM), Japan should promote the deployment of decarbonization technologies, including renewable energy, energy storage, high-efficiency thermal power, CCS, and DAC, to developing countries. Such technology transfer will help maximize global emissions reduction potential while enhancing Japan's international responsibility and technological leadership.

8.7 Future Work

In this study, I quantitatively evaluated multiple decarbonization policy scenarios for Japan and clarified the trade-offs between emissions reduction and economic impacts toward 2050. To further apply this analysis in real-world policymaking, future work must advance the application of the model and explore institutional design, focusing on the following five areas:

1. **Assessment of Social Fairness and Burden Distribution**
   The economic costs of decarbonization—such as carbon pricing, infrastructure investment, and public subsidies—are ultimately borne by households, firms, or the government. Future research should clarify how these costs are distributed among Japan's population of different income and demographics, and assess their impacts on consumption behavior, investment decisions, employment, and wage structures. Quantifying the disparities in burden by income level and identifying the risks of energy poverty will help establish a stronger institutional foundation that enhances the fairness and social acceptability of the decarbonization transition.

2. **Fiscal Redistribution and Institutional Design**
   Revenues from carbon taxes or emissions allowance auctions serve not only as funding for carbon reduction but also as financial resources for inequality mitigation and transition support. Future analyses should evaluate how and to whom these revenues are redistributed. In particular, designing fiscal strategies that combine refundable tax credits, energy cost subsidies, industrial support, and investment in green infrastructure will be essential for building a broad public consensus.

3. **Regional Economies and a Just Transition**
   While the current analysis is based on national averages, the effects of decarbonization vary significantly across regions. In areas where power generation facilities or energy-intensive industries are concentrated, economic transformation may directly affect employment and income. Future work should extend the model to incorporate regional industrial structures and energy dependencies, enabling quantitative evaluation of local transition support policies and reinvestment strategies at the municipal level.

4. **Carbon Constraints Across the Supply Chain and Impacts on Export Industries**
   Future regulations are expected to increasingly cover Scope 3 emissions across international supply chains, especially in sectors like manufacturing. To prepare for such developments, future research must analyze in more detail the carbon cost of imported goods and the broader implications for international trade (for example, from the EU Carbon Border Adjustment Mechanism, CBAM), assessing the risks Japanese companies face and identifying necessary policy responses.

5. **Institutional Stability and Risks in the International Carbon Market**
   My analysis showed that introducing international emissions trading and facilitating the use of carbon credits can significantly lower Japan's mitigation costs. However, for such systems to function stably, mechanisms for accurate measurement, reporting, and verification (MRV), standardized rules across participating countries, and the political stability of trading partners are all essential. In particular, if credit-supplying countries experience political instability, the entire market may become volatile, with large price fluctuations. Future research should incorporate these risks into modeling and examine what institutional conditions are necessary for a stable and reliable international trading system.

My research provides a thorough analysis of options for decision-makers in Japan both at a government and industry level. Practical solutions developed in my thesis can help to understand the tradeoffs between different choices that would affect the well-being of Japan for many years ahead. Incorporating additional details to my research would lead to even more nuanced quantification of options for decarbonization of Japan.

References

[1] Cabinet Secretariat, Government of Japan. *Realizing a Green Society*. Accessed: May 5, 2025. 2020. URL: https://www.kantei.go.jp/jp/headline/tokushu/green.html.

[2] Economic and Social Research Institute, Cabinet Office, Government of Japan. *Economic Analysis No.206*. 2023. URL: https://www.esri.cao.go.jp/jp/esri/archive/bun/bun206/bun206a.pdf.

[3] I. E. Agency. *Real-world Policy Packages for Sustainable Energy Transitions*. Tech. rep. International Energy Agency, 2023. URL: https://iea.blob.core.windows.net/assets/07a1adb2-b7a6-4f8c-bc5e-b40c19d7ef9a/Realworldpolicypackagesforsustainableenergytransitions.pdf.

[4] Agency for Natural Resources and Energy, METI. *Energy White Paper 2023*. 2023. URL: https://www.enecho.meti.go.jp/about/whitepaper/2023/pdf/.

[5] O. for Economic Co-operation and Development. *Packaging and Sequencing Policies for More Effective Climate Action*. Tech. rep. OECD, 2025. URL: https://www.oecd.org/content/dam/oecd/en/publications/reports/2025/04/packaging-and-sequencing-policies-for-more-effective-climate-action_51d3656b/fced4e28-en.pdf.

[6] J. Ministry of the Environment. *The Joint Crediting Mechanism (JCM)*. Accessed May 2025. 2024. URL: https://www.jcm.go.jp/.

[7] UNFCCC. *Cooperative Implementation: Article 6 of the Paris Agreement*. Accessed May 2025. 2021. URL: https://unfccc.int/process/the-paris-agreement/cooperative-implementation.

[8] MIT Joint Program. *2023 Global Change Outlook*. Report. MIT Center for Global Change Science, Joint Program on the Science, and Policy of Global Change, 2023. URL: https://cs3.mit.edu/publications/signature/2023-global-change-outlook (visited on 04/26/2025).

[9] UNFCCC. *Japan’ s Updated NDC Submission (2025)*. 2025. URL: https://unfccc.int/sites/default/files/2025-02/Japans%202035-2040%20NDC.pdf (visited on 05/05/2025).

[10] Climate Action Tracker. *Japan: Climate Action Tracker Country Assessment*. Accessed 2025-05-05. 2024. URL: https://climateactiontracker.org.

[11] J. Ministry of the Environment. *Japan’s Greenhouse Gas Emissions Data (2023)*. Accessed 2025-05-05. 2023. URL: https://www.env.go.jp/content/000215754.pdf.

[12] J. Ministry of the Environment. *Document 5: Emissions Status and Future Outlook for the Mid-term Review*. Accessed 2025-05-05. 2024. URL: https://www.env.go.jp/council/content/i_05/000234692.pdf.

[13] Ministry of the Environment, Japan. *Global Warming Countermeasures Plan (Revised 2025)*. 2025. URL: https://www.env.go.jp/earth/ondanka/domestic.html.

[14] Ministry of Economy, Trade and Industry. *GX Implementation Policy and Investment Promotion Strategy*. 2023. URL: https://www.meti.go.jp/policy/energy_environment/global_warming/index.html.

[15] *Japan: Climate Action Tracker Country Assessment*. 2023. URL: https://climateactiontracker.org/countries/japan/.

[16] Ministry of Economy, Trade and Industry. *G7 Climate and Energy Communiqué (May 2024)*. 2024. URL: https://www.meti.go.jp/press/2024/05/20240501001/20240501001-c.pdf.

[17] Ministry of Economy, Trade and Industry, Japan. *Interim Report on the 7th Strategic Energy Plan*. Ministry of Economy, Trade and Industry, Japan, 2025. URL: https://www.enecho.meti.go.jp/en/category/others/basic_plan/ (visited on 04/26/2025).

[18] Ministry of Economy, Trade and Industry, Japan. *CCS Long-Term Roadmap Study Group Report (September 2023)*. Accessed: 2025-05-05. 2023. URL: https://www.meti.go.jp/shingikai/enecho/shigen_nenryo/carbon_management/pdf/005_04_00.pdf (visited on 05/05/2025).

[19] D. S. Herran and S. Fujimori. "Beyond Japanese NDC: energy and macroeconomic transitions towards 2050 in emission pathways with multiple ambition levels". *Sustainability Science* 17.1 (2022), pp. 245–258. DOI: 10.1007/s11625-021-00930-1. URL: https://link.springer.com/article/10.1007/s11625-021-00930-1.

[20] K. Oshiro and S. Fujimori. "Mid-century net-zero emissions pathways for Japan: Potential roles of global mitigation scenarios in informing national decarbonization strategies". *Energy Policy* (2024). Accessed: 2025-05-05. URL: https://pure.iiasa.ac.at/id/eprint/19536/1/1-s2.0-S2666278724000047-main.pdf.

[21] T. Walmsley, A. Aguiar, and B. Narayanan. *Introduction to the Global Trade Analysis Project and the GTAP Data Base*. Tech. rep. GTAP Working Paper No. 67. Global Trade Analysis Project (GTAP), Purdue University, 2012. DOI: 10.21642/GTAP.WP67. URL: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=3965.

[22] S. Kasahara, S. Paltsev, J. Reilly, H. Jacoby, and A. D. Ellerman. *Climate Change Taxes and Energy Efficiency in Japan*. Tech. rep. Report 121. Joint Program Report Series. MIT Joint Program on the Science and Policy of Global Change, 2005, p. 30. URL: https://globalchange.mit.edu/publication/13740.

[23] Ministry of the Environment, Japan. *Update on Japan's Nationally Determined Contribution (NDC)*. In Japanese. Feb. 2025. URL: https://www.env.go.jp/earth/earth/ondanka/ndc.html (visited on 04/26/2025).

[24] Ministry of the Environment, Japan. *Global Warming Countermeasures Plan (February 2025)*. In Japanese. Feb. 2025. URL: https://www.env.go.jp/earth/ondanka/keikaku/250218.html (visited on 04/26/2025).