

Sustainable Energy Transition in the Indonesian Power Sector:
A Whole System Perspective

インドネシア電力部門における持続可能なエネルギー移行の全体
システム視点からの分析

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Abstract

Indonesia's electricity demand is expected to increase eightfold by 2050. The government aims for at least 31% renewable energy (RE) share by then, moving away from coal's dominance. While renewable energy is seen as a key to sustainability, its adoption may present economic, social, and environmental challenges. Policies to increase the adoption of renewables in the power sector may also lead to negative effects, such as economic instability from a carbon tax or higher electricity prices from feed-in tariffs. These challenges highlight the need to approach the energy transition from a systems perspective, taking into account the economic, social, and environmental impacts, rather than focusing only on reducing emissions. This broader goal prompts an important question: how can Indonesia sustainably increase renewable energy adoption in its power sector while considering economic, social, and environmental factors?

The energy transition involves complex interlinkages between energy systems, users, the economy, and the environment, which often creates complications in energy policy implementation. In addition to the whole system, uncertain technology transition processes are uncertain in both supply and demand sides is also unfolding. The rising electricity demand may create opportunities for renewable energy adoption. As such, the whole system approach must be integrated with a bottom-up approach to understanding the technological adoption paths. This integration means there is feedback as well as material, monetary, and information flows within the system. Thus, system dynamics was chosen as the main methodology.

This thesis first presents an overview of the energy transition from a holistic systems perspective, qualitatively analyses the economic, social, and environmental effects of the shift to renewable energy in the power sector. By incorporating feedback loops between energy, economic, and environmental systems, the chapter proposes a model to evaluate different energy policies. Using systems thinking, a dynamic hypothesis is formulated, proposing that increasing energy demand could hinder the transition to renewables in the power sector due to economic and resource limitations. The thesis then continues by investigating the energy transition happening on the demand sectors, namely the transportation, residential, and industrial sectors.

The transportation sector is becoming a crucial part in the power sector transition, as vehicle electrification has become a central policy focus. Indeed, the result showed the sector could become a major electricity consumer in the future, surpassing the residential sector. In addition, the adoption of electric vehicle could lead the sector to become more dependent in coal as opposed to crude oil products if the power sector fails to transition to renewables. The discussion of transportation sector also provides clues as to how sustainable energy transition could occur which will be pivotal in the power sector transition.

The residential sector – currently the largest electricity consumer – is the subject of two technology adoption. The first is electric stove which is aimed to reduce Indonesia's dependency on LPG which are mostly imported, while the second is rooftop solar PV to reduce grid electricity demand. The transition in the sector is assessed according to the energy security framework in both the household and national levels to explore their potential trade-offs and to accentuate the energy transition impact on the social dimension. The results showed that residential electricity demand would continue to increase, driven by population and economic growth. The adoption of electric stove would exacerbate the electricity demand growth, adding

burden to the power sector which could negatively impact national energy acceptability due to increased electricity consumption assuming no significant change in the power mix. On the other hand, electric stoves may enhance all household energy security indicators. The adoption of rooftop solar could improve energy affordability at the household level and reduce grid emissions at the national level. However, promoting the adoption of electric stoves may be a more cost-effective way to enhance both household and national energy security, as it requires only half the adoption level needed for rooftop solar to achieve similar benefits.

The discussion for industrial sector energy transition initiates the link between the supply-side and demand side of the transition. The steel industry used as a case study since the production pathway electrification requires another energy source: hydrogen. The results showed that the alternative fuels availability could significantly determine the adoption of the electrified production pathways in the industrial sector, which then affects electricity demand in the power sector. In addition, GDP growth and technology adoption risk tolerance as the primary uncertainties affecting electrified production pathways. The result also showed that the industrial sector will be the largest electricity consumer in the future, contributing to more than 70% of all the electricity demand.

Building on the electricity demand changes, the power sector transition discussion evaluates the barriers and examine the necessary policies for a sustainable energy transition, considering economic, social, and environmental factors, as well as the roles of stakeholders. The model results suggest that achieving the renewable energy target by 2050 may be challenging without effective policies. The adoption of renewables in the power sector could eventually reach a plateau due to land constraint to which the power sector has small contribution. Instead, the aggressive adoption of biofuel in the transportation sector led to the land availability depletion. In addition, aggressively promoting green technology adoption in both the supply and demand sides could have adverse social and environmental effects while still failing to meet the RE target since the stagnating renewable electricity and the increasing demand would eventually decrease the share of renewables in the power mix. Learning from the Shift strategies in the transportation sector, emphasizing on sustainable consumption resulted in the least negative impact across all indicators, making it the most effective strategy for a sustainable transition.

This research contributes to sustainability transition literature by offering a holistic perspective integrating economic, social, and environmental systems with the power sector. It highlights energy price-demand balancing forces, state budget, and resource capacity as structural barriers in RE transition. This research advocates multidimensional indicators rather than focusing on narrow goals in evaluating transition pathways. The bottom-up approach used to determine energy demand across sectors, the technology adoption model, and the whole system perspective help address the limitations of top-down analyses, particularly in dealing with energy price elasticity. By separating the model into supply-side and demand-side components, the research evaluates the interaction between these policies and their impacts on economic, social, and environmental indicators, as well as sector-specific policies. Although the model is based on an Indonesian case study, it employs a generalized system structure, unlike typical system dynamics models that are tailored to specific problems. This general framework allows the model to be more adaptable and applicable to a wide range of issues through parameter adjustments.

Acknowledgement

All praises to Allah for His blessings in helping me go through all the obstacles in finishing my doctoral research. His divine guidance and interventions, flowing through the people around me, has made it possible for me endure these three life changing years.

I'd like to extend my deepest gratitude to Professor Benjamin McLellan for his patience in guiding me since before starting my doctoral study until finishing this thesis. Our bi-weekly discussion for the last three years has always been fruitful and has always guided me on how to proceed with my research. I deeply appreciate all the opportunities he has given me not only for my academic pursuit but also for my professional development as a researcher. おかげさまで、終えることができました。心から感謝しています。

My journey to finalize my doctoral studies would have been difficult if it weren't for the support and appreciation from my family. My wife, Rinka Apsari, for her support and push in every step of my life since we met. I am very proud of her determination in finding ways to carry her own weight in Japan, which made living here enjoyable. My parents for their endless kindness and support and for being inspiration to me to reach the same education level as they have obtained. My brothers and sisters for their occasional visit to Japan that eases up my homesickness.

I would like to thank Jordi-sensei, Fara-sensei, and my lab mates. Their inputs for my thesis have enriched my research and have broaden my knowledge. Meeting them have made my doctoral studies more fun and exciting. Also, I would like to thank Hung Mayumi, our lab secretary, who has been kindly helping with all the administrative and logistical aspects of my research.

I am also grateful to all the professors in the Socio-Environmental Energy Science Department for sharing their knowledge during the coursework part of my doctoral program, and especially for Unesaki-sensei and Shimoda-sensei as my thesis reviewers for their inputs and fruitful discussion during my defence.

Finally, I dedicate this thesis to my late grandmother, Emih, who had pushed me to pursue this doctoral degree and had always put faith in me. Her kindness and discipline to me since my childhood has shaped who I am today. Her faith in me to be something great has always motivated me to continue pushing my limit. I hope this milestone would make her proud.

Table of Contents

Abstract	i
Acknowledgement	iii
Table of Contents	iv
List of Figures	viii
List of Tables.....	xvi
List of Abbreviations.....	xvii
Chapter 1 Introduction.....	1
1.1. Background and Motivation	1
1.2. Research Questions and Objective.....	2
1.3. Overarching Research Methodology and Research Stages	3
1.4. System Dynamics Model Building	4
1.5. Research Contribution	6
1.6. Thesis Structure	6
Chapter 2 Negative and Positive Forces in the Power Sector Energy Transition: A Conceptual Model.....	9
2.1. Background	9
2.2. Literature Review.....	10
2.2.1. Energy Sustainability	10
2.2.2. Energy Transition Policy in Indonesia	11
2.2.3. Energy Transition Assessment Criteria	12
2.3. Methodology	13
2.4. Results.....	14
2.4.1. Qualitative Model Development.....	14
2.4.2. Selection of Relevant Indicators	19
2.4.3. Stakeholders Identification	20
2.4.4. System Boundary	22
2.4.5. System Diagram.....	23
2.5. Discussion	23
2.6. Conclusion	25
Chapter 3 Energy Demand Shifts: Case Study in The Indonesian Transportation Sector....	27
3.1. Introduction.....	27
3.2. Recent Trends and Challenges in Transportation and Energy-Related Policies	29
3.2.1. Public Transportation Network Development	29

3.2.2.	Vehicle Electrification.....	29
3.2.3.	Biofuel.....	30
3.2.4.	Renewable Energy Uptake in the Power Sector	30
3.3.	Model Building	31
3.3.1.	Model Development.....	31
3.3.2.	Indicators.....	32
3.3.3.	Uncertainties	33
3.3.4.	Model Testing	34
3.4.	Base Run Result.....	36
3.5.	Uncertainty Test	40
3.5.1.	Policy Tests	40
3.5.2.	Uncertainty Tests.....	55
3.6.	Scenario Analysis.....	62
3.6.1.	Final energy consumption.....	62
3.6.2.	Primary energy demand	64
3.6.3.	Land requirements	66
3.6.4.	Emissions	67
3.6.5.	Minerals demand.....	70
3.6.6.	Primary energy intensity	71
3.6.7.	Comparisons of scenarios	73
3.7.	Economic implication of the transportation sector policy	74
3.8.	Conclusion	75
Chapter 4	Assessments of the Energy Security Impacts of Two Energy Transition Technologies in the Residential Sector in Indonesia	77
4.1.	Introduction.....	77
4.2.	Model Building	78
4.2.1.	Residential energy consumption in Indonesia	78
4.2.2.	Conceptual Model of technology adoptions	79
4.2.3.	Adoption Factors.....	82
4.2.4.	National and household level energy security indicators	84
4.2.5.	Simulation Model.....	85
4.2.6.	Model Testing	85
4.3.	Results.....	86
4.3.1.	Household income shifts.....	86
4.3.2.	Electrified residences	86

4.3.3.	Housing sizes	87
4.3.4.	Electric stove adoption.....	88
4.3.5.	Household home appliances electricity consumption.....	90
4.3.6.	Rooftop solar adoption.....	91
4.3.7.	Residential sector energy security assessment.....	93
4.4.	Discussion	98
4.4.1.	Home appliances power rate	98
4.4.2.	Electric Stove Adoption	101
4.4.3.	Rooftop solar Adoption.....	107
4.4.4.	Energy Subsidy Budget.....	110
4.5.	Conclusion	116
Chapter 5	Interplay Between Energy Demand, Energy Supply, and The Environment: Case Study in The Steel Industry Decarbonisation.....	120
5.1.	Introduction.....	120
5.2.	General Energy Demand Model and Technology Adoption the Industrial Sector.	123
5.2.1.	Industrial Sector Demand	123
5.2.2.	Fuel Switch and Technology Adoption in the Industrial Sector	124
5.2.3.	Factors affecting energy intensity in the energy-intensive industries.....	127
5.2.4.	Fuel mix in the energy intensive industries	128
5.2.5.	Model Testing	130
5.3.	Steel Industry Decarbonisation Case Study.....	132
5.3.1.	Steel Industry Energy Transition Model Building	134
5.3.2.	Model Uncertainties.....	138
5.3.3.	Base Run	141
5.3.4.	Supply-Demand Sensitivity Test.....	144
5.3.5.	Scenario-driven Sensitivity Test	151
5.3.6.	Interactions between the sub-systems involved.....	155
5.4.	Aggregate Energy Demand and Grid Electricity Demand in The Industrial Sector	157
5.4.1.	Technology adoption in the other energy-intensive industries	157
5.4.2.	Effect of uncertainties on industrial sector demand.....	160
5.4.3.	Effect of uncertainties on electrified production pathway adoption.....	162
5.4.4.	Energy demand and grid electricity demand in the industrial sector.....	163
5.5.	Implications of the Industrial Sector Energy Transition	168
5.6.	Conclusion	171

Chapter 6	A Sustainable Transition in The Power Sector from the Whole System Perspective	173
6.1.	Background	173
6.2.	Model Building	175
6.2.1.	The State of the Power Mix in Indonesia	175
6.2.2.	Renewables adoption in the power sector	176
6.2.3.	Indicators	179
6.2.4.	Model Tests	180
6.3.	Base Run	181
6.3.1.	Renewables adoption in the power sector	181
6.3.2.	Economic Indicators	182
6.3.3.	Social Indicators	186
6.3.4.	Environmental Indicators	187
6.4.	Policy Tests	190
6.4.1.	Feed-in Tariff (FIT)	191
6.4.2.	The early retirement and future ban of CFPP	197
6.4.3.	Carbon tax	203
6.4.4.	Fossil fuel subsidy	209
6.4.5.	Depletion Premium	214
6.5.	Uncertainty Tests	219
6.5.1.	Risk tolerance	220
6.5.2.	Renewable development rate	221
6.5.3.	Thermal efficiency	222
6.6.	Scenario Analysis	223
6.6.1.	National Energy Plan Scenario (NEP)	224
6.6.2.	Green Technology Utopia Scenario (GTU)	231
6.6.3.	Sustainable Energy Transition Scenario (SET)	238
6.6.4.	Comparison of scenarios	244
6.7.	Discussion	245
6.8.	Conclusion	247
Chapter 7	Conclusion	249
7.1.	Thesis Summary	249
7.2.	Future work	252
	List of Publications	254
	References	256

List of Figures

Figure 1.1. The interconnection of elements in the whole system perspective according to ecological economics ¹⁸ .	2
Figure 1.2. The overarching research methodology. The system dynamics modelling approach is based on Sterman ²³ while the scenario analysis and policy making process is based on Walker ²⁴ .	3
Figure 1.3. Example of a Causal Loop Diagram (CLD).	5
Figure 1.4. Example of a Stock and Flow Diagram (SFD) used in the Simulation Model.	5
Figure 1.5. The structure of the thesis.	7
Figure 2.1. Choosing between fossil-based power plants or RE-based power plants is an investment decision between two alternatives.	15
Figure 2.2. Substitution between non-renewable energy and renewable energy.	16
Figure 2.3. Environmental capacity linked to the supply of non-renewable energy and renewable energy.	17
Figure 2.4. The macroeconomic sub-model showing aggregate demand as a key driver to the economy.	18
Figure 2.5. Stakeholders in the renewable energy adoption for electricity generation in Indonesia.	21
Figure 2.6. System Diagram of Energy Transition for Electricity Generation in Indonesia.	23
Figure 3.1. Energy profile in the transportation sector: (a) proportion of energy consumption by type of transport ¹³⁶ and (b) the energy mix in the transportation sector ¹³⁵ .	27
Figure 3.2. Model structure overview of the transportation module	31
Figure 3.3. Causal Loop Diagram of the energy and resources demand for transportation system	32
Figure 3.4. Number of vehicles validation.	35
Figure 3.5. Road length validation.	35
Figure 3.6. Total final energy consumption validation.	36
Figure 3.7. Baseline simulation transportation mode split.	37
Figure 3.8. Adoption of Electric Vehicles under the Base Run.	37
Figure 3.9. Base runs of final energy demand.	37
Figure 3.10. Base runs of primary energy consumption in the transportation sector.	38
Figure 3.11. Land requirements for energy demand in the transportation sector in the base run.	38
Figure 3.12. Base runs of total (a) CO ₂ , and (b) NO _x , PM ₁₀ , and SO ₂ emissions.	39
Figure 3.13. Base runs of mineral demands.	39
Figure 3.14. Base runs of urban, domestic, and freight transportation, and (b) road freight transportation compared to total freight transportation energy intensity.	40
Figure 3.15. The effect of public transportation network development on mode split.	41
Figure 3.16. Sources of shifts to public transportation (PT).	41
Figure 3.17. The effect of public transportation network development on final energy demand.	42
Figure 3.18. The effect of public transportation network development on primary energy demand.	43
Figure 3.19. The effect of public transportation network development on land requirement.	43

Figure 3.20. The effect of public transportation network development on observed emissions.	44
Figure 3.21. The effect of public transportation network development on the observed mineral demands.	45
Figure 3.22. The effect of public transportation network development primary energy intensity.	45
Figure 3.23. The effect of BEV incentives on BEV share.	46
Figure 3.24. The effect of BEV incentives on final energy demand.	47
Figure 3.25. The effect of BEV incentives on primary energy demand.	48
Figure 3.26. The effect of BEV incentives on land requirement.	48
Figure 3.27. The effect of BEV incentives on observed emissions.	49
Figure 3.28. The changes in exhaust emissions, grid emissions, and net changes of CO ₂ when no EV incentives are given.	49
Figure 3.29. The effect of BEV incentives on minerals demand.	50
Figure 3.30. The effect of BEV incentives on energy intensity.	50
Figure 3.31. Biofuel blending level progression under restricted and unrestricted land availability.	51
Figure 3.32. The effect of increasing biofuel blending level on final energy consumption.	51
Figure 3.33. The effect of increasing biofuel blending level on primary energy consumption.	52
Figure 3.34. The effect of increasing biofuel blending level on land requirements.	53
Figure 3.35. Biofuel domestic production sufficiency under restricted and unrestricted land availability.	53
Figure 3.36. The effect of increasing biofuel blending level on emissions.	54
Figure 3.37. The effect of increasing biofuel blending level on the minerals demand.	55
Figure 3.38. The effect of biofuel policy on energy intensities.	55
Figure 3.39. Sensitivity test of final energy consumption.	56
Figure 3.40. Sensitivity test of primary energy consumption.	57
Figure 3.41. Sensitivity test of land requirement.	58
Figure 3.42. Sensitivity test of emissions.	59
Figure 3.43. Sensitivity test of minerals demand.	60
Figure 3.44. Sensitivity test of primary energy intensity.	61
Figure 3.45. Annual changes of urban transportation primary energy intensity and the effects of uncertainties.	61
Figure 3.46. Final energies demand under the defined scenarios.	63
Figure 3.47. Comparisons of demand for fossil resources under different scenarios.	65
Figure 3.48. Comparisons of demand for biomass resources under different scenarios.	66
Figure 3.49. Land requirements under the defined scenarios.	67
Figure 3.50. Emission result under the defined scenarios.	69
Figure 3.51. Demands of observed minerals under the defined scenarios.	70
Figure 3.52. Primary energy intensity (EI) in the transportation sector under the defined scenarios.	72
Figure 3.53. Relative resources demand and environmental impacts of the policy sets under the disadvantageous and advantageous uncertainties.	73
Figure 3.54. Total cost of sustainability transition in the transportation sector	74
Figure 4.1. Conceptual model of the energy transition dynamics in the residential sector.	81
Figure 4.2. Sub-models and the relationship used in this study	85

Figure 4.3. Validation of (a) biomass, (b) LPG, and (c) electricity consumption of residential sector.	86
Figure 4.4. GDP per Capita and the number of households by income group.	86
Figure 4.5. Progression of electrification ratio and the resulting electrified households.	87
Figure 4.6. Correlation between Property price and GDP.	87
Figure 4.7. Average house size by size-class and the relative size compared to 2005 level....	88
Figure 4.8. Aggregate house size in each household group.	88
Figure 4.9. Stove transition in each household income group.	89
Figure 4.10. Stove transition in all households.	90
Figure 4.11. Home appliances electricity consumption by household income group.	90
Figure 4.12. Home appliance total residential electricity consumption by devices.	91
Figure 4.13. Aggregate rooftop solar adoption.	91
Figure 4.14. Aggregate rooftop solar market share and in each household income group.	92
Figure 4.15. Adoption of rooftop solar and generation capacity in each household income group.	92
Figure 4.16. Sufficiency of rooftop solar generation in each household income group.	93
Figure 4.17. Household Energy Availability.	94
Figure 4.18. Household Energy Accessibility.	94
Figure 4.19. Household Energy Affordability.	95
Figure 4.20. Household Energy Acceptability.	95
Figure 4.21. National Energy Availability.	96
Figure 4.22. National Energy Accessibility.	97
Figure 4.23. National Energy Affordability.	97
Figure 4.24. National Energy Acceptability.	98
Figure 4.25. Residential sector electricity consumption under different home appliances power rate improvements.	99
Figure 4.26. Home appliances power rate changes effect on household energy affordability.	99
Figure 4.27. Home appliances power rate changes effect on national energy accessibility.	100
Figure 4.28. Home appliances power rate changes effect on national energy acceptability.	100
Figure 4.29. Home appliances power rate changes effect on national energy availability.	101
Figure 4.30. The effect of supporting installed power capacity upgrades on electric stove adoption and the resulting residential sector electricity consumption.	102
Figure 4.31. Electric stove purchase cost incentives effect on its adoption and the resulting residential sector electricity consumption.	103
Figure 4.32. The effect of increasing electric stove adoption on the household energy availability.	103
Figure 4.33. The effect of increasing electric stove adoption on the household energy accessibility.	104
Figure 4.34. The effect of increasing electric stove adoption on the household energy affordability.	104
Figure 4.35. The effect of increasing electric stove adoption on the household energy acceptability.	104
Figure 4.36. The effect of increasing electric stove adoption on the national energy availability.	105
Figure 4.37. The effect of increasing electric stove adoption on the national energy accessibility.	106

Figure 4.38. The effect of increasing electric stove adoption on the national energy affordability.	106
Figure 4.39. The effect of increasing electric stove adoption on the national energy acceptability.	107
Figure 4.40. The effect of purchase incentive on rooftop solar adoption and the resulting residential sector electricity consumption.	107
Figure 4.41. The effect of rooftop solar purchase incentive on household energy affordability.	108
Figure 4.42. The effect of rooftop solar purchase incentive on national energy availability.	109
Figure 4.43. The effect of rooftop solar purchase incentive on national energy acceptability.	110
Figure 4.44. Energy subsidy adjustment effect on subsidised LPG price and electricity price.	111
Figure 4.45. Energy subsidy adjustment effect on electric stove adoption and electricity consumption.	111
Figure 4.46. Energy subsidy adjustment effect on rooftop solar adoption.	112
Figure 4.47. Energy subsidy adjustment effect on household energy availability.	113
Figure 4.48. Energy subsidy adjustment effect on household energy affordability.	114
Figure 4.49. Energy subsidy adjustment effect on household energy acceptability.	115
Figure 4.50. Energy subsidy adjustment effect on national energy accessibility.	115
Figure 4.51. Energy subsidy adjustment effect on national energy affordability.	116
Figure 4.52. Energy subsidy adjustment effect on national energy acceptability.	116
Figure 5.1. 2011-2022 energy consumption by demand sectors ¹ .	121
Figure 5.2. Industrial sector energy consumption by industry classification ¹ .	121
Figure 5.3. Industrial sector energy consumption by industry classification ²⁷⁴ .	121
Figure 5.4. Technology Adoption Framework	125
Figure 5.5. General Technology Adoption Model in the Industrial Sector	127
Figure 5.6. The “technology lock-in” phenomenon in the Industrial Sector	127
Figure 5.7. Steel Industry Production Pathway Shift ^{297,335} .	129
Figure 5.8. Fuel Mix in the other Indonesian energy intensive industries 2001-2021 ²⁷⁴ . Electricity consumption is calculated based on Input-Output Table ³³⁵ .	129
Figure 5.9. Model Demand Validation.	130
Figure 5.10. Model validation of energy consumption for the industrial sector.	131
Figure 5.11. Causal Loop Diagram in the DRI-EAF Adoption in the Iron & Steel Industry.	135
Figure 5.12. System diagram for the transition to the H ₂ -DRI-EAF steel production pathways.	138
Figure 5.13. Model simulation result under the baseline adoption drive weights as presented in Table 5.6.	142
Figure 5.14. Total Steel Capacity and Production	143
Figure 5.15. Clean hydrogen total production, demand from and allocated hydrogen supply to the steel industry under the baseline scenario	143
Figure 5.16. Capacity Utilization in the Steel Production under Different Economic Growth	144
Figure 5.17. Effect of GDP growth on the selected indicators	145
Figure 5.18. Changes in Coal, Natural Gas, and Grid Electricity in the Steel Production Energy Mix under Different Economic Growth	146
Figure 5.19. Energy Availability and Hydrogen Injection Rate in DRI-EAF	146

Figure 5.20. Effect of maximum injection rate on the observed indicators	147
Figure 5.21. Effect of risk-tolerance on the observed indicators	148
Figure 5.22. Effect of risk-tolerance on hydrogen production.....	149
Figure 5.23. Effect of risk-tolerance on steel industry hydrogen demand and allocated supply	149
Figure 5.24. Effect of renewables development rate on the observed indicators	150
Figure 5.25. The effect of resources development rate on the carbon storage and renewables availability.....	151
Figure 5.26. The effect of resources development rate on the production of clean hydrogen.	151
Figure 5.27. Fossil energy prices effect on the observed indicators	152
Figure 5.28. Fossil energy prices effect on hydrogen production and supply to the steel industry	153
Figure 5.29. BEV penetration level on the observed indicators	154
Figure 5.30. BEV penetration level effect on hydrogen production and supply to the steel industry	155
Figure 5.31. Summary of uncertainty results on the observed indicators.....	156
Figure 5.32. Share of electrified production technologies in each industry	158
Figure 5.33. Baseline energy and electricity demand, and the proportion of grid electricity in the industrial sector	159
Figure 5.34. Energy-intensive industries demand under different uncertainties	161
Figure 5.35. Electrified production pathway adoption in the industrial sector under different uncertainties	163
Figure 5.36. Energy demand in the base metals industry under different uncertainties.	165
Figure 5.37. Energy demand in the cement industry under different uncertainties.	165
Figure 5.38. Energy demand in the chemical and petrochemical industry under different uncertainties	166
Figure 5.39. Total energy and grid electricity demand, and the proportion of grid electricity in the industrial sector under different uncertainties.....	167
Figure 5.40. Industrial mix and energy demand under different economic growth.....	167
Figure 5.41. Effect of transition cost on price level of goods.....	168
Figure 5.42. Effect of transition cost on state budget deficit ratio to GDP.....	169
Figure 5.43. Effect of transition on industrial sector primary resources demand.....	170
Figure 5.44. Effect of transition on industrial sector carbon emissions.....	171
Figure 6.1. Indonesian Power Sector Generation Mix from 2000 to 2022.....	175
Figure 6.2. Technology adoption factors in the power sector.	177
Figure 6.3. Renewables adoption dynamics in the power sector.	178
Figure 6.4. Comparison between the actual and modelled total installed capacity in the power sector.	180
Figure 6.5. Power mix in the power sector comparing the actual and simulation results	181
Figure 6.6. Power mix in the power sector baseline simulation result.	182
Figure 6.7. Electricity price under the baseline simulation result.....	183
Figure 6.8. State budget deficit ratio to GDP under the base run.	183
Figure 6.9. The burden of energy subsidies.	184
Figure 6.10. Price level and cost-push drivers	184
Figure 6.11. Share of final energy demand in the economy under the base run.....	185
Figure 6.12. Real GDP growth under the base run.	186

Figure 6.13. Share of Electricity Expenditures in Households Income and Energy Expenditures	186
Figure 6.14. Labor demand in the whole economy and unemployment rate.....	187
Figure 6.15. Emissions from the power sector.....	188
Figure 6.16. Land use for bioenergy and land availability.....	189
Figure 6.17. Domestic fossil fuel reserves under the base run.	189
Figure 6.18. Domestic critical minerals reserve under the base run.	190
Figure 6.19. Effect of changes in FIT on the share of fossil energy and renewables in the power mix.	192
Figure 6.20. Electricity demand and price under different FIT.	192
Figure 6.21. Effect of FIT on state budget deficit ratio to GDP	193
Figure 6.22. Effect of FIT on price level	193
Figure 6.23. Effect of FIT on Real GDP Growth.....	194
Figure 6.24. Share of Electricity Expenditures under different FIT.	194
Figure 6.25. Effect of changes in FIT on Labor demand in the whole economy and unemployment rate.....	195
Figure 6.26. Emissions from the power sector under different FIT.	195
Figure 6.27. Effect of FIT changes on land use for power plants and land availability.	196
Figure 6.28. Fossil fuel domestic reserves under different FIT.	196
Figure 6.29. Critical minerals domestic reserves under different FIT.	197
Figure 6.30. Effect of CFPP early retirement and ban on the power mix.....	197
Figure 6.31. Electricity demand and price under different FIT.	198
Figure 6.32. Effect of CFPP early retirement and ban on state budget deficit ratio to GDP.	198
Figure 6.33. Effect of CFPP early retirement and ban on price level.	199
Figure 6.34. Effect of CFPP early retirement and ban on Real GDP Growth.	199
Figure 6.35. Electricity expenditures in households with CFPP early retirement and ban....	200
Figure 6.36. Effect of CFPP early retirement and ban on Labor demand and unemployment rate.	200
Figure 6.37. Emissions from the power sector with CFPP early retirement and ban.	201
Figure 6.38. Effect of CFPP early retirement and ban on land use for power plants and land availability.....	201
Figure 6.39. Effect of CFPP early retirement and ban on Fossil fuel domestic reserves.....	202
Figure 6.40. Effect of CFPP early retirement and ban on critical minerals domestic reserves.	202
Figure 6.41. Effect of carbon tax on the power mix.	203
Figure 6.42. Electricity demand and price under different carbon tax.	204
Figure 6.43. Effect of carbon tax on state budget deficit ratio to GDP and energy subsidy sufficiency.	204
Figure 6.44. Effect of carbon tax on price level.....	205
Figure 6.45. Effect of carbon tax on real GDP growth.	206
Figure 6.46. Effect of carbon tax on household expenditure for electricity.....	206
Figure 6.47. Effect of carbon tax on labour demand and unemployment rate.....	207
Figure 6.48. Changes in Emissions from the power sector with carbon tax.....	207
Figure 6.49. Effect of carbon tax on land use for power plants and land availability	208
Figure 6.50. Effect of carbon tax on fossil fuel domestic reserves.....	208
Figure 6.51. Effect of carbon tax on critical minerals domestic reserves.....	208
Figure 6.52. Effect of reducing fossil fuel subsidy on the power mix.	210

Figure 6.53. Electricity demand and price under different fossil fuel subsidy reduction	210
Figure 6.54. Effect of fossil fuel subsidy reduction on state budget deficit and energy subsidy sufficiency	210
Figure 6.55. Effect of fossil fuel subsidy reduction on price level	211
Figure 6.56. Effect of fossil fuel subsidy reduction on real GDP growth.....	211
Figure 6.57. Effect of fossil fuel subsidy reduction on household expenditure for electricity.	212
Figure 6.58. Effect of fossil fuel subsidy reduction on labour demand and unemployment rate.	212
Figure 6.59. Effect of fossil fuel subsidy reduction on emissions from the power sector.	213
Figure 6.60. Effect of fossil fuel subsidy reduction on land use for power plants and land availability.....	213
Figure 6.61. Effect of fossil fuel subsidy reduction on fossil fuel domestic reserves.	214
Figure 6.62. Effect of fossil fuel subsidy reduction critical minerals domestic reserves.	214
Figure 6.63. Effect of coal depletion premium on the power mix.	215
Figure 6.64. Electricity demand and price under different coal depletion premium.	215
Figure 6.65. Effect of fossil fuel subsidy reduction on state budget deficit and energy subsidy sufficiency	216
Figure 6.66. Effect of carbon tax on price level.....	216
Figure 6.67. Effect of fossil fuel subsidy reduction on real GDP growth.....	217
Figure 6.68. Effect of fossil fuel subsidy reduction on household expenditure for electricity.	217
Figure 6.69. Effect of fossil fuel subsidy reduction on labour demand and unemployment rate.	218
Figure 6.70. Effect of coal depletion premium on land use for power plants and land availability.	218
Figure 6.71. Effect of depletion premium on fossil fuel domestic reserves.	219
Figure 6.72. Effect of carbon tax on critical minerals domestic reserves.....	219
Figure 6.73. Effect of risk tolerance changes on the fossil energy and renewables share in the power mix.	221
Figure 6.74. Electricity demand and price under different risk tolerance.....	221
Figure 6.75. Effect of renewables development rate share in the power mix.....	222
Figure 6.76. Electricity demand and price under different risk tolerance.....	222
Figure 6.77. Effect of renewables development rate share in the power mix.....	223
Figure 6.78. Electricity demand and price under different risk tolerance.....	223
Figure 6.79. Fossil energy and renewables share in the power mix under the NEP scenario.	226
Figure 6.80. Electricity demand and price under the NEP scenario.	226
Figure 6.81. Effect of NEP policy on state budget deficit and energy subsidy sufficiency...	227
Figure 6.82. Effect of NEP policy on price level	228
Figure 6.83. Effect of NEP policy on real GDP growth.	229
Figure 6.84. Effect of NEP policy on household expenditure for electricity.	229
Figure 6.85. Effect of NEP policy on labour demand and unemployment rate.	229
Figure 6.86. Effect of NEP policy on emissions from the power sector.	230
Figure 6.87. Effect of NEP policy on land use for power plants and land availability.....	230
Figure 6.88. Effect of NEP policy on fossil fuel domestic reserves.	230
Figure 6.89. Effect of NEP policy on critical minerals domestic reserves.	231

Figure 6.90. Fossil energy and renewables share in the power mix under the GTU scenario.	232
Figure 6.91. Electricity demand and price under the GTU scenario.	233
Figure 6.92. Effect of GTU policy on state budget deficit and energy subsidy sufficiency.	233
Figure 6.93. Effect of GTU policy on price level.	234
Figure 6.94. Effect of GTU policy on real GDP growth.	235
Figure 6.95. Effect of GTU policy on household expenditure for electricity.	235
Figure 6.96. Effect of NEP policy on labour demand and unemployment rate.	236
Figure 6.97. Effect of GTU policy on emissions from the power sector.	236
Figure 6.98. Effect of GTU policy on land use for power plants and land availability.	237
Figure 6.99. Effect of GTU policy on fossil fuel domestic reserves.	237
Figure 6.100. Effect of GTU policy on critical minerals domestic reserves.	237
Figure 6.101. Fossil energy and renewables share in the power mix under the SET scenario.	239
Figure 6.102. Electricity demand and price under the SET scenario.	239
Figure 6.103. Effect of SET policy on state budget deficit and energy subsidy sufficiency.	239
Figure 6.104. Effect of SET policy on price level.	240
Figure 6.105. Effect of SET policy on real GDP growth.	241
Figure 6.106. Effect of SET policy on household expenditure for electricity.	241
Figure 6.107. Effect of SET policy on labour demand and unemployment rate.	242
Figure 6.108. Effect of SET policy on emissions from the power sector.	242
Figure 6.109. Effect of SET policy on land use for power plants and land availability.	243
Figure 6.110. Effect of SET policy on fossil fuel domestic reserves.	243
Figure 6.111. Effect of SET policy on critical minerals domestic reserves.	244
Figure 6.112. Overall comparison of the policy economic, social, and environmental outcomes	245

List of Tables

Table 2.1. Renewable energy transition policy in the electricity generation sector ¹⁰	12
Table 3.1. Current situation and benchmark values of factors for adopting public transportation. Actual values are weighted from 186 origins to the two CBDs in Jakarta at peak hour.	29
Table 3.2. Policy sets used in the scenario analysis.	62
Table 3.3. Uncertainty setup for scenario analysis	62
Table 4.1. Summary of fuel transition for cooking in households.....	82
Table 4.2. Adoption drivers and indicators for rooftop solar	84
Table 4.3. Indicators of energy security used in this study	84
Table 4.4. Summary of the technology adoption impact on household and national energy security	117
Table 5.1. Decarbonisation and sustainability strategies in different industrial sub-sectors .	122
Table 5.2. Energy policies in Indonesia aimed at the industrial sector. ¹⁰	123
Table 5.3. Nonlinear Regression Result for Industrial Sector Demand	124
Table 5.4. The weights of the adoption factors and criteria. Factors with “N/A” value indicates it was not found to be relevant by the interviewed experts.....	126
Table 5.5. List of loops in the system model.	136
Table 5.6. Adoption drivers weights emulating risk-tolerance of the potential hydrogen producers.....	139
Table 5.7. Renewables and carbon storage potential development rate parameters	140
Table 5.8. Projected annual price changes of fossil fuels	141
Table 5.9. Weights of adoption drivers to emulate different risk-tolerance of the industries	160
Table 6.1. Renewable potential, its planned utilization by 2050 ¹⁰ and capacity factor ⁸	176
Table 6.2. The weights of the adoption factors and criteria.	177
Table 6.3. Adoption drivers weights emulating risk-tolerance in the power sector.....	220
Table 6.4. Renewables and carbon storage potential development rate parameters	221
Table 6.5. Values of potential thermal efficiency in the power sector under different uncertainty settings	223
Table 6.6. The values of the uncertainty parameters under different settings.....	224
Table 6.7. The values of the uncertainty parameters in the NEP scenario	225
Table 6.8. The values of the uncertainty parameters in the GTU scenario	232
Table 6.9. The values of the uncertainty parameters in the ST scenario.....	238

List of Abbreviations

4A	Availability, Accessibility, Affordability, and Acceptability energy security framework
ADB	Asian Development Bank
AHP	Analytic Hierarchy Process
APERC	Asia Pacific Energy Research Centre
ASI	Avoid-Shift-Improve framework
A-USC	Advanced Ultra Super Critical
BAPPENAS	Badan Perencanaan Pembangunan Nasional (Indonesian National Planning Agency)
BePP	Bioenergy Power Plant
BEV	Battery Electric Vehicles
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BRI	Belt and Road Initiative
BRT	Bus Rapid Transit
CCGT	Combined-Cycle Gas Turbine
CCUS	Carbon Capture, Utilization and Storage
CFPP	Coal-fired Power Plant
CLD	Causal Loop Diagram
COVID-19	Corona Virus Disease 2019
CPI	Consumer Price Index
CPO	Crude Palm Oil
DF-PCCI	Dual-Fuel Premixed Charge Compression Ignition
DPP	Diesel Power Plant
DRI	Direct Reduction Iron
EAF	Electric Arc Furnace
EIA	U.S. Energy Information Administration
EPC	Engineering, Procurement, and Construction
ETM	Energy Transition Mechanism
ETS	Emission Trading System
EV	Electric Vehicle

FE	Fossil-based Electricity
FIT	Feed-in Tariff
GDP	Gross Domestic Product
GFPP	Gas-Fired Power Plants
GFPP	Gas-Fired Power Plant
GHG	Green House Gasses
GOI	Government of Indonesia
HEV	Hybrid Electric Vehicles
HFE	Household Final Expenditure
HPAL	High-Pressure Acid Leach
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IES	Illuminating Engineering Society
IPP	Independent Power Producer
LCA	Life-Cycle Assessment
LED	Light Emitting Diode
LFP	Lithium Iron Phosphate battery
LPG	Liquid Petroleum Gas
LRT	Light Rail Transit
MAPE	Mean Absolute Percent Error
MEMR	Indonesian Ministry of Energy and Mineral Resources
MPV	Multi-Purpose Vehicle
MRT	Mass Rapid Transit
NCA	Nickel Cobalt Aluminium battery
NDC	Nationally Determined Contribution
NMC	Nickel Manganese Cobalt battery
NPI	Nickel Pig Iron
OECD	Organisation for Economic Co-operation and Development
PLN	Perusahaan Listrik Negara
PPP	Purchasing Power Parity
PV	Photovoltaic
R/P	Resources to Production Ratio

RDF	Refuse-Derived Fuel
RE	Renewable Electricity
RPO	Renewables Purchase Obligation
SFD	Stock-Flow Diagram
TOE	Technology, Organization, and Environment framework
USC	Ultra Super Critical
VKT	Vehicle Kilometre Travelled
VRE	Variable Renewable Electricity
WHO	World Health Organization
WTA	Willingness-To-Accept

Chapter 1

Introduction

1.1. Background and Motivation

Indonesia's final energy demand is projected to grow from 7 million TJ in 2022¹ to 23 million TJ in 2050², and around 35% of this is expected to be in the form of electricity because of increased electrification in multiple sectors². On the other hand, Indonesia faces a surging level of CO₂ emissions, which increased from only 131.3 Mt in 1990 to 542.9 in 2018³, making it the 10th highest CO₂ emitter in the world⁴. Around 50% of CO₂ emissions come from the power sector, since around 86% of the electricity is generated from fossil fuels^{2,5}. Indonesia's Nationally Determined Contribution (NDC) aims to reduce greenhouse gases (GHG) by 29% unconditionally by 2030⁶. To support the goal, the Government ambitiously plans to increase the renewables uptake in the power sector by up to 80% by 2050².

Many have argued that the shift to renewable energy is in line with the aim of achieving sustainability. However, its adoption could lead to effects contradicting the goal. One must remember that electricity is a secondary energy produced from primary resources, which are mostly finite. For example, even though renewables theoretically generate electricity from an infinite source, the land on which the solar PV is installed is also finite. In addition, some renewable energy sources, like hydro, solar, and wind power, require a larger land footprint than fossil energy^{7,8}. Researchers have also found undesirable effects on food and water security from the use of biodiesel⁹, which is being planned to replace diesel to generate electricity¹⁰. Furthermore, biodiesel is subject to supply risk since it is also used in the transportation sector, while palm oil as one of its feedstocks is used in the residential and industrial sectors¹.

In an economy that relies on fossil fuel like Indonesia, shifting away from it could also lead to adverse impacts. For example, phasing out fossil fuel could also lead to economic instability, as it provides almost 18% of the Indonesian government's revenue through tax and non-tax revenues¹¹. Moreover, although the cost of renewable energy has been declining significantly in the last decade⁸, an extensive integration of variable renewable energy into the grid may also increase the electricity price when the system cost is considered^{12,13}, which may be particularly true in case of Indonesia where the system cost of, solar PV for example, is more expensive than in other countries^{8,14}.

The Indonesian government is planning to employ an array of energy policies to support the transition in the power sector. However, even some policies could lead to negative impacts on the economy. For example, the application of a carbon tax could lead to a decline in real GDP¹⁵. Other policies which are subsidies in nature, like the Feed in Tariff (FIT)¹⁶ or tax credits could increase government budget deficit and leave less revenue for other purposes like subsidies, which could create a greater burden for lower income households. In addition, a FIT could lead to a spike in electricity prices^{16,17}.

These adverse effects indicate that the energy transition must not be viewed from the narrow goal of reducing CO₂ emissions, but from a whole system perspective. From the perspective of

ecological economics shown in Figure 1.1., energy is the foundation of an economic system, which flows through resources, production processes, and goods consumed. Unlike the isolated energy economics view which disconnects the implications of energy use, ecological economics considers the feedback of the diminishing environmental capacity with energy use¹⁸ on top of its effect on aggregate demand which drives the economy.

Note: A = Emissions, C = Consumption, E = Energy, I = Interest, K = Capital, L = Labour, R = Resources, W = Waste

1.2. Research Questions and Objective

1. Who are involved and what factors exist in the renewable energy transition?
2. What are the dynamics of the energy transition on the supply and demand side of the system?
3. How do the current policies and regulations affect economic, social, and environmental indicators?
4. What policies are necessary for a sustainable energy transition?

the first and second questions would help to understand the structural barriers to energy transition in the system. The answers to the second question also serve as the basis for answering the third question, which would help in understanding the economic, social, and environmental strengths and weaknesses of current policies and regulations. Finally, by answering the fourth question this study aims to propose policies that are necessary for a sustainable energy transition.

1.3. Overarching Research Methodology and Research Stages

At the same time as the transition in the supply-side, i.e. the power sector itself, transition is also happening in the demand sectors. For example, the residential sector has been pushed to adopt electric stoves to reduce dependency on liquid petroleum gas (LPG)¹⁹, while aggressive efforts to adopt electric vehicles have been pushed in the transportation sector²⁰. While both could increase electricity demand, which potentially opens the opportunity for renewables adoption, the power sector could still opt for fossil-based generation if policies are not supportive.

Due to the complexity of technology adoption, it is necessary to consider the transition using a bottom-up approach rather than a top-down approach. In a top-down approach, technology adoption level is commonly simplified by using a predetermined scenario. While this is useful to explore the impact of such scenario, it is often uncertain whether the desired adoption level is feasible to which a technology adoption model could help to answer. In doing so, a bottom-up approach needs to be used instead of a top-down approach. In addition, a top-down approach has difficulties dealing with energy price elasticity^{21,22} – a factor that is important in the energy transition, since renewable energy prices are often more expensive.

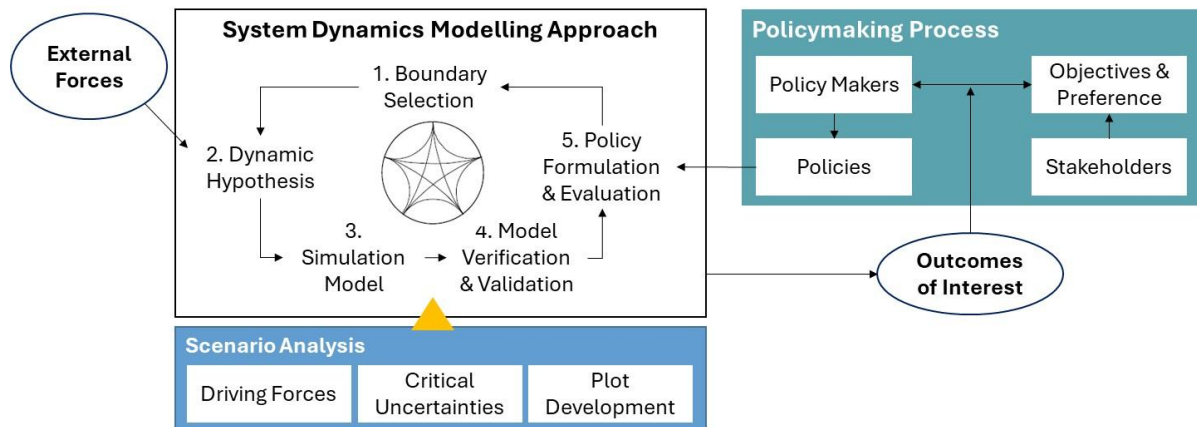


Figure 1.2. The overarching research methodology. The system dynamics modelling approach is based on Sterman²³ while the scenario analysis and policy making process is based on Walker²⁴.

To accommodate the complexity of the energy transition, the method used should be able to model the system's non-linear behaviour during the transition period and the uncertainties associated with the system. Modelling approaches such as agent-based models, real options, game theory, system dynamics, economic modelling, and scenario analysis are suitable for such kinds of problem²⁵. There have been many tools that model the energy system. However, some energy modelling tools such as MARKAL, TIMES, or NEMS are based around an optimization approach^{26,27}. On the other hand, tools like LEAP are more explorative by accommodating scenarios. However, LEAP does not estimate the impact of energy policies on the economy²⁸, something this study wishes to address. Hence, the use of system dynamics to model the problem is proposed.

System dynamics is built upon the dynamic relationship of variables within the system and has been used to model complex systems, including economic systems²⁹, technology diffusion²³, and energy systems³⁰. System dynamics is also suitable for explorative studies as it can include scenario analysis and deal with uncertainty³¹. More recently, a tool based on system dynamics called MEDEAS³² has been developed, however it still lacks several key feedbacks in the system, such as environmental capacity. In addition, this research also incorporates the policy analysis framework proposed by Walker as a guide in developing proposed policies²⁴. The overarching methodology used for this research is presented in Figure 1.2. Following the research questions and methodology, this research is broken down into three main stages:

1. **Model conceptualization**

The objective of the first stage is to answer the first research question. In doing so, a conceptual model is developed to identify the stakeholders involved and the factors within the transition from fossil fuel to renewable energy using actor analysis and Causal Loop Diagram (CLD). System boundaries and outcome indicators are also identified at this stage.

2. **Simulation model building**

Using the understanding built from the qualitative model, the second stage transforms the qualitative model into a quantitative model by developing a simulation model based on the system dynamics approach.

3. **Policy development**

This stage serves as an explorative stage where scenarios are developed based on the critical uncertainties identified in Stage 2. Policy sets are formulated to explore their effect on the outcome indicators from which their sustainability is assessed.

1.4. System Dynamics Model Building

System dynamics modelling is an iterative process as illustrated in Figure 1.2. The modelling process is initiated from setting up the system boundary in which the problem is articulated²³. The scope of the system must be able to capture all the necessary elements involved in the problem that is being addressed while not being too broad that it loses its purpose²³. Rather than modelling the entire system, the model should be built upon a specific problem²³. In this thesis, the problem being addressed is the energy transition in the power sector from a whole system perspective which is articulated in the research question. The whole system perspective necessitates the inclusion of a broad system encompassing energy, economic, environmental, and social systems as illustrated in Figure 1.1 and will be elaborated in detail in Chapter 2.

After the problem has been articulated, the next step is to build a hypothesis of how it could arise. In the system dynamics methodology, the hypothesis is dynamic (hence the name dynamic hypothesis) because it should explain how the problem manifests from the system's underlying feedback and stock-and-flow structure²³. A Causal Loop Diagram (CLD) is used in visualizing the system's structure as illustrated in Figure 1.3. It expresses the problem's dynamics by mapping the relationships between variables within the system using two types of links. The first type is a positive relationship (commonly represented as a blue arrow with “+” sign) which indicates that the two linked variables increase or decrease together (statistically or logically), while the second is a negative relationship (commonly represented as a red arrow with “-” sign). A looping relationship could be generated from the relationships between variables which represents the feedback within the system, which are either reinforcing (positive feedback) or balancing (negative feedback). The feedback in the model

should (hypothetically) explain the problem that is being addressed. The dynamic hypothesis of this study will be elaborated in detail in Chapter 2.

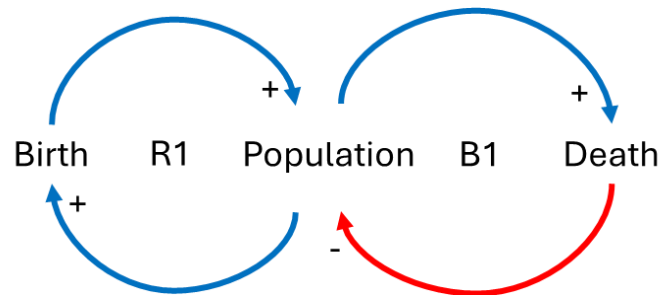


Figure 1.3. Example of a Causal Loop Diagram (CLD).

Up to this point, the system dynamics modelling is still conceptual. Step three of the iterative process is to quantify this qualitative model. At this step, the variables which are stocks, a variable whose value accumulates overtime, and flows or rates, a variable which define how the stock variables change overtime are specified. In mathematics and control theory, stocks are also known as integrals while flows are derivatives²³. Identifying the stocks and flows in the system transforms the CLD to a Stock-Flow Diagram (SFD) which is used to visualize the quantitative simulation model. The relationship between variables is quantified in several potential ways, which could be based on previous research, historical data, or regression. It is often the case that the relationship between variables is based on expert opinion or even the modeller's own judgement in case of lack past data. In this thesis, the model quantification is done in Chapter 3 to Chapter 6, while the relationships between variables are presented in the Appendices.

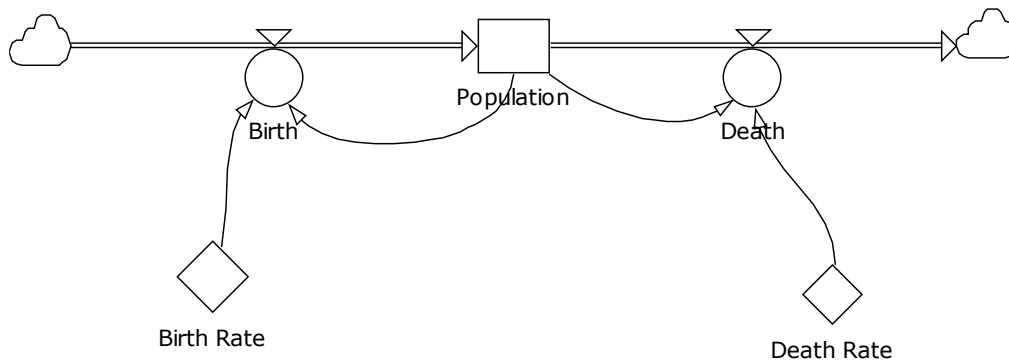


Figure 1.4. Example of a Stock and Flow Diagram (SFD) used in the Simulation Model.

The next step is to validate the simulation model where the output of the model is compared with historical data. This research utilizes three validation methods: model correlation, mean absolute percent error (MAPE), and Theil's inequality statistics. The model correlation provides the overall behaviour reproduction of the model while the MAPE indicates the accuracy of the model. The Theil's statistics identifies the source of the error through three types of error: bias (U^M), unequal variation (U^S), and unequal covariation (U^C)²³. The statistics can easily help modelers to identify the main source of the error since $U^M + U^S + U^C = 1$. Bias error is the result of different means between the model and the actual data. Unequal variation arises when the variances of the model and actual data are different. Unequal covariation indicates that the model output is are correlated imperfectly. Large bias error is usually the result of errors in the parameter estimation. A large unequal variation indicates that the model has different trends. On the other hand, if the main source of error is the unequal

covariation, the model captures both the mean and the trend of the actual data but does not capture its point-by-point value. While large U^M and U^S indicates a systematic error, large U^C is not systematic if the model is not aiming to model cyclic behaviour in the actual data. The validation result of the model is presented in Chapter 3 to Chapter 6.

After the model has been validated, policies are introduced into the system. The way the policies are implemented depends on their mechanism. It may modify the flows in the system or other variables that ultimately leads to the flow. Policies can also modify the structure of the system by cutting a link between variables or even changing the feedback. In any case, the effect of the policies on the system is observed, and if it does not yield the expected behaviour, the modelling process can return to either necessary step, and the modelling process restarts again from that point.

1.5. Research Contribution

This research fills the gap of energy transition literature in several ways:

1. Whole system perspective

By integrating economic, social, and environmental systems with the power system this research can identify the structural barriers of the energy transition instead of only the barriers in the power system itself. This research includes feedback between the economic system, social system, environmental system and the power sector which has not been done in previous research.

2. Sustainability Indicators

The implication of using a whole system perspective is the use of a more holistic set of indicators in assessing the energy transition. Instead of only focusing on carbon emissions, this research proposes economic, social, and environmental indicators, which enables trade-off analysis of a policy.

3. Bottom-up approach

The bottom-up approach enables this research to breakdown the energy price elasticity structure which will otherwise be left as a black-box if using a top-down approach. By understanding the system structure, a clear mechanism as to why demand is sensitive or not to price can be explained.

4. Supply-side and demand-side energy transition

This research breaks down the energy transition to each of the elements in the system, namely the supply-side and demand-side. While previous studies have only investigated individual sectors, this research fills in the gap by investigating the interaction between the supply-side and demand-side policies of the energy transition using the technology adoption model.

5. Primary data collection

Experts in the industrial sector and power sector were involved in this research. The technology adoption factors were the result of expert interviews. These factors provide technology adoption characteristics unique to Indonesia's case which are central in the model and in explaining the dynamics of the system.

1.6. Thesis Structure

The thesis structure is shown in Figure 1.5. Chapter 2 serves as the base for the study providing the landscape of the energy transition from the whole system perspective. The chapter qualitatively explores the economic, social, and environmental impacts of renewable energy

transition in the power sector. By incorporating structural feedback between it and economic, energy, and environmental systems, the qualitative model enables the assessment of different energy policies. A combination of system dynamics modelling, and a policy analysis framework was applied to explore these issues. This chapter proposes a dynamic hypothesis that the increasing energy demand could cause the transition to renewables in the power sector to falter when faced by the economic and resources capacity constraints.

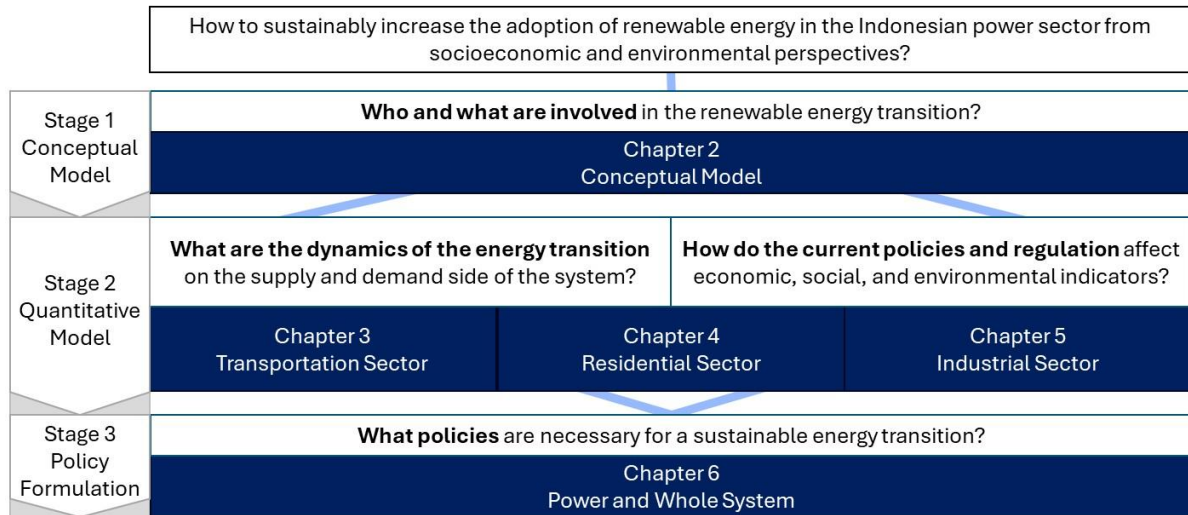


Figure 1.5. The structure of the thesis.

Chapter 3 initiates the discussion of energy transition dynamics in the demand sectors, starting with the transportation sector. The discussion of this sector is pivotal, as vehicle electrification is a key policy which may lead the sector to be a dominant electricity consumer in the future. This chapter introduces the concept of primary energy intensity as a sustainability indicator as well as the other indicators to holistically assess the transition. In addition, this chapter discusses the economic implications of the transition policy in the transportation sector.

Chapter 4 continues the exploration of the demand-side energy transition effect on the power sector by discussing transition in the residential sector, using the same approach as in Chapter 3. The residential sector is the largest electricity consumer and is projected to grow further based on two drivers. First is the natural growth of electricity consumption driven by improving household income, and second is from the push to use electric stoves to replace gas cookers. On the other hand, the sector can reduce grid electricity consumption by installing rooftop solar systems. Thus, this chapter looks at developments in electricity demand from both sectors under these circumstances.

Chapter 5 discusses the energy transition in the industrial sector, the last demand sector considered in detail here. In addition, this chapter will be the one which explores the interplay between transition in the energy demand sectors and energy supply. Aside from the overall industrial sector, this chapter takes on the energy transition in the steel industry – a hard-to-abate sector – as a case. Similar to the transportation sector, electrification also comes as one potential decarbonisation pathway in the steel industry. The other option is to introduce green hydrogen to replace coal and natural gas as both reducing agent and heat source. The addition of green hydrogen establishes a unique link between the steel industry and the power sector as one of its potential producers. The use of hydrogen in the steel industry also creates a link

between the steel industry and the fertilizer industry which would have an interesting role as a prosumer of hydrogen.

In Chapter 6 the focus is turned to the supply-side of the transition under the constraints from the demand-side transition, as well as social, economic, and environmental constraints. The demand side transition outputs in Chapter 3 through 5 are fed back to the supply-side transition and the socio-economic model. In doing so, the effect of both the supply-side and demand-side transitions on the indicators identified in Chapter 2 are investigated, making Chapter 6 the integration of the outcomes of the previous chapters. Finally, Chapter 7 concludes this thesis by providing summary of previous chapters, how has the research question been addressed, limitations of this research and also future works.

Chapter 2

Negative and Positive Forces in the Power Sector Energy Transition: A Conceptual Model

2.1. Background

There have been several previous studies which evaluated the effectiveness of energy transition policies in the Indonesian power sector. For example, Hidayatno et al. compared the effectiveness between net metering policies and net billing mechanisms in increasing the adoption of rooftop solar photovoltaics and concluded that net metering was more effective³³. Another study investigated the effectiveness of a FIT in increasing the adoption of geothermal adoption and found that this policy alone is not sufficient to achieve the national target³⁰. While insightful, these studies have not comprehensively examined the whole energy system and policy landscape. Many of the complications in energy policy implementation, as previously mentioned, involve linkages and feedback between different systems—the economic system in particular—which creates complexities in the energy transition. Hence, increasing the power sector energy transition should be viewed from the energy system and the economic system³⁴. One study has viewed the power sector energy transition issue from a wider perspective³⁵. Although they have considered the link with economic growth, they view the problem predominantly from the perspective of the state-owned PT Perusahaan Listrik Negara (Persero) (PLN), which limits the discussion with regards to structural feedback on the economic system. Furthermore, these studies used a specific model to assess each of the different policies. While this is an excellent way to analyse a specific policy, a generalized model would be more useful to understand the system as whole.

The objectives of this study are therefore threefold. First, is to understand the underlying system structure that could hold back the energy transition in the power sector—this includes technological, social, economic, and policy-related factors. Secondly, the study reviews the current policies that the Indonesian government has enacted or may enact to promote the energy transition. Energy transition policies involve multiple variables and stakeholders, which create a complex system with uncertainties due to nonlinear interactions³⁶. Thus, the third objective is to explore “what would happen” and “how does it happen” when these energy transition policies are implemented.

Given the complexity of energy transitions, it would be beneficial to have an in-depth elaboration on the variables involved and how their relationship affects the transition in the power sector. Thus, this chapter will present a dynamic conceptual model that is aimed towards understanding the under-lying structure and the behaviour of the power sector energy transition in Indonesia using systems thinking approach – the precursor of system dynamics²³. A systems thinking approach analyses the relationships within a complex system to uncover the dynamics behind the relationship between variables³⁷.

The next section of this chapter presents a literature review on theories, policies, and indicators relevant to the energy transition. This policy review identifies specific policies that Indonesia has implemented or may be considered, addressing the second objective of this paper. Section 3 discusses the proposed method used to evaluate energy transition policies. Section 4 shows

the process of building the conceptual model, and then the policy evaluation using the constructed model is discussed in Section 5. Finally, Section 6 concludes and present the implications of this study on current and future energy transition policies.

2.2. Literature Review

2.2.1. Energy Sustainability

The aggregate demand from multiple sectors drives the economy and becomes the basis for producers' production quantity, which induces a requirement for energy and resources²⁹. The by-products of economic activity are wastes and emissions that flow back into the environment¹⁸. This cycle emphasises the importance of aggregate demand in the economy to scale energy consumption and its environmental impact.

There are two fundamentally distinct analytical approaches for estimating energy demand. First, the bottom-up approach centres on the demand for different energy sources based on the intensity of use and efficiency of energy-using capital used by different energy consumers. On the other hand, the top-down approach attempts to relate macroeconomic variables such as Gross Domestic Product (GDP), relative energy price, and income to approximate energy demand²¹. Both approaches have advantages and disadvantages. For example, the bottom-up approach can be used to analyse the energy supply sector's restructuring but cannot endogenously model the saturation level of energy-using products. Top-down analysis can incorporate various economic scenarios but has difficulties dealing with energy price elasticity^{21,22}. Nonetheless, these two approaches synergistically provide a better outlook on future energy demand^{22,38}.

The top-down approach is useful when analysing the effect of the energy price on energy demand^{21,22}. Energy price is often related to other macroeconomic price indices, such as Consumer Price Index (CPI), to measure the real price of energy. In general, the price elasticity of energy demand is negative, indicating that the energy demand would decrease with an increase in real energy prices. However, with various energy sources, a decrease in one energy source could mean an increase in the other, which shows a substitutive relationship between energy sources. Conversely, two energy sources can also be complementary. The cross-price elasticity would be negative in the former case while positive in the latter²¹.

Theoretically, the price of any goods, including energy, is affected by scarcity²¹. This scarcity is not to be confused with physical scarcity, as the price of energy is more driven by an imbalance in supply and demand³⁹. Energy supply can be increased through more intensive exploration and extraction, thereby decreasing its reserve. In the case of a finite resource, ongoing extraction could cause a decreased supply in the future.

The notion of sustainability aims to maintain the availability of a finite resource for future generations. There are two concepts of sustainability. Weak sustainability allows for a reduced stock of an energy resource if the demand for future generations is met through substitution with reproducible capital for example the development of alternative energy, a principle called the Hartwick rule^{21,40}. On the other hand, strong sustainability requires a certain amount of stock for subsequent generations which relates to the physical stock of a resource. Non-renewable energy sources could be entirely substituted by renewable energy sources if their potential and production inputs are sufficient for future primary energy demand²¹. However, with a growing population and economy, ensuring enough energy resource may be a challenge for the Indonesian government and other stakeholders in the whole energy system.

2.2.2. Energy Transition Policy in Indonesia

The Indonesian power sector is based on a single-buyer model dominated by PLN. The PLN generates most of the electricity through its subsidiary and transmits and distributes it to consumers⁴¹. Independent power producers (IPP) also participate in electricity generation, albeit with a limited share⁴².

By 2021, Coal-fired power plants (CFPP) accounted for 50.4% of all installed capacity in Indonesia. Gas-fired power plants were the second largest, with 28.9%, hydropower 8.6%, diesel 6.7%, geothermal 3.1%, biomass 2.4%, and small fractions of variable renewable energy, such as solar and wind¹. Consequently, the electricity generated was also dominated by coal-fired power plants with 65.6%, followed by gas-fired power plants 19.1%, hydropower 6.8%, geothermal power plants 5.5%, and diesel power plants 2.2%¹. With this mix, the power sector consumed more than 66 Gt of coal (46.68 Mtoe), as well as 9.54 Mtoe gas and 2.36 Mtoe oil¹. The government plans to shift the energy mix to a share of at least 23% of renewable energy by 2025 and 31% by 2050¹⁰. In a more ambitious scenario, the government aims to have around 80% of electricity generated from renewable sources by 2050². The government plans to focus on hydropower and geothermal power plants until 2030². Afterwards, solar is projected to have the largest share among renewables, which is expected to account for 68% of the electricity generated by 2050².

The government has planned a set of energy policies aiming to increase renewable energy use and support energy security¹⁰. From the perspective of the power sector, these policies can be grouped into policies that affect the energy supply for electricity generation, electricity demand, and electricity generation itself. These policies can be further grouped into market-based and regulatory-based policies⁴³.

The most common market-based policies are financial incentives or subsidies, which artificially reduce the cost of goods. The Indonesian government has long provided large electricity subsidies to consumers⁴⁴, a common practice in developing countries⁴⁵. The government also provides subsidies to energy producers, which amounted to USD 644.8 million for the coal industry and USD 132.8 million for renewable energy in 2015⁴⁶. The subsidy reform in 2015 removed some of the artificial cost reductions of fossil fuel generation⁴⁴. However, pricing-based policies often pose consequences that counteract their goal⁴⁷. For example, a poorly designed FIT can lead to higher electricity costs owing to overinvestment^{16,17}. In some cases, other market-based policy instruments, like carbon pricing and taxes, only result in a shift from higher carbon fuels to lower carbon fuels, such as a switch from coal to gas^{43,48}. This phenomenon not only led to a less than anticipated carbon level reductions, but also imposes a considerable cost⁴⁹. Finally, subsidies could create economic inefficiency, deadweight loss, and overconsumption⁵⁰.

The Indonesian government also designed a number of regulatory-based policies, such as Domestic Market Obligations for coal⁵¹, purchase obligations for renewable electricity imposed on PLN, and installation obligations for solar PV in the residential sector^{10,51}. These policies aim to increase a demand for renewable energy. However, obligatory policies could create uncertainty in price when the price is not regulated, leading to high investment costs, which could lead to an increased electricity cost⁵². Poor compliance with obligatory policies hinders their implementation⁵³. Other regulatory-based policy includes budget allocation, energy price regulation, and energy intensity standardization¹⁰. Table 2.1 shows a summary of

energy policies in Indonesia relevant to the renewable energy transition in the electricity generation sector.

Table 2.1. Renewable energy transition policy in the electricity generation sector¹⁰.

Policy Group	No.	Policy	Mechanism
Market-Based	1.	Carbon Tax	A tax is imposed on individuals or institutions when purchasing or using carbon emitting energy-using products.
	2.	Energy Price Subsidy	The government provides subsidies for energy sources for consumers or producers.
	3.	Feed-In Tariff	The government mandates PLN to purchase electricity generated from renewable sources at a set price, and provides subsidies for this to PLN.
	4.	Fossil Fuel Disincentives	Implement excise or other disincentives on fossil fuels for a more favourable price comparison with renewable sources.
Regulatory Based	1.	Bureaucracy/Institutional Reform	The government improves bureaucratic processes to increase renewable energy investment attractiveness including by easing investment procedures and reducing the time for renewable energy auction processes.
	2.	Energy-Using Products Electrification	Increases the use of electricity in energy-using products especially for the residential and transportation sectors.
	3.	Construction/Installation Obligation	Obligates institutions to construct or install a minimum quantity of renewable energy.
	4.	Depletion Premium	Imposes a premium on the extraction of fossil fuel to be allocated for renewable energy.
	5.	Domestic Market Obligation (DMO)	The government requires energy producers to supply a minimum quantity of their production for the domestic market.
	6.	Energy Price Regulation	The government regulates energy prices by setting a base price, price ceilings, progressive pricing, price localization, or other pricing schemes.
	7.	Fiscal Budget Re-allocation	Readjusting fiscal budgets for energy price subsidy, renewable energy financing, energy accessibility, and research and development.
	8.	Fiscal Incentives	Incentives are provided by the government to consumers, industries, and institutions who participates in energy transition efforts, including the construction/installation of renewable energy or the use of energy efficient energy-using capital stock.
	9.	Purchase Obligation	Obligates a minimum purchase quantity of renewable energy to institutions.

2.2.3. Energy Transition Assessment Criteria

Several studies were identified that assess energy transition pathways. Each of these studies used different indicators that can be broadly grouped into three dimensions: economic, social, and environmental, in accordance with the United Nations' Sustainable Development Goals dimensions⁵⁴.

2.2.3.1. Economic Indicators

Numerous studies have established economic indicators relevant to the energy transition. The most frequently used economic indicators were GDP related, including GDP growth, GDP loss, GDP per capita, and final energy intensity to GDP^{18,55,56}. Supply and demand indicators are also often used to assess the energy transition pathway, among others, total primary energy supply per capita, shares of energy sources in total energy supply, and sectoral energy demand^{18,56,57}. Massive changes to the system structure raise questions related to investments, such as costs and their returns, as well as policy costs, mitigation costs, and abatement costs^{56–59}. Other authors include fiscal indicators, government budgets, and trade balance^{18,60}. Finally, due to the unstable nature of transition, some studies add risk indicators such as GDP volatility, investment volatility, consumption volatility, the likelihood of crises, volatility of total debt, economic risks to ratepayers, long-term economic viability, and energy security^{55,60–62}.

2.2.3.2. Environmental Indicators

CO₂ emissions are an obvious indicator when discussing the impacts of the transition to renewable energy. However, broader impacts on the environment should also be considered. Madlener and Stagl further classified the environmental impacts on the resources needed for energy production and the potential environmental consequences of energy production, use, and conversion⁶⁰. Land use, water use, and resource depletion appear in multiple studies as indicators of resources for required energy production^{18,55,63–67}. Aside from CO₂ emissions, other air pollutants such as NO_x, SO_x, and Particulate Matter (PM) have been mentioned in several references as environmental consequences of energy production, use, and conversion^{18,55,60,65}.

2.2.3.3. Social Indicators

Most studies are concerned with how an energy transition would affect the labour market, in particular, unemployment and job creation, since there will be a shift between the fossil fuel industry and the renewable energy industry^{18,55,60,68}. Other studies account for indicators that are related to income equality, including income distribution, the Gini coefficient, and household income disparity, as well as household income, in particular the cost of electricity^{18,60,68,69}. Some authors include public health indicators related to environmental effects, such as morbidity, human toxicity, and life expectancy at birth because it is widely understood that certain pollutants adversely affect health^{70–72}. Finally, other authors have also considered occupational hazards related to energy transition^{60,65,70}.

2.3. Methodology

This study used the policy analysis framework to develop the conceptual dynamic model²⁴. The first step in this framework is problem identification, where the systems dynamics approach is employed since the energy transition is a complex issue²³. The qualitative relationship between relevant variables in the system is illustrated using with the aid of a Causal Loop Diagram (CLD). The causal links between variables are represented using arrows with two polarities, “+” and “-”, which indicates a positive influence and negative influence of one variable on the other²³. Literature reviews are done to identify the variables relevant to the formulated problem and the polarity between variables. Based on the qualitative relationship between the variables, a dynamic hypothesis – the idea of how the behaviour of the system arises based on the system structure – is formulated.

The analysis proceeds by investigating the indicators relevant to the identified problem. Indicator investigation is an essential step in the policy analysis framework, as it will eventually

be the basis for discussing the outcomes of different policies. To enrich the analysis, a stakeholder analysis is incorporated to help understand each of the stakeholder's positions and interests in the problem^{24,73}. Their reaction to or influence on policies which ultimately affect the outcomes of the system are explored.

Both system dynamics and the policy analysis framework acknowledge that there are exogenous factors to the system that could affect the system's behaviour^{23,24}. Hence, as a final step, a system diagram is developed connecting the preceding steps with these external factors to the problem, representing uncertainties.

2.4. Results

2.4.1. Qualitative Model Development

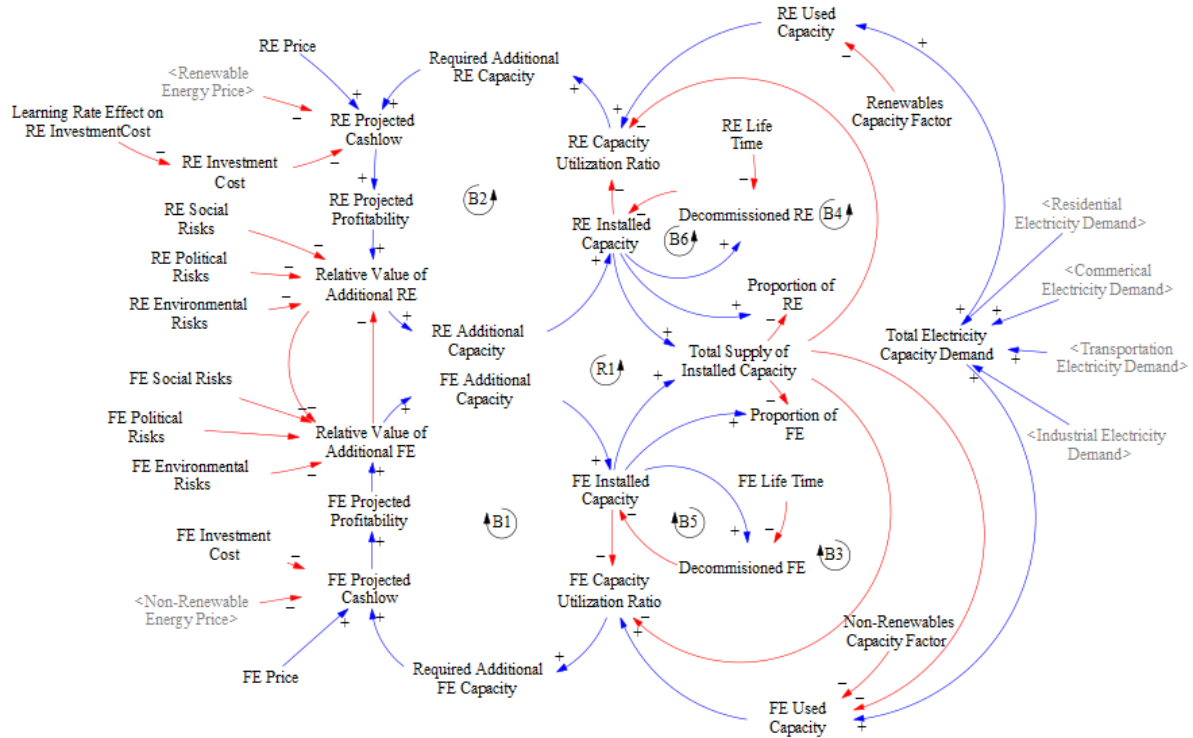
The proposed qualitative model is broken into four sub-models. The first part presents the dynamics in the power plant investment which is generalised into the selection between non-renewable and renewable energy power plants and how it relates to the energy transition in general. The conceptualisation of the energy substitution dynamics between fossil fuels and renewable energy is conducted which is then linked to the environmental carrying capacity which serves as a limitation to both energy sources. Afterwards the connection of the previous sub-models to the economy is discussed. The developed sub-model represents a generic model for all energy sources; thus, it is possible that a characteristic of one energy source is not present in the other sources.

2.4.1.1. Investments in Power Plants: Selection of Two Alternatives

Figure 2.1 shows the investment dynamics of two power plant technologies: fossil-based power plants or RE-based power plants. The total electricity demand from the residential, industrial, transportation, and commercial sectors can be served by electricity generated from fossil-based electricity (FE) or renewable energy electricity (RE). The installed capacity and capacity factor of the respective technology are considered in this model instead, as they are the decision variables for the electricity generated. When the capacity factor is constant and the total capacity is insufficient, additional capacity is required. Investment assessment for the additional capacity uses projected cash flow, profitability, and other investment risks to determine the investment execution, which may or may not fulfil the desired additional capacity for that technology (B1 and B2 loops). The realised additional capacity from either technology would add to the total installed capacity, ultimately fulfilling the total electricity demand (B3 and B4 loops). The current installed capacity is subject to de-commissioning (B5 and B6 loops), which would create its own trigger to add capacity from either technology.

The decision to build either a non-renewable or renewable power plant would depend on the relative value of the respective technology. One of the factors influencing the relative value is the projected investment profitability of a power plant which is affected by the energy price used for that power plant⁶⁰. Investment risks are also added to the technology's overall value, including environmental, social, and political risks⁷⁴. A comparison of the relative value of one technology would induce shifting or persistent behaviour (R1 loop). If, for example, when there is a need for added total capacity and FE is perceived to be more valuable after considering profitability and risks, then all additional capacity would be provided by RE. On the other hand, investment for RE would be preferred when it is perceived to be the better alternative. Thus, the tendency to use one technology can persist if its relative value is consistently more than the other. However, a shift could occur when there is a change in their relative value.

According to the developed conceptual model, the decision to build a particular power plant is heavily dependent on factors outside the power plant boundaries. It involves relative energy prices and environmental, social, and political risks, forming a bigger picture of the energy transition. The following section elaborates on the general dynamics of the energy transition.



Note:

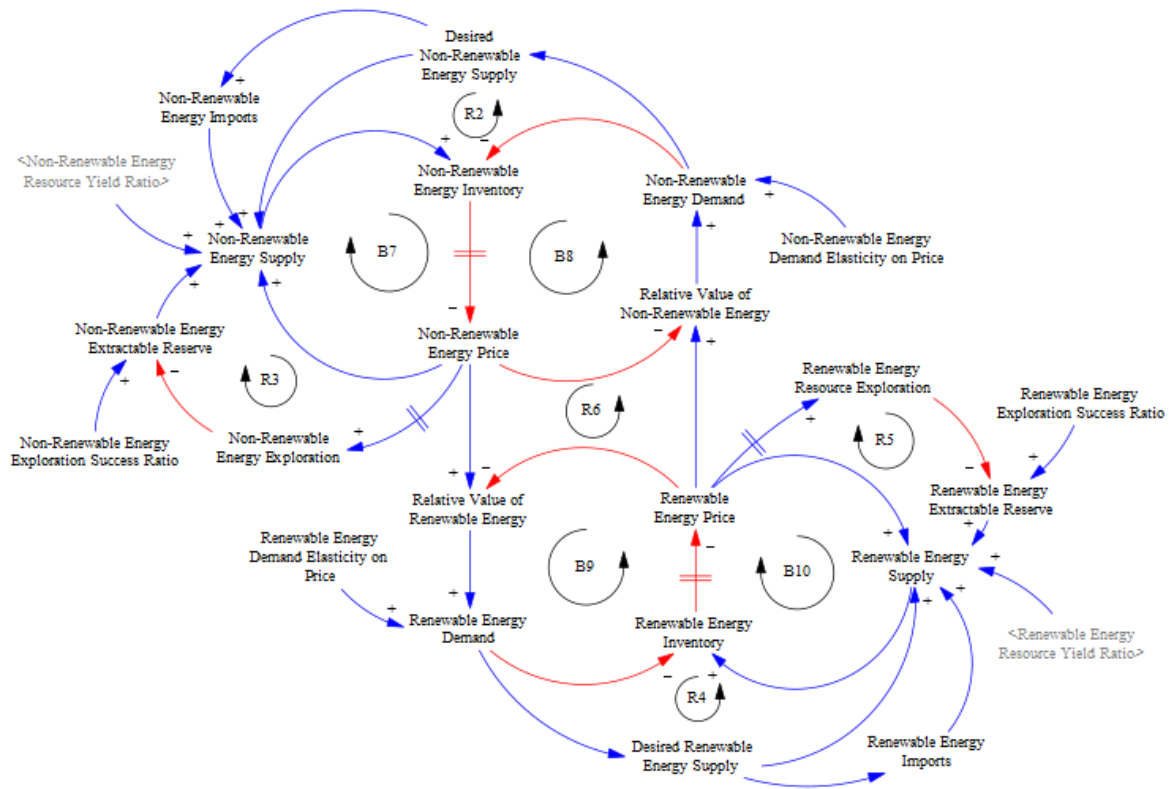
Blue arrows (→+) indicate a positive relationship between two variables, while red arrows (→-) a negative relationship.

Figure 2.1. Choosing between fossil-based power plants or RE-based power plants is an investment decision between two alternatives.

2.4.1.2. Fossil Fuel and Renewable Energy Substitution Dynamics

Renewable energy can be seen as a substitute for non-renewable energy, which is especially true in the context of achieving net-zero emissions. Hence, the demand for one energy type would also be affected by its relative value over the other. To understand energy demand dynamics, this study uses the supply-demand perspective and adopt the idea of scarcity as the driver of commodity prices.

As a commodity, the scarcity of energy inventory drives energy prices. When there is a negative imbalance between supply and demand, energy prices would increase, signalling energy suppliers to provide more energy either from domestic production or imports, shown as B7 loop in Figure 2.2. The price increase would also drive consumers to consume less energy, governed by their demand elasticity to price (B8 loop). As with the supply and demand system archetypes, the interaction between these two balancing loops generates a seesaw behaviour of the system that tries to stabilise energy prices^{23,75}. As demand is met with sufficient supply, energy prices would remain stable, thus encouraging more demand and creating a consumption-driven supply (R2 loop). This condition remains true as long as supply can be maintained. Short-run price changes would be the basis of the expected price in the future; hence, a rise in energy price makes investing in reserve exploration and extraction economically attractive²¹. However, increased extraction would eventually deplete reserves and limit the supply of energy which could lead to an increased price (R3 loop).



Note:

Blue arrows ($\rightarrow +$) indicate a positive relationship between two variables, while red arrows ($\rightarrow -$) a negative relationship.

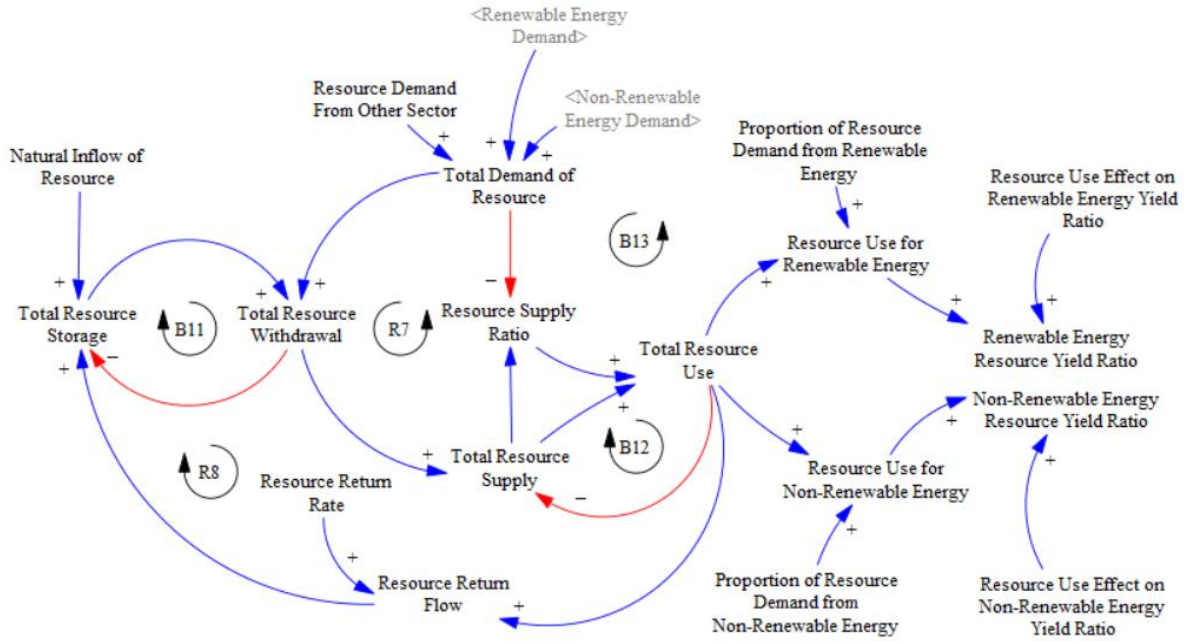
Figure 2.2. Substitution between non-renewable energy and renewable energy.

A reinforcing loop connecting both groups of energies is developed by differentiating the supply and demand dynamics of non-renewable and renewable energy (R6 loop). This reinforcing loop shows that there will be a period of price increase or decrease for both non-renewable and renewable energies, subject to the price of the other alternative. The interaction between supply and demand dynamics in non-renewable energy is also present in renewable energy, which is represented as B9 and B10 loops in Figure 2.1. Similarly, R4 loop shows the consumption-driven supply of renewable energy. Renewable energy is also subject to resource limitations (R5 loop), as briefly mentioned in the introduction.

From a substitution perspective, energy with a more sustainable supply will have a more stable price which would add to its relative value over the other. The supply of both energies is, however, are limited to resource constraints which will be explained next.

2.4.1.3. Environment Carrying Capacity

Figure 2.3 shows the dynamics of resource constraints, or carrying capacity, to energy supply. Some energy sources use a common resource, of which land and water are the primary examples⁹. Land is a finite resource where there is competition for its use, resulting in a potential shortage of land for a particular purpose, including energy production⁷⁶. Similarly, water is used to grow crops for biofuels, running turbines in hydropower plants, and coal mining processes. Thus, land and water shortages threaten the energy supply, but on the other hand, energy supply contributes to resource shortages. Moreover, the fact that land and water are used by other sectors, such as agriculture, residential, and industry, adds complexity to the problem.



Note:

Blue arrows ($\rightarrow +$) indicate a positive relationship between two variables, while red arrows ($\rightarrow -$) a negative relationship.

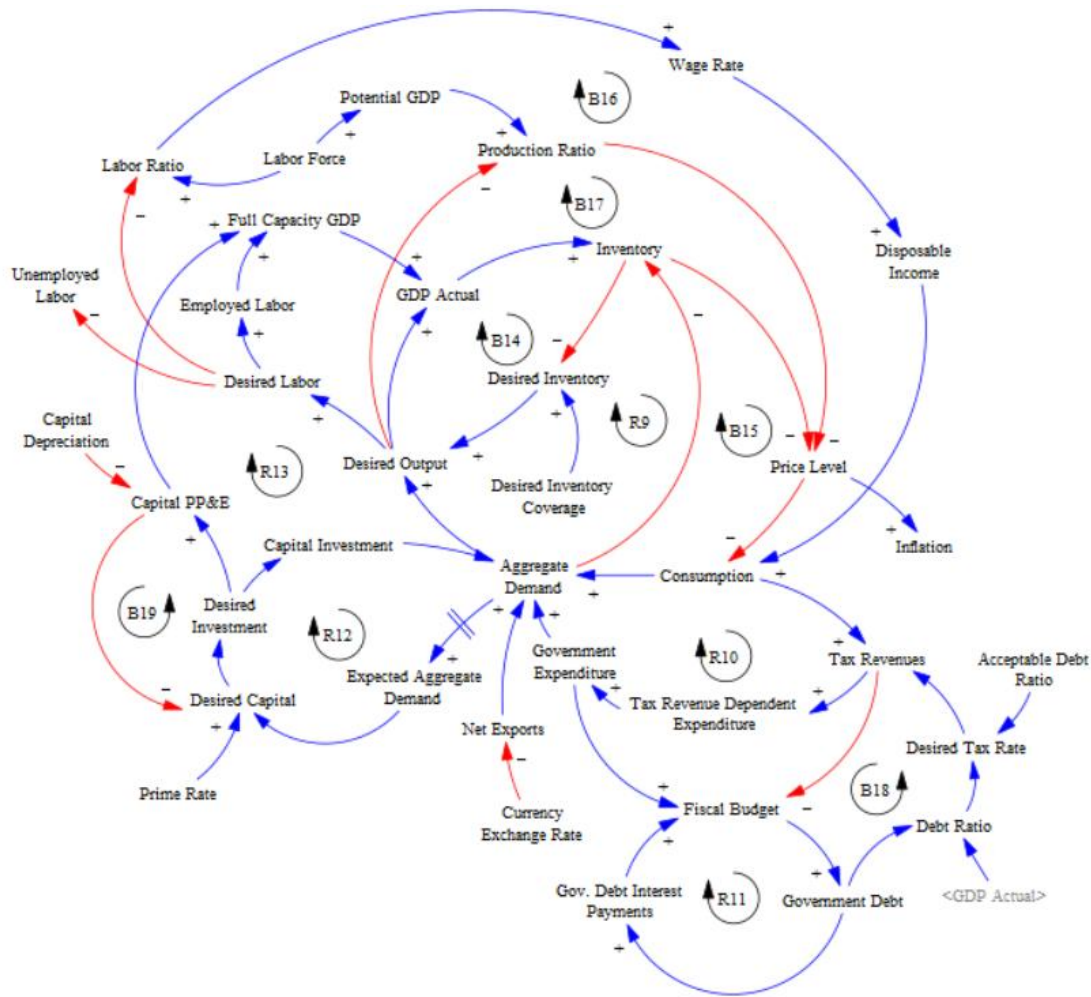
Figure 2.3. Environmental capacity linked to the supply of non-renewable energy and renewable energy.

As the demand for a particular resource increase with the increase of energy demand, so will the amount of resource required to be withdrawn and supplied (R7 loop). Also, in the case of renewable resources, there can be a return flow as an inflow for the resource storage alongside the natural inflows (R8 loop). However, the amount of withdrawable and suppliable resources is limited by its storage (B5 loop) and supply (B12 loop). Furthermore, the suppliable resource must then be allocated to other users across sectors, as pointed out before. These limitations affect the resource that can be used and, in turn, the resource's actual yield ratio for energy supply, which is linked to the yield ratio in Figure 2.1. (B13 loop). For example, if biofuel crops do not receive enough water, the actual crop yield would not be sufficient to fulfil the actual demand for biofuel production⁷⁷. Different energies would require different amounts of common resources. With limited environmental capacity, energy supply can be compromised, leading to an increase in energy prices.

2.4.1.4. Macroeconomic Loop

Numerous studies have found a relationship between the economy and energy consumption. A set of studies support the hypothesis of unidirectional causality from economic growth to energy consumption^{78–80} which is particularly true for the consumption of renewable energy^{81,82}. Conversely, some studies found that the causality is the other way around: energy consumption drives the economy^{83–85}. Yet further studies suggest that the causality is bidirectional, involving feedback from energy consumption to the economy^{86–88}. The causality between the economy and energy also depends on the length of observation. Most studies agree that there is a long-term causality between the economy and energy consumption, but some have dismissed the relationship between them in the short term^{86,89}. However, a study among OECD countries found that there is a threshold in which GDP per capita would have a short-term and long-term effect on energy consumption⁹⁰. In addition, it has also been suggested that the causality between the two variables may be in a different polarity between countries or even absent^{80,91,92}.

Since this study observes the dynamics of energy transition in the long term, this study adopts the bidirectional causal relationship between energy consumption and economic growth.



Note:

Blue arrows ($\rightarrow$) indicate a positive relationship between two variables, while red arrows ($\rightarrow$) a negative relationship.

Figure 2.4. The macroeconomic sub-model showing aggregate demand as a key driver to the economy.

Figure 2.4 shows the macroeconomic sub-model used in this study, adapted from Yamaguchi's work, which models the macroeconomy in a closed economy setting²⁹. The model consists of two parts: the short-run effect and the long-run effect of aggregate demand. In the short run, aggregate demand from consumption and government expenditure creates a reinforcing loop for GDP (R9 and R10 loops). Short-run aggregate demand drives the expectation of long-run aggregate demand, leading to an increased capital formation (R12 loop) and, with increased capital, so will the economic output (R13 loop). Aggregate demand would also affect the labour market through the desired output needed to fulfil that demand. The labour market then affects household income and, later, aggregate demand (B16). This sub-model also includes a fiscal budget essential for incentivizing the use of renewable energy in the economy, including for electricity generation.

The dynamics of supply and demand for goods in the macro economy are shown as the B14 and B15 loops, illustrating that production balances gaps in inventory and demands are fulfilled with sufficient inventory. The link between the economy and energy is the price of goods. When energy prices increase, the price of goods increase, decreasing aggregate demand, which leads to lower production and then GDP, creating a spiralling decline based on the reinforcing loops.

The effect will be multiplied if the energy is produced from common resources for other goods, such as biofuels, which can create a spillover to food prices⁹³. Conversely, an increase in aggregate demand drives energy consumption, creating fluctuations in energy prices governed by the dynamics shown in Figure 2.2 and affecting the power plant dynamics shown in Figure 2.1.

2.4.2. Selection of Relevant Indicators

From the power plant investment dynamics, this study presents environmental, social, and political risks as factors in the relative value of a power plant technology, aside from the economic risks represented by the energy price. This study shows that energy price is related to environmental capacity and stress the importance of energy within the whole economy, connecting to the labour market and fiscal budget. Hence, renewable energy adoption for electricity generation needs to be evaluated from a broader perspective, involving economic, environmental, and social dimensions.

This section discusses which indicators would fit each of the dimensions. This research proposed the use of outcome-based indicators in line with the policy analysis framework method described in earlier sections.

2.4.2.1. *Economic Dimension Indicators*

As pointed out in the literature review, the Indonesian economy is dependent on fossil fuels. For example, in 2010, 83% of the energy supply in the transportation sector came from fossil fuels. In the last decade, this share shrank to 56%, owing to a gradual substitution of biofuel from Crude Palm Oil (CPO)¹. However, this substitution affects supply and demand in the agriculture sector, leading to cooking oil price hikes, causing 3% food inflation and burdening the government budget with 250 million USD spent on subsidies^{94,95}. This phenomenon shows the cross-sectoral impact of the energy transition on the economy. Thus, structural changes in the national energy supply and demand would influence the economy. This research proposes to use real GDP growth as the overall economic indicator and the state of the government budget to capture the burden of energy policy on the government. The macroeconomic sub-model in Figure 2.4 includes both indicators as part of its dynamics.

Considering the challenge of fossil fuel phase-out while the Indonesian economy is dependent on it, this study proposes to include economic volatility as an indicator to evaluate the energy transition pathway. Economic volatility is often measured as a standard deviation of an economic variable from its reference value⁹⁶. Different economic variables have been used in various studies, such as GDP growth^{55,97}, GDP per capita growth^{98–100}, and price of primary goods or inflation⁹⁸. This work proposed to use the latter as another economic indicator, as it can directly capture the effect of energy price on aggregate demand, as shown in Figure 2.4.

2.4.2.2. *Environment Dimension Indicators*

Considering Indonesia will likely continue to use coal in its energy mix in the long term¹⁰, there are other emissions that would be relevant together with CO₂. Since coal has the highest emissions factor of NO_x, PM, and SO₂ among fossil fuels¹⁰¹. The inclusion of these pollutants will provide a more complete understanding of the environmental impacts because NO_x and SO₂ emissions may result in acid rain¹⁰² among others. In addition, NO_x and PM is often used associated with adverse impacts on human health^{103,104}.

This study also considers land use to evaluate the energy transition pathway for electricity generation. Some of Indonesia's most prominent renewable resources, such as solar power,

hydropower, and bioenergy which, respective to their required land area per megawatt output, are typically among the more land intensive. One study showed that solar power requires 17.6 ha of land for electricity production, transmission, and waste disposal per megawatt capacity, while large hydropower requires much more, with 127.6 ha per megawatt. These land requirements far surpass the land requirements of fossil fuel-based power generation such as coal which only requires 4.93 ha per megawatt⁷. When the latest capacity factor is considered, solar power would require 0.012 ha and hydropower requires 0.024 ha of land to produce 1 MWh of electricity, but coal power would only need less than 0.001 ha of land⁸.

Resource depletion is another crucial factor to be considered. For example, a study on battery materials found that the availability of a certain minerals may not be enough for the energy transition, even when recycling is considered^{10,105}. Likewise, fossil resources depletion is also important to be considered since Indonesia is a major coal producer¹⁰⁶ and the power sector is dependent on it¹. Another reason to account for resource depletion is the premium depletion policy of fossil fuels that will be enforced by the government, in which fractions are to be allocated to the renewable energy development budget¹⁰.

2.4.2.3. *Social Dimension Indicators*

One of the prominent arguments for the transition towards renewable energy is the creation of green jobs. Multiple studies have supported the finding that the total jobs created by the energy transition can offset the jobs lost in the fossil fuel industry^{107–110}. However, it is likely that those who lose their jobs will not be the ones who get the newly created green jobs. For example, a closed coal mining location might not be suitable as a renewable energy site, thus leading to unemployment in that area. The transition process needs to be considered, including retraining and relocation^{107,111–113}. Hence, aside from the number of jobs created, this study also proposes to observe the unemployment rate over time. The match between job supply and demand during the transition period can be captured using both indicators.

Regarding the potentially higher electricity cost from renewables, this study proposes to use household electricity burden as one of the social indicators, measured as the ratio of electricity expenditure to total household expenditure. This indicator is crucial for households, especially in rural areas since almost 13% of their expenditure is on electricity which is equal to expenditure on staple food^{114,115}.

2.4.3. Stakeholders Identification

There are multiple stakeholders involved in the adoption of renewable energy for electricity generation. The stakeholders are grouped into energy users, energy producers, operators, and legislators⁷³. The identified stakeholders are presented in Figure 2.5.

First are the energy users. Energy demand is commonly grouped into four sectors: residential, transportation, industrial, and commercial. The transportation and industrial sectors make up two of the largest energy consumers. Although both sectors currently consume fossil fuels, in the coming decade electricity consumption is expected to dominate. In the transportation sector, if all road transport was electrified by 2050, the sector has been estimated to require 107.25 MTOE of energy or equivalent to 1247.3 TWh of electricity^{1,2}. The use of electricity in the Industrial sector has also been growing substantially, by 61% in the last decade, compared to coal which declined 22% owing to the rapid growth of the food and beverage industry, chemical industry, and electronics industry which primarily consume electricity for their production^{2,116}.

Similarly, electricity demands from the residential sector, electricity's largest consumer, is expected to grow further with plans to replace gas cookers with electric cookers².

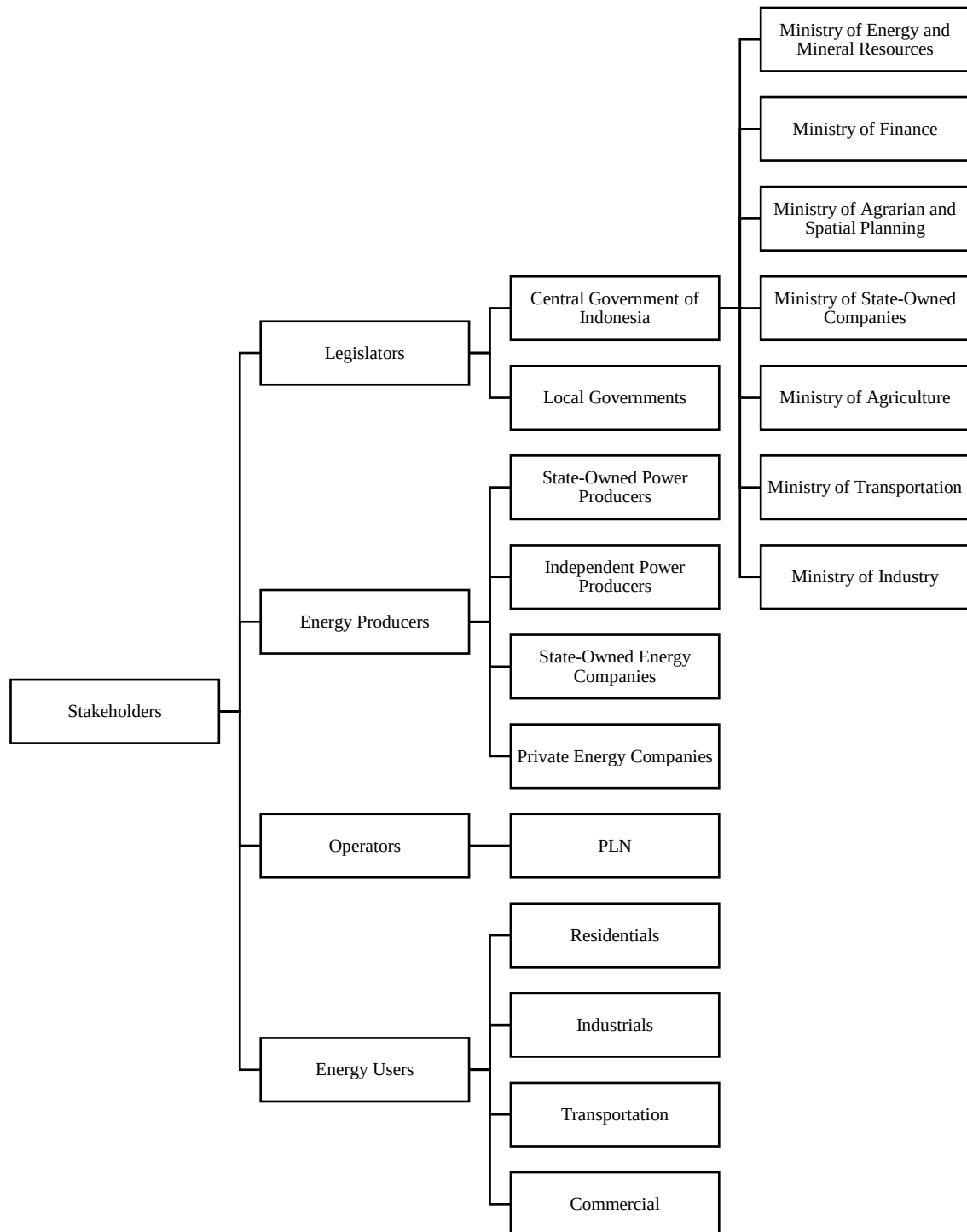


Figure 2.5. Stakeholders in the renewable energy adoption for electricity generation in Indonesia.

The state-owned electricity company, Perusahaan Listrik Negara (PLN), holds a unique role since it is both a power producer and an electricity distributor. Thus, it has dual objectives and interests in this problem. Since 2002, the electricity market has become open to Independent Power Producers (IPPs). However, their participation has been low because the market is only quasi-competitive and political constraints cause IPPs to be less competitive^{41,117}. Both state-owned power producers and IPPs can purchase fuel from state-owned or private energy

companies to run their power generation. These energy companies hold an important role in power generation, as is evident from recent domestic coal supply shortages that led to blackouts in Indonesia¹¹⁸.

Policies developed by legislators are affecting and affected by other stakeholders. The central government of Indonesia, through its ministries, has different roles in supporting the renewable energy goal, as stated in the National Energy Plan¹⁰. However, in fulfilling their roles, some programs clash, or at least depend on other ministerial programs. For example, carbon emissions from the biomass CFPP co-firing policy are not accounted for as emissions from power generation but are allocated to the forestry sector instead¹¹⁹. There is also a dependency between actors when incentivising renewable energy projects using instruments such as FIT. The Ministry of Finance would need to carefully reallocate fiscal budgets to avoid other economic problems¹⁰. These short examples show that the adoption of renewable energy is not limited to just one actor in the system. The central government needs to involve local governments, particularly for policies involving local interventions, such as aligning land use for energy with the Regional Spatial Plan¹⁰.

2.4.4. System Boundary

The system boundary for the modelling exercise identifies the scope of the problem that is being discussed, which variables are endogenous, exogenous, or completely excluded. This is necessary because different contexts may lead to different perceptions of the problem. As previously mentioned, this study aimed to capture the qualitative phenomenon of the renewable energy adoption dynamics for electricity generation in Indonesia. This problem is observed from the perspective of the Government of Indonesia, whose goal is to increase renewable energy use for electricity generation while maintaining socioeconomic stability and environmental protection.

In modelling the economy, the role of banks and central banks are considered, as initially designed by Yamaguchi²⁹, but the actions taken by both actors, such as setting interest rates, exchange rates, and other monetary policies, are considered as exogenous factors to the system. Labour and capital elasticities to GDP are also considered to be exogenous, as they are essential to the economic output, but modelling them as endogenous does not directly relate to the energy transition. Population dynamics as the primary driver of aggregate demand is also modelled as endogenous. Other behavioural factors affecting aggregate demand, such as the propensity to consume, are also considered to be exogenous. Finally, the importance of investment in energy transition is included through the learning rate as it may lead to a reduced renewable energy investment cost¹²⁰. However, the learning rate effect on technology cost itself is considered as an exogenous factor.

The effects of pollution and waste on public health and the economy, as suggested by Shmelev¹⁸ is not considered since it can indirectly be gauged from the level of emissions that cause adverse health effects, such as SO_x, NO_x, and PM. Furthermore, to comprehensively discuss the impacts of public health, the public health provision should be considered in itself—something out of context when discussing energy transition. This study also does not consider the dynamics of income inequality, including multiple social factors outside the system boundary set in this study. Furthermore, the wage rate, one of the factors of income inequality, can be captured from employment based on the macroeconomic sub-model.

2.4.5. System Diagram

The system diagram summarises the dynamics within and between the sub-models, indicators used, involved stakeholders, and policies supporting renewable energy adoption for electricity generation in Indonesia (Figure 2.6).

A dynamic hypothesis from the relationship between sub-models is to formulate on the underlying structural limitations to the power sector energy transition. First, from Figure 2.1, the demand for additional capacity, either from an increase in electricity demand or a decrease in supply due to decommissioning, triggers investments in new power plants. Once there is a demand for more capacity, power producers have the option to either invest in non-renewable energy or renewable energy. Power producers will invest in the technology which provides them with a higher value subject to economic, environmental, social, and political constraints. Next, the economic and environmental constraints are represented by the energy substitution dynamics and environmental capacity limitations in Figure 2.2 and Figure 2.3, respectively. Based on the dynamics between the two models, it is understood that energy prices could continue to increase due to resource depletion and increased demand. When the relative value of one energy is less than its substitute, a shift towards the substitute could happen and it could continue to be the better alternative if the situation persists.

In the meantime, the price of energy affects the price of electricity which is inversely related to electricity demand. This relationship was confirmed when the subsidy reforms in 2015 led to higher electricity prices, which consequently reduced electricity consumption by around 7%⁴⁴. The effect of an increase in the electricity price creates a chaining effect on the economy, as described in the macroeconomic sub-model in Figure 2.4. Without changes in household income, an increase in the price of electricity could lead to a decreased aggregate electricity demand, narrowing the opportunity for renewable energy power plants to gain investment. Thus, the dynamic hypothesis is that the increasing energy demand could cause the transition to renewables in the power sector into a halt due to the economic and resources capacity. The dynamic hypothesis can be assessed using a system dynamics simulation model.

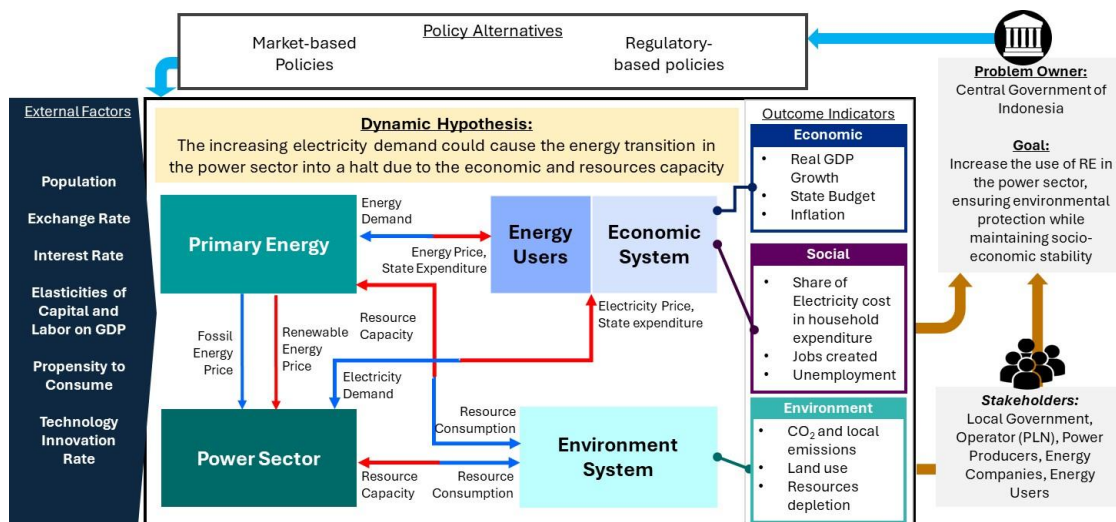


Figure 2.6. System Diagram of Energy Transition for Electricity Generation in Indonesia.

2.5. Discussion

The Indonesian Government has designed several policies to increase renewable energy adoption in electricity generation. This study discusses the economic, social, and

environmental effects of market-based and regulatory-based policy examples using the developed conceptual model. Two policies are taken as initial examples: the market-based policy to be discussed is FIT, whereas the discussed regulatory policy is RPO. The FIT is one of the most common renewable energy policies implemented in developed countries such as Germany, Japan, and Denmark^{121,122}, as well as in developing countries such as China, India, and Thailand^{53,123,124}. Indonesia has been implementing a FIT since 2011. Initially targeting geothermal power plant adoption³⁰, the FIT policy is planned to be expanded to other renewables^{53,125}. While the FIT policy aims to increase the renewable energy supply, an RPO obligates institutions to purchase electricity from renewable sources^{10,53}. Hence, these two policies represent the supply side and demand side of renewable energy. The two policies have a more direct government intervention on renewable energy supply and demand as opposed to other policies presented in Table 2.1, and therefore are selected for further discussion in this study.

Renewable energy investment is perceived as risky due to its higher cost⁴³. The FIT policy aims to reduce this risk by eliminating the gap between the actual generation cost and the electricity market price¹⁶. In the conceptual model, this policy would increase the projected annual cash flow, which pushes the probability of investing in RE when there is a demand for additional installed capacity. The RE investment will balance out the demand, rendering additional fossil-based power generation capacity unnecessary. However, like other incentives, FIT requires a substantial amount of the government's fiscal budget. When the budget deficit increases, the government can take on new debts, which in turn increases the budget deficit and creates a reinforcing loop shown as R11 in Figure 4. Governments use the ratio of debt to GDP, as opposed to its amount, to gauge whether it is acceptable or not. To reduce the debt ratio, the government can increase the tax rate or reduce its spending. Alesina et al. found that increasing the tax rate was more harmful to economic growth than cutting expenditures¹²⁶. If the government chooses to cut spending, this could limit the amount of FIT policy that can be deployed. On the other hand, the increasing tax could lead to a slowing economic activity¹²⁷, which would lead to reduced electricity demand, reducing the prospects of adding new RE capacity, as shown as B4 in Figure 2.1. In either case, the FIT would be limited to the government's fiscal budget; hence it should be paired with other policies that could alleviate the fiscal budget deficit. The problem with the FIT policy and the fiscal budget was hinted by Setiawan et al. who noted that despite the push for renewable energy³⁰, the Indonesian government still promotes the use of coal which is a vital commodity for the nation's economy.

The RPO obligates institutions to purchase a minimum amount of their electricity from renewable energy sources. In Indonesia, this policy is imposed on the PLN as the national electricity distributor, government institutions, and even some residential consumers¹⁰. As more renewable energy penetrates on-grid electricity through purchases by the PLN, electricity prices would increase^{13,14}. This would directly lead to an increased burden on households and industries. Furthermore, if industries cannot mitigate or absorb the increase, they would pass this through to the price of goods, which becomes an additional burden on households. Consumers could then (potentially) reduce their electricity consumption, creating balancing loops B3 and B4, as shown in Figure 2.1. Consumers can also find substitutes for electricity, as explained by the energy substitution dynamics in Figure 2.2, which makes electrification policies such as shifting to electric cookers or EV adoption ineffective. The regulatory-based policy would function as a new constraint to affected stakeholders, which would lead them to re-optimize their activities. However, as Scheinkman stated, optimizing agents in a dynamic

system can create chaotic behaviour¹²⁸. Moreover, RPO also requires incentives to be enforced which, based on the issue found in the FIT policy, would be limited to the fiscal budget.

The fiscal budget limitation from both policies would be expected to lead to a slow renewable adoption and hinder the government's efforts to reduce GHG emissions. In line with this, the government has planned to develop an Energy Security Fund to support renewable energy policies sourced from, among others, the depletion premium and consumption of fossil fuels¹⁰. The use of a fossil fuel depletion premium, which follows the Hartwick Rule for weak sustainability^{21,129}, could be helpful for enhancing the outcomes of the system because its value would increase over time based on R3 in Figure 2.2. However, imposing premiums on fuel consumption could increase consumer costs, which could reduce the aggregate demand and slow down the economy based on R14 in Figure 2.4. Based on the energy substitution dynamics in Figure 2.2, fuel consumption premiums can be safely enforced when there is a substitution whose relative value is close to fuel is available and accessible. More importantly, the funds must be allocated correctly to the right policies. As previously mentioned, a poorly designed policy could lead to counterproductive economic, social, and even environmental effects.

2.6. Conclusion

This work is an explorative study to understand the economic, social, and environmental effects of renewable energy policies on electricity generation. Common energy modelling tools to investigate this issue such as MARKAL, TIMES, or NEMS tools are more appropriate to answer “what should happen” questions, while LEAP addresses “what would happen”, it also cannot help to answer the impact of energy transition policies on the economy more broadly. Thus, a combination of the system dynamics approach and policy analysis framework is used in the current study. The model also accommodates the integration of bottom-up and top-down approaches. This work enhances previous studies that attempted to understand the power sector's energy transition from a system perspective by exploring the structural feedback between it and the economic, energy, and environmental systems. The expansive view of this study enables a more unified approach in assessing different energy policies using more macro indicators which further emphasises this work's novelty.

Using the conceptual model, this study qualitatively assessed the effects of renewable energy policies. Both market-based and regulatory-based policies, represented by FIT and RPO are evaluated. FIT is a commonly used policy globally to increase the supply of renewable energy, due to its simplicity¹³⁰. On the other hand, the RPO obligates institutions to purchase a certain amount of renewable electricity. This study found that both policies are limited by the government's fiscal budget which could be passed on to the state-owned PLN that is required to increase RE supply or other state-owned institutions and government entities obligated to purchase RE. This finding is in line with that of Burke et al.⁴², who found the PLN resistant to increasing their renewable energy uptake due to economic constraints as well as the ineffectiveness of RPO. The government must find more financing sources to fund the transition towards renewable energy sustainably. The prospects of using fossil fuel depletion premiums to create fiscal space for renewable energy is also explored in this study. This instrument could support a smooth energy transition for fossil fuel-dependent countries because it allows them to continue the extraction of fossil fuels while steadily financing renewable energy¹³⁰. However, it should be noted that this fund must be carefully managed and coordinated.

Externally, the Indonesian government can obtain funds from bilateral or multi-lateral entities such as the Energy Transition Mechanism (ETM) of the Asian Development Bank (ADB). ETM specifically aims for an early replacement of CFPP with renewable energy in three different funding models: CFPP asset transfer, debt, and equity¹³¹. With the cash received from the CFPP acquisition, asset owners are expected to invest in renewables which is in line with the Hartwick Rule²¹. Alternatively, the government can pursue green financing through loans and bonds^{132,133}. Funding through debt should be treated with caution, especially in developing countries, as it could lead to increased taxation and, in turn, reduce consumption and investment¹³⁴.

This research is a precursor to a complete system dynamics study. A quantitative expansion of the presented conceptual model could provide a better understanding of the problem discussed to which the next chapters shall address.

Chapter 3

Energy Demand Shifts: Case Study in The Indonesian Transportation Sector

3.1. Introduction

The transportation sector energy demand has been increasing rapidly on a global scale, as well as in the focus country of this study – Indonesia. It was the second largest energy consumer in 2011 at 33% of the national energy consumption, before surpassing the industrial sector three years later¹³⁵. By 2022, the sector’s consumption reached 2.6 million TJ¹³⁵. Of this, road transportation consumes 85% of the energy, with 70% attributed to passenger transportation and the rest for freight¹³⁶ as shown in Figure 3.1(a). In 2020, the sector’s CO₂ emission reached 126 Mt, around 24% of the national emissions¹³⁷, which is linked to the dominance of fossil fuel in the sector¹³⁵, as shown in Figure 3.1(b). The fine particulate matter (PM_{2.5}) contribution from this sector is also significant, and in Indonesia the mean concentration nationally exceeded four times the World Health Organization (WHO) recommendation in 2020¹³⁸. Although the power generation and industrial sectors are also significant contributors to both these environmental issues, the transportation sector is a considerable proportion^{137,138}, and is therefore an important sector to focus on with respect to achieving greenhouse gas reduction targets, as well as providing co-benefits for health by reducing localised pollutants.

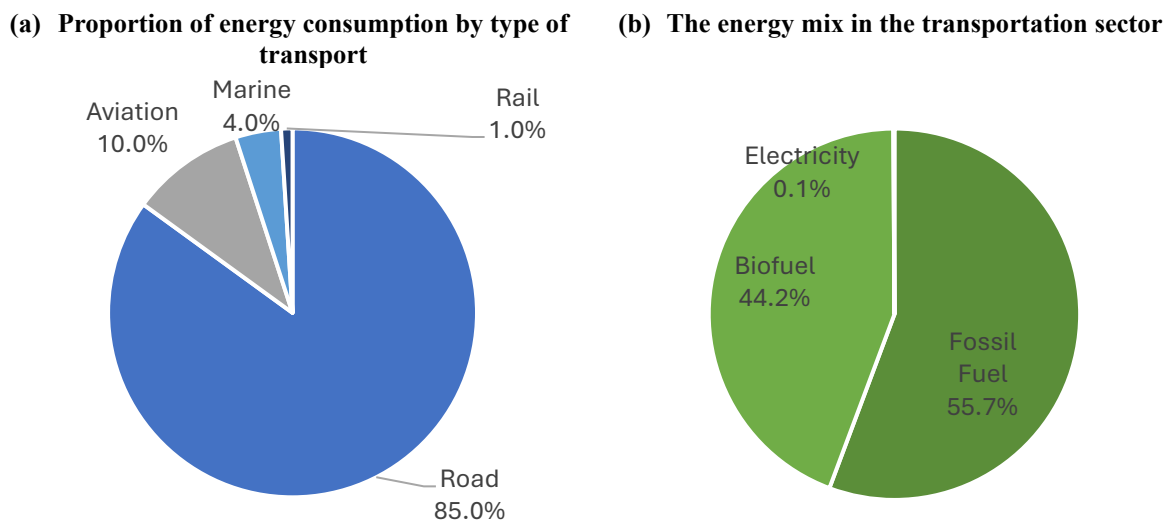


Figure 3.1. Energy profile in the transportation sector: (a) proportion of energy consumption by type of transport¹³⁶ and (b) the energy mix in the transportation sector¹³⁵.

The “Avoid-Shift-Improve” (ASI) framework is a set of strategies aimed to achieve a sustainable transportation system, comprised of three distinct strategies: avoiding travel, shifting to more efficient modes of transport, and improving current modes of transport¹³⁹. In accordance to the framework, the Indonesian government plans to increase the use of public transportation in several metropolitan cities¹⁴⁰, which represents the “shift” strategy. The government is also promoting the use of electric vehicles (EV), mainly targeting passenger vehicles¹⁴¹. Another policy that is being actively pushed is the use of biofuels. Indirectly, the power sector must also be decarbonised, especially related to vehicle electrification¹⁴². The

government plans to shift the power mix to a share of at least 23% of renewable energy by 2025 and 31% by 2050 as stated in the National Energy General Plan ¹⁴³. These three policies are categorised as “improve” strategies.

The benefits of such policies, however, are debated. For example, EV may have lower global warming potential life cycle impacts than internal combustion engine vehicles (ICEV) ^{144–146}, but may be more harmful for human health and have higher SO₂ emissions across the lifecycle in some cases ¹⁴⁶. Increasing renewables in power generation could also lead to higher system costs ¹⁴⁷ and larger land footprint ¹⁴⁸. In addition, both mass adoption of EV and renewable electricity (RE) leads to higher resource flow ^{149,150}, which could produce a greater burden to the environment. Finally, biofuels may compete with other land purposes, such as food production and forestry ¹⁵¹, in addition to uncertain effectiveness in decarbonisation ¹⁵².

While there has been progress in improving the benefits of these policies, implementing the policies can be challenging if the benefits valued by the potential adopters are not clearly understood. For example, although the benefits of public transportation in reducing congestion and air pollution are clear, recently only around 8% of people are willing to use it in Indonesia due to the lack of time and its inconvenience ^{153,154}. Similarly, while EV have been touted as an environmental solution for the transportation sector, potential buyers put environmental benefits below economic, performance, infrastructure, and brand considerations ^{155–157}. Therefore, it is important to understand the adoption structure to identify effective interventions.

Most studies on the environmental impacts of the low-carbon transportation transition have been using the life-cycle assessment (LCA) method. While LCA is a useful tool to investigate the environmental impacts of a certain product, it relies on constant values of variables making dynamic assessments challenging. Furthermore, this exogenous treatment of parameters may not be realistic since many parameters are in fact endogenous, such as vehicles kilometre travelled (VKT), travel speed, and modal split. On the other hand, studies projecting energy demand commonly use top-down approaches. While this is convenient in making projections, it is difficult to understand the effect of a specific policy on the energy demand since policy interventions usually address a specific structural issue in the system. The endogeneity and the complexity of policy interventions to support the transition to a low-carbon transportation system makes the use of system dynamics attractive for examining such problems.

The aim of this study is to investigate transportation sector demand-side policies and transportation-related energy policies on energy demand, resource demand, and its environmental impacts, and to evaluate which policies would lead to a more sustainable outcome. This study is limited on the adoption of EV in the road transportation sector as recent strategies to improve air and maritime transport have been mainly to use biofuel, energy efficiency, and operational efficiency ^{158,159}.

The next section presents in more detail the current situation and recent research that helps us to understand the underlying structure related to the policies to be investigated. The study continues with the method used as will be explained in Section 3.3 in which the indicators used to measure sustainability are elaborated. Section 3.4 until Section 3.7 discuss the results of the model simulation before concluding in Section 3.8.

3.2. Recent Trends and Challenges in Transportation and Energy-Related Policies

This section briefly examines the current situation and latest trends of the policies within the ASI framework investigated in this paper.

3.2.1. Public Transportation Network Development

Pushing public transportation use has been challenging in Indonesia. The national public transportation share was only 4.85% in 2017, and slightly increased to 5.74% in 2020¹⁶⁰. On the other hand, public transportation use in metropolitan areas has decreased. For example, the share of public transportation use dropped from 30% in 2014 to 20% in 2019 in the Greater Jakarta Area, the economic centre of Indonesia^{153,161}. The remaining commuters use private vehicles, primarily motorcycles¹⁶².

Based on the Greater Jakarta Area survey¹⁶³, only 8.4% of commuters wanted to shift to public transportation, with 52% complaining that it is impractical and difficult to access, while 40% highlighting its longer time travel. These factors are supported by other academic studies. For example, a study in Indonesia found that time is indeed one of the main barriers in shifting to public transportation¹⁶⁴. Similarly, a study in four different countries showed that public transportation required up to 2.6 times longer than driving a car¹⁶⁵. Regarding impracticality, a study found commuters would sacrifice travel time for less transfers¹⁶⁶, while accessibility measured by walking time showed a 5-minute walk is desirable¹⁶⁷. The actual average travel time, walking distance, and number of transfers are presented in Table 3.1 for Jakarta.

The main strategy to increase public transportation usage is by expanding the public transportation network – primarily in the metropolitan regions. While the government approaches each city differently, in general the public transportation network would consist of one, or a combination of: Bus Rapid Transit (BRT), commuter railway, Light Rail Transit (LRT), and Mass Rapid Transit (MRT) railway¹⁴⁰, ultimately aiming to improve network integration which would reduce transfer times, improve accessibility, and travel duration¹⁶⁸.

Table 3.1. Current situation and benchmark values of factors for adopting public transportation. Actual values are weighted from 186 origins to the two CBDs in Jakarta at peak hour.

Factors for adopting public transport	Current situation	Benchmark
Average travel time	2.2-2.6x	2.6x ¹⁶⁵
Walking distance	24.8-32.3 minutes	≤5 minutes ¹⁶⁷
Number of transfers	3-3.4	≤3 ¹⁶⁸

3.2.2. Vehicle Electrification

Previous work concludes that EV adoption rate is affected by economic factors, driving range, infrastructure readiness, charging time, and environmental benefits. Egbue and Long found that limited driving range was the key factor in adopting EV while environmental factors were ranked last¹⁵⁵. A more recent study in Indonesia agrees that driving range is the main consideration when adopting EV while emissions level was ranked second from the bottom, above charging time¹⁵⁶. Secinaro et al. concluded that price and charging issues were the main barriers¹⁶⁹. Another study suggested that providing incentives for charging infrastructure can increase EV adoption rate¹⁷⁰. Two studies added the brand of the vehicle as another adoption factor, noting that consumers prefer to purchase EVs from familiar brands^{157,171}. Similar adoption considerations were also found for medium and heavy-duty vehicles customers¹⁷².

The benefit of a new alternative can be defined as the gap between it and the value offered by the incumbent alternative¹⁷³. As suggested by Egbue and Long, significant increases in ICEV cost alone do not stimulate EV purchase intention but must be followed by a considerable decrease in EV cost¹⁵⁵. The same conclusion was also stated by Shafiei et al. who found that the maximum adoption rate occurred under high gasoline and low EV cost¹⁷⁴. To enhance this, the relative benefit of EV must be maximized on the other adoption criteria also, namely the driving range, infrastructure readiness, and charging time. Unfortunately, the government has only intervened on the economic benefit of EVs by providing tax incentives and electricity price subsidy at charging stations¹⁴¹. Recent application of the regulation provides a generous 4,400 USD incentive for electric cars and 440 USD for electric motorcycles (1 USD = 15,720 IDR)¹⁷⁵.

3.2.3. Biofuel

Although its decarbonisation impact is debated¹⁵², biofuel utilisation is an important strategy to reduce fossil resource depletion and energy imports¹³⁵. The current blending levels for biodiesel in Indonesia have reached 30% (B30) with one study suggesting an increase to 40% (B40) or 50% (B50) in the future¹⁷⁶, while bioethanol blends of 5% (E5) were just recently marketed¹⁷⁷.

One research found up to 76% land expansion if biodiesel were to be increased significantly¹⁷⁶. This could lead to a land competition with food and forestry as suggested by another research who found a 31% overlap with suitable land for energy crops¹⁵¹. Furthermore, there is also found a potential economic loss from CPO exports which could negate the savings from diesel imports¹⁷⁶.

Biofuels were shown to lower some gaseous emissions while increasing others. For example, one study found that the combustion of gasoline blended with bioethanol tends to reduce hydrocarbon (HC) and carbon monoxide (CO) emissions while increasing CO₂ and NO_x emissions, due to its lower calorific content and high flame velocity of the fuel, respectively¹⁷⁸. Similarly, biodiesel blends were also found to have lower HC, CO, SO₂, and PM, but higher CO₂ and NO_x emissions^{179,180}. The increase in CO₂ in biodiesel is due to its higher cetane number, leading to a more complete combustion and hence higher CO₂¹⁸¹. The higher NO_x is associated with higher combustion temperature as a result of the higher density and bulk modulus¹⁸². Furthermore, a study also found that combustion engines using biofuels require more fuel to generate the same amount of energy compared to conventional fuels, leading to higher fuel consumption rate^{183,184}.

3.2.4. Renewable Energy Uptake in the Power Sector

The EV boom has made the power sector an integral part in the transport sector's decarbonisation. One study found that the minimum grid emission factor for EVs to have benefit in reducing carbon emissions was 0.82 kgCO₂/kWh¹⁴² in the operational phase. While Indonesia's grid emissions factor fluctuates depending on which power generation is more dominant, coal-fired power plants (CFPP) have been increasing steadily as a proportion and reached almost 67% in 2022¹³⁵. Furthermore, the CFPP emission factors range from 0.79 to 1.22 kgCO₂/kWh, with an average around 0.96 kgCO₂/kWh¹⁸⁵. The second most dominant power source was gas-fired power plants (GFPP), providing around 18% of electricity¹³⁵. On the other hand, renewables only provided around 13% of the power¹³⁵.

Moving forward, the government is planning to increase the proportion of renewables to 25% in 2025 and 31% in 2050¹⁴³. While the government did not mention the future proportion of CFPP among the non-renewables, they specified the targets for each renewable technology. 43% of the renewables power generation is planned to come from solar power, followed by wind 27%, hydro 14%, biomass 10%, and geothermal 6%¹⁴³.

3.3. Model Building

3.3.1. Model Development

We divided the model into urban, domestic (travel between cities), and freight transportation. The urban transportation system is differentiated into private vehicles and public transportation. Furthermore, the private transportation is divided into cars and motorcycles. All road transportation, including freight and public transportation, have the option between ICEV or Battery Electric Vehicles (BEV), except for cars which also have the option for Hybrid Electric Vehicles (HEV). Rail, marine, and air transportation are also included for freight although their electrified options are not included. The overall model structure is shown in Figure 3.2.

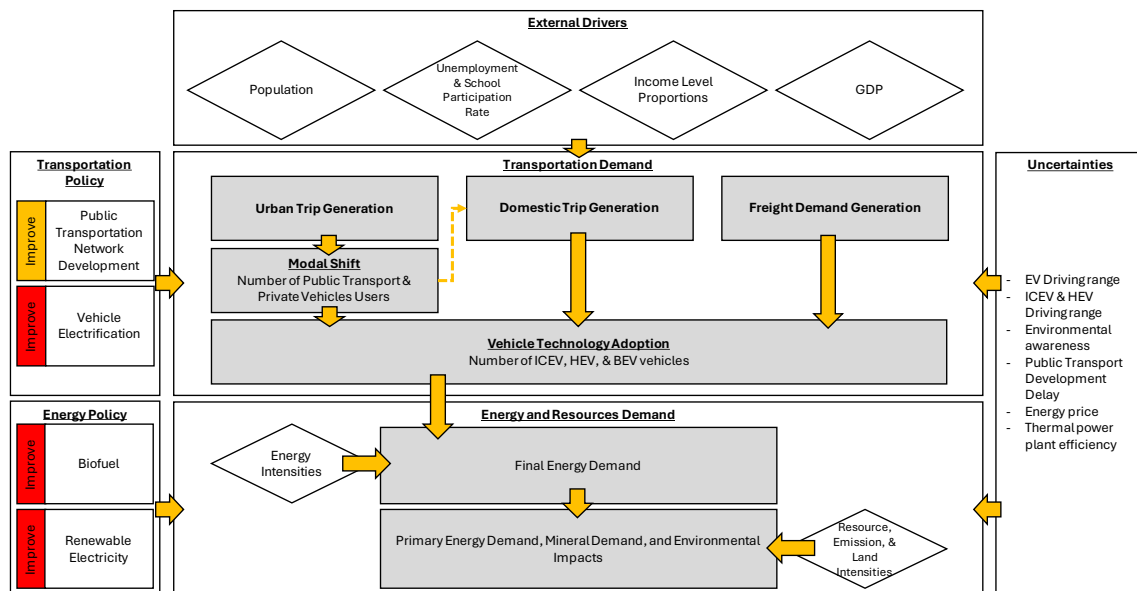


Figure 3.2. Model structure overview of the transportation module

There are two key exogenous drivers to the system which are population and GDP. It is assumed that urban trips are primarily for going to work or school, hence population, together with unemployment rate and school participation rate, is used to estimate transportation demand for urban transportation, i.e. number of commuters¹⁵³. The commuters will have the option to use private vehicles or public transportation. Though it is possible for a commuter to combine private and public transportation for daily transportation, this study only considers the main mode they use for simplification. While the shifting structure in freight transportation is not included, the urban transportation modal split result is used as an approximation for domestic travel demand. Freight transportation demand is estimated using GDP with elasticity based on the work from Odette¹⁸⁶ for road freight and calculated from historical data obtained from the Indonesian Central Bureau of Statistics for rail, marine, and aviation^{187–189}.

The modal shifting and vehicle technology adoption dynamics are illustrated in Figure 3.3. As the number of public transport users increase, they could influence others which would further increase the adoption rate as illustrated by the R1 loop. On the other hand, the increasing

adoption rate would decrease the number of active private vehicle users, hence leading the adoption rate to decrease overtime, represented by the B1 loop. The interaction between R1 and B1 creates an s-curve of the public transportation users.

Private vehicles users have different technology options, in this case ICEV and BEV. The diffusion mechanism is similar to that of the adoption from private vehicles to public transportation as can be seen by the relationship between loops R2 and B2. Thus, a similar s-curve in the BEV adoption could be expected. The adoption rate itself is affected by several factors which have been explained in Section 3.2.1 and Section 3.2.2.

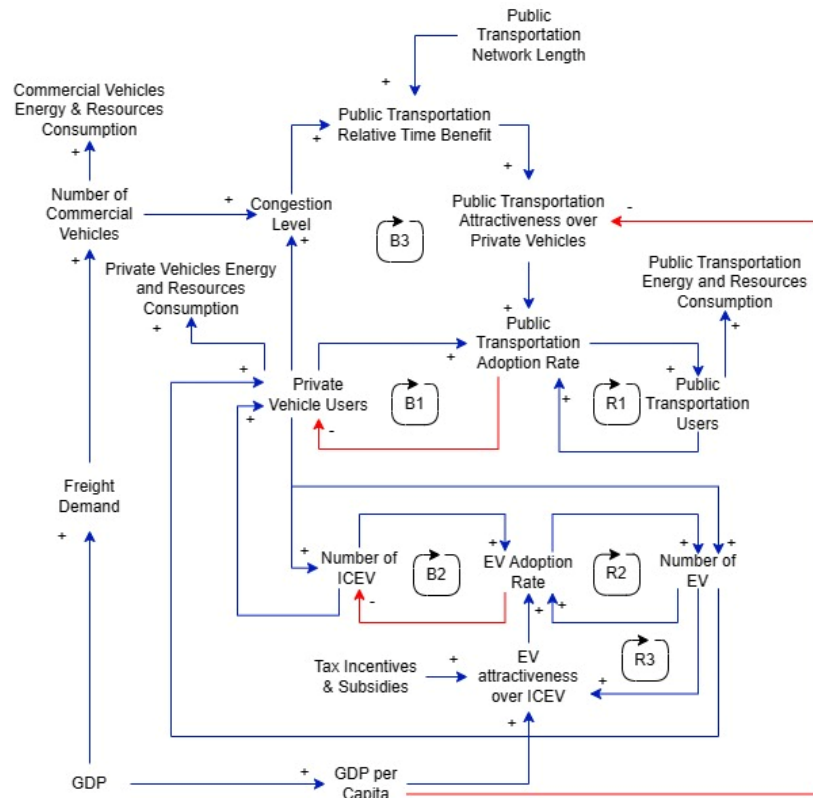


Figure 3.3. Causal Loop Diagram of the energy and resources demand for transportation system

We modelled some of the adoption factors to be endogenous. For example, this study linked the number of vehicles with the public transportation adoption rate through road congestion level which would affect travel time, shown as B3 loop. The BEV adoption rate is also affected by the number of EV through technology learning rate which could reduce BEV price¹⁹⁰, one of the main barriers to adopt as elaborated in Section 3.2.2. The amount of the respective transportation mode used, measured in VKT, is then converted to the energy consumed, and in turn, the resources it would require. As for domestic and freight transportation, the demands are translated into number of vehicles, VKT, and finally energy and resources demand.

3.3.2. Indicators

The first indicator considered in this work is final energy consumption. This study includes fossil-based fuels, biofuels and electricity. Fossil-based fuels include gasoline used for road transportations, diesel – used in road transportations and power generation – marine diesel, and aviation fuel. Secondly, primary energy demand is included as the transportation sector is becoming more coupled with the power sector. Primary energy demand provides the actual energy resources needed to fulfil the transportation sector demand and induces associated

environmental impacts. This study took a step further by including primary energy intensity as a measure of sustainability.

Land use is a direct consequence of primary energy demand, particularly relevant for biofuels and renewable power. The land requirement for biofuel would depend on the feedstock used. In Indonesia, the main feedstocks are palm for biodiesel and sugarcane for bioethanol. The land intensity for both biodiesel and bioethanol are reported in ¹⁹¹. Renewable power was found to be more land intensive compared to conventional thermal power plants. For example, to produce 1 MW of electricity a thermal power plant would require around 5 hectares while solar and wind requires 17.6 and 28.6 hectares ¹⁴⁸.

Emissions are also important indicators – CO₂ is selected due to its relevance to climate change. NO_x and PM₁₀ are also considered, since they are especially important for urban air quality. NO_x was proposed to be a sustainability indicator by Shaw and Van Heyst due to its strong link with environmental, social, and economic aspects¹⁹². Furthermore, NO_x was added to capture the impacts of biofuels since it is known to have higher NO_x emissions compared to conventional fuels^{178,179}. On the other hand, PM₁₀ is included since it is often used to estimate the impacts of air pollution to human health¹⁹³. The inclusion of PM₁₀ and SO₂ becomes more apparent, particularly in Indonesia's case where coal is still the main energy source to generate electricity¹³⁵ and coal has higher PM and SO₂ emissions than gasoline or diesel¹⁹⁴.

Copper, nickel, lithium, and aluminium are essential for use in clean energy production and storage ¹⁹⁵. In addition, Indonesia is home to large reserves of all these minerals except for lithium, which provides geographical relevancy to the selection ¹⁹⁶. However, the use of these minerals in EVs and renewable energy is higher their conventional counterparts. For example, EV's have larger consumption of metal resources of which 75% is attributed to their batteries ¹⁴⁵, using almost 1 kg of nickel and 2.4 kg of copper per kilowatt-hour battery capacity ¹⁹⁷. For renewables, even though solar and wind use only a quarter of nickel and copper per megawatt of installed capacity, but they consume three times of the resources per megawatt-hour of electricity generated since they have much lower capacity factors compared to coal power plants ^{198,199}.

3.3.3. Uncertainties

A variety of uncertainties need to be considered. For example, EV driving range has been improving along with battery technology advancement. Depending on the technology, common energy density of market-ready batteries ranges from 180 Wh/kg for lithium-iron-phosphate (LFP), to more than 250 Wh/kg for nickel-manganese-cobalt (NMC) and nickel-cobalt-aluminium (NCA) batteries ²⁰⁰. Nonetheless, Li-ion batteries have a theoretical limit of 350 Wh/kg ^{201,202}. Indeed, advancement in solid-state batteries is also ongoing, with the potential to double Li-ion batteries' energy density, but cost could limit their mass adoption ²⁰³. On the other hand, manufacturers are also continuing to improve ICEV efficiency with a potential of over 30% improvement from engine and powertrain developments alone, while weight reduction could improve vehicle efficiency by 50% [54]. Pairing internal combustion engine with hybrid systems could further reduce fuel consumption by 50% [54].

Shafiei et al. found that when consumers have less preference for economic factors, EV uptake could accelerate faster ¹⁷⁴. A study showed a shift from economic concerns to environmental protection could happen subject to what is perceived as the more pressing issue, as indicated by the environmental protection rank declining between 2008-2010 amidst the global financial

crisis to its lowest since 1985²⁰⁴. Since then, environmental protection has been gaining more attention as the economy recovers²⁰⁴.

The shift to public transportation relies heavily on the time and convenience benefits over private vehicles^{164,205}. Both factors are affected by public transport network development, as suggested by the number of transfers and travel time in Table 3.1. However, infrastructure development projects are prone to delays. 72% of all urban transportation projects in Jakarta, the economic centre of Indonesia, were delayed, where specifically for public transportation, more than 73% of planned projects were delayed¹⁶⁸. Construction projects in Asia were take an average 37% longer than initially planned²⁰⁶. Some projects could even take twice the planned project duration - as evident by the LRT project in Jakarta^{168,207}.

The cost of gasoline in Indonesia increased by 35% while diesel increased 53% post pandemic¹³⁵, similar case also happened in the U.S.²⁰⁸. The electricity cost has also been increasing steadily at 6% per year between 2012 to 2022, unlike fossil fuels which are fluctuating¹³⁵. A study found that an increase in fuel price will have both an immediate and long-term impact on travel demand, where the short-term elasticity ranges from -0.12 to -0.35 and the long-term elasticity was between -0.25 and -0.69²⁰⁹. Fossil fuel price is heavily influenced by supply, where simulations have shown a potential 16% increase from the base case by 2050 if there is a shortage but a 10% decrease if there is a high supply²¹⁰. These deviations are larger than other cases such as high or low economic growth and high or low zero-carbon technology costs²¹⁰.

3.3.4. Model Testing

The model has undergone statistical test by means of model correlation, mean absolute percent error (MAPE), and Theil's inequality statistics as suggested in Chapter 1. The variables that are validated the number of vehicles, road length, and total final energy consumption. These parameters are selected based on the importance in driving the indicators selected and data availability. Furthermore, this study focus on validating road transportation system since it consumes most of the energy in the sector. Number of vehicles is a key driver to energy consumption. The number of vehicles drives road construction, while road length would affect fuel efficiency of vehicles. Thus, the two parameters must be validated. The result of the two parameters are the final energy consumptions, namely gasoline, diesel, and electricity. Total final energy consumption is added as a summary of all the fuels, which includes jet fuel and marine fuel. The parameters are validated by comparing the actual values from year 2011 up to 2022 or latest available data.

Figure 3.4 shows the number of vehicles validation result. The available record was from 2011 to 2021 for cars and motorcycles while the number of trucks records was only available from 2016. The MAPE for the number of cars, motorcycles, and trucks are 4%, 3%, and 3%, respectively. Although the MAPE for the number of trucks is relatively high, most of its error is not systematic ($U^M = 0.30$), hence the result is satisfying for the purpose of this model.

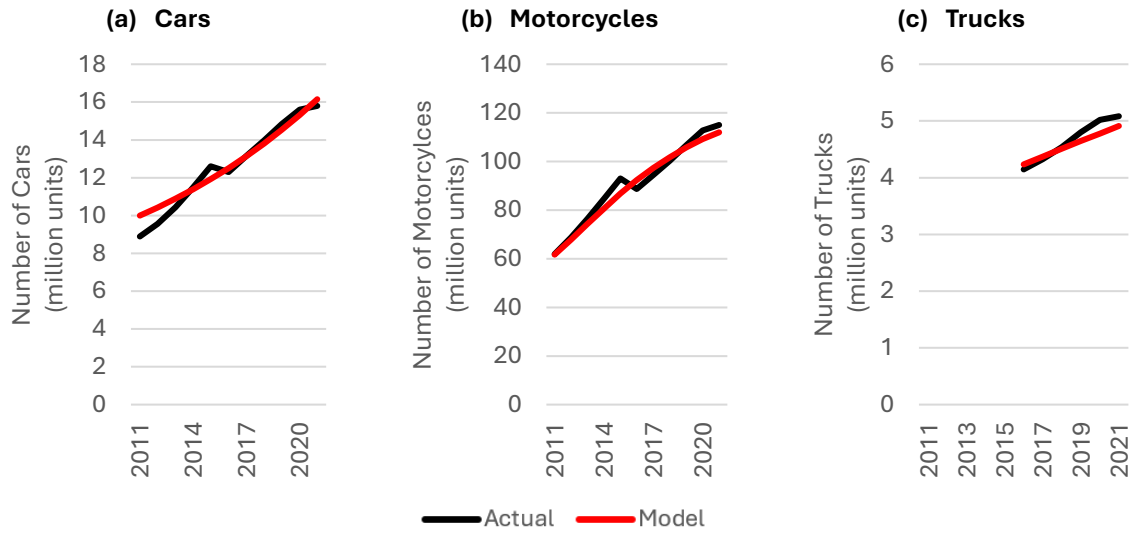


Figure 3.4. Number of vehicles validation.

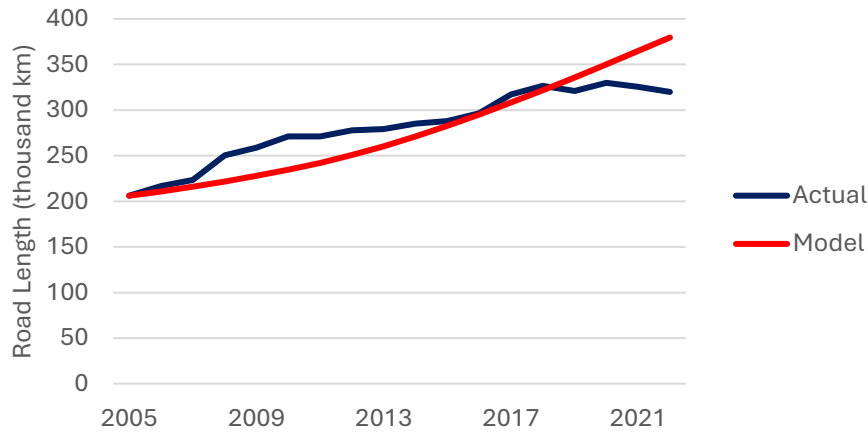


Figure 3.5. Road length validation.

Figure 3.5 shows the validation for road length. Although the MAPE is 7%, the error is not systematic since most of it is covariance error ($U^C = 0.54$). This study acknowledges the different slope with the actual trend. The discrepancies may lie in the constant time needed for road construction assumption used, while it would vary depending on many variables that are outside the scope of this study such as time to acquire land permit and budget constraints. Nonetheless, the low MAPE is sufficient for this study. Finally, the validation for final energies is shown in Figure 3.6. The MAPE for gasoline, diesel, electricity, and total final energy consumption are 5%, 9%, 8%, and 5% respectively and not systematic.

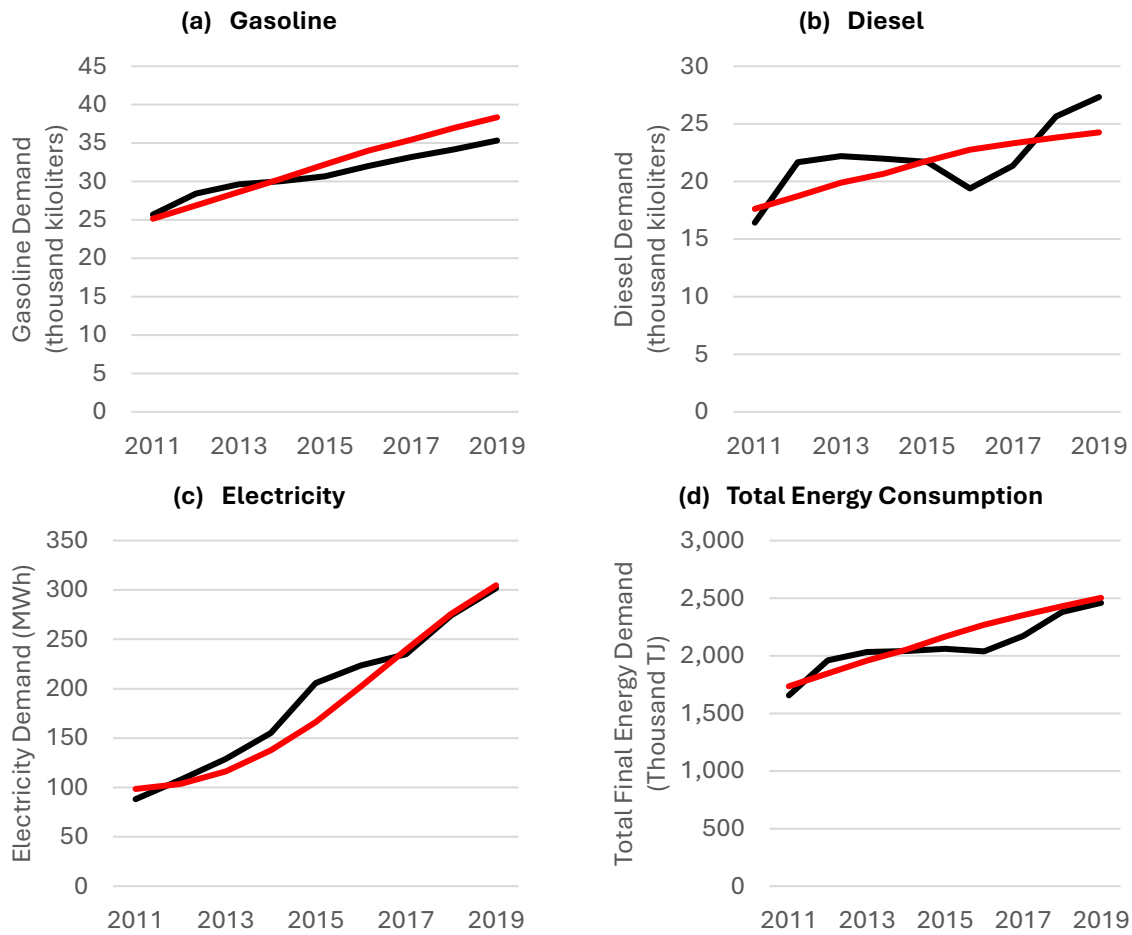


Figure 3.6. Total final energy consumption validation.

3.4. Base Run Result

Under the baseline, it is assumed that there is no change in the state of policies from 2025 onwards. Figure 3.7 shows, without any intervention, commuters will continue to be hesitant to use public transportation. As the result, the proportion of public transportation users continuously drop from 60% to 4% in 2050. Commuters adopts private vehicles instead, mostly motorcycles in the first two decades but then start to move to cars along with the increase in GDP per capita²¹¹. The adoption of electric vehicles (EV) would progress quickly as shown in Figure 3.8, again mostly in private vehicles. In aggregate, the share of EV could reach 25%, and as in the shift in private vehicles, most of the EV would be cars reaching around 57 million units in 2050.

The result in modal split and vehicle shift leads to the demand for fossil-based fuels continuing to increase at 2.76% annually from 2025 to 2050 as shown in Figure 3.9. Biofuel demand would also continue to grow, but at faster rate of 4.2% per year with the increasing demand of road freight transportation which primarily uses diesel engines, despite the biodiesel blending level remaining at 30%. The most significant increase, however, would be the electricity demand increases which increased 11.5% per year. The 192 TWh electricity consumption in 2050 is almost 17 times larger than 2025 despite the share of electric vehicles in only 25%.

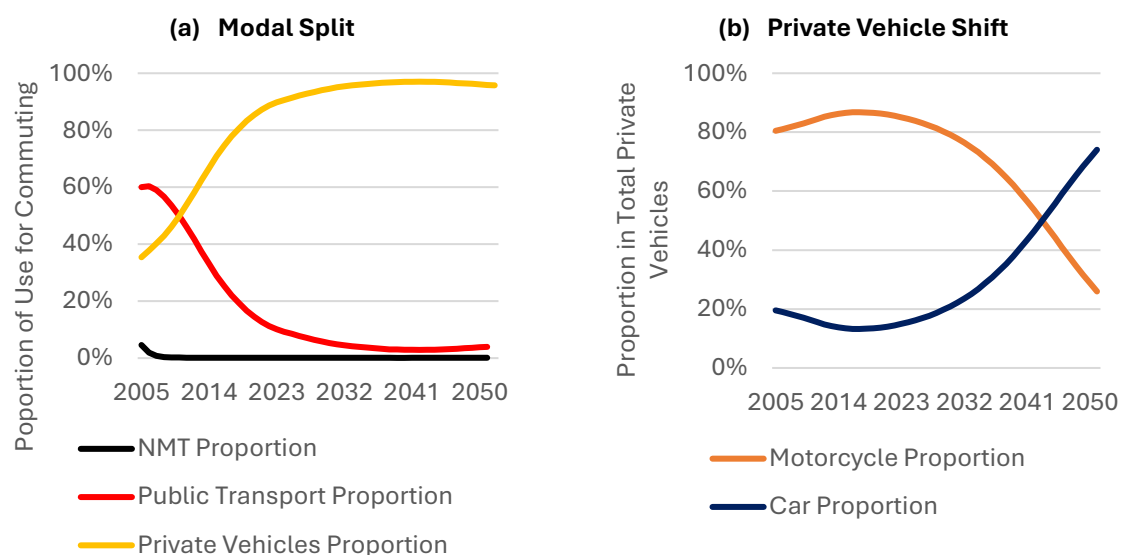


Figure 3.7. Baseline simulation transportation mode split.

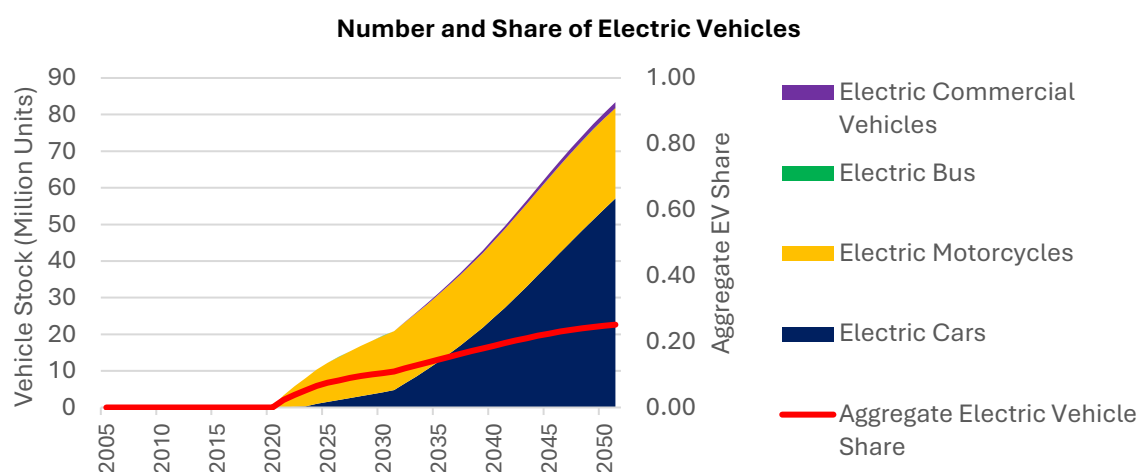


Figure 3.8. Adoption of Electric Vehicles under the Base Run.

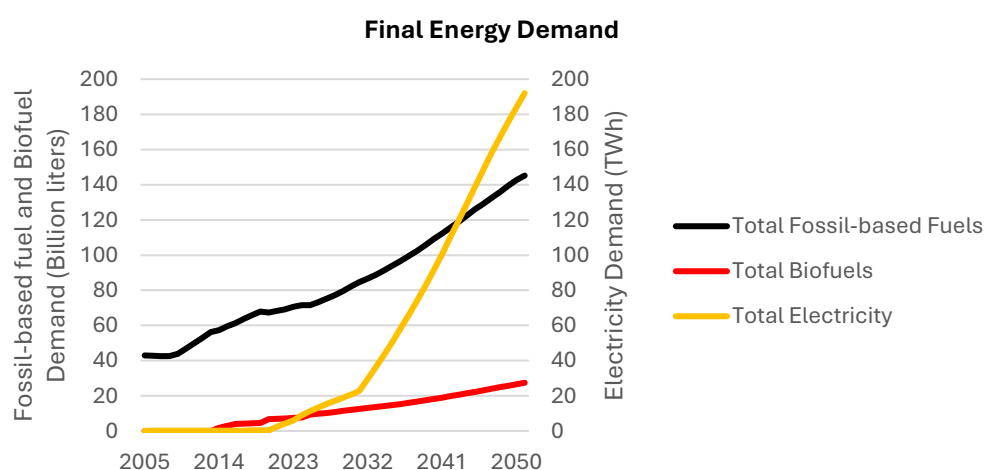


Figure 3.9. Base runs of final energy demand.

Figure 3.10 shows the primary energy demand trend follows the changes in final energy demand. Crude oil demand would continue to increase at 2.78% per year. The growth is slightly

higher than final energy demand since biofuels are only used for diesel-engine road vehicles at the moment, while gasoline, jet fuel, and marine diesel fuel demand also continues to increase which adds to the increasing demand for crude oil. With the increasing demand for electricity in the transportation sector, coal and natural gas demand for electricity generation would also increase by 11.2% and 10.6% per year respectively.

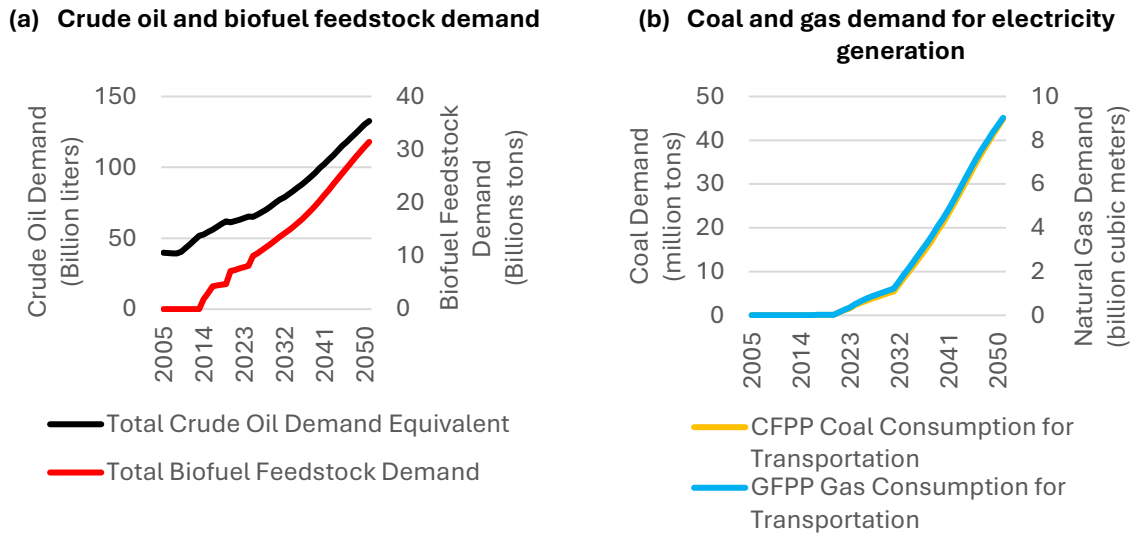


Figure 3.10. Base runs of primary energy consumption in the transportation sector.

The increase in biofuel demand and decrease in electricity translates into land requirement, as shown in Figure 3.11. Similar to the increase in primary energy demand, the increase in land requirement for biofuel would be smaller than the renewable electricity, however the total land would be much larger. The land required for biofuel would increase by 4.2% per year and could reach 91 million hectares, while the land required for renewables would be only 0.03 million hectares. The land required for variable renewable electricity (VRE) would increase 10.2% per year while dispatchable renewables would increase by 12% due to the higher resources development rate as will be explained in Chapter 6. Another consequence of the increasing fossil fuel consumption is the increasing CO₂, NO_x, PM₁₀, and SO₂ emissions as shown in Figure 3.12 where the annual rate increase is 3.9%, 3.7%, 4.1% and 10.2%, respectively.

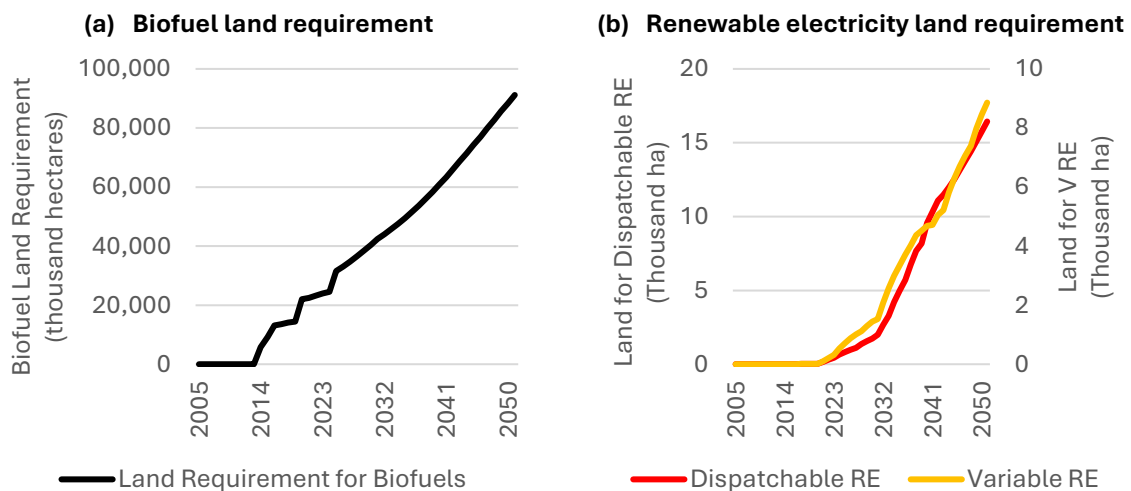


Figure 3.11. Land requirements for energy demand in the transportation sector in the base run.

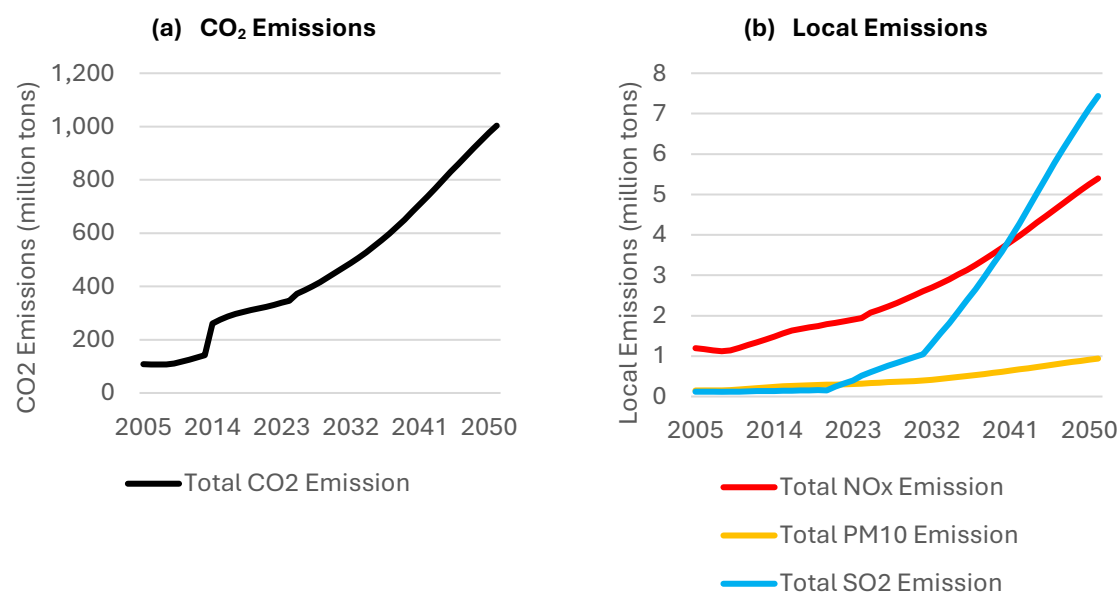


Figure 3.12. Base runs of total (a) CO₂, and (b) NO_x, PM₁₀, and SO₂ emissions.

The demand for minerals would start to increase with the increasing market share of HEVs and renewables penetration in the grid. The increase in lithium was highest among all minerals which reach 13.4% per year, followed by nickel 12.8%, and then copper and aluminium 10.7% each as shown in Figure 3.13. However, due to the weight composition, the demand for aluminium would be the largest at 21,265 thousand ton per year by 2050, followed by nickel 10,853 thousand ton per year, copper 7,686 thousand ton per year, and lithium only 31 thousand ton per year.

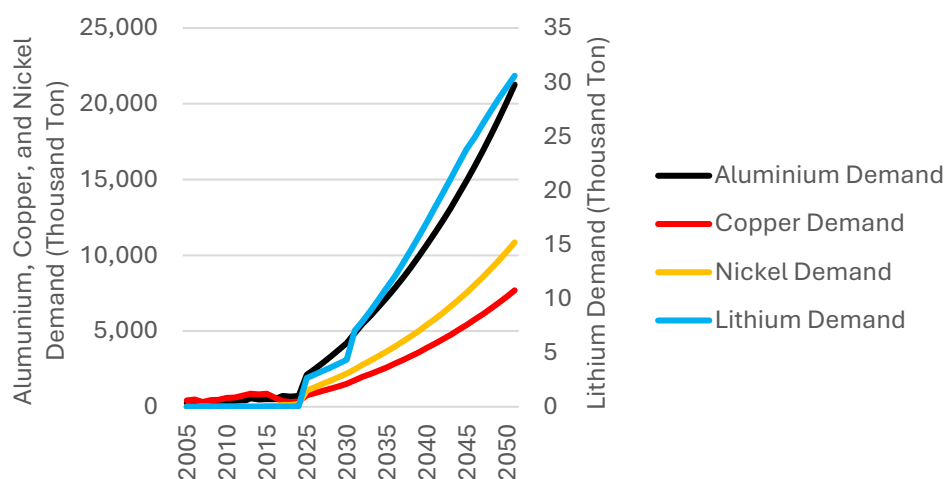


Figure 3.13. Base runs of mineral demands

Finally, Figure 3.14(a) shows the base runs of urban, domestic, and freight transportation primary energy intensity. The urban transport primary energy intensity increase following the increase in private vehicle use. In addition, the intensity accelerates after the higher adoption of EV due to the lower efficiency of the thermal power generation compared to combustion engines. As a result, urban transport energy intensity would increase 46% per year between 2025 to 2050. Freight transportation energy intensity shows different behaviour, where it declines in the first half of the period, and slightly increased afterwards. Figure 3.14(b) explains the behaviour by showing that initially the energy consumed by road freight was around 84%

of total energy consumption for freight. However, this proportion increases to greater than 90% as time progresses, shifting the total energy intensity closer to road freight energy intensity. Afterwards the freight energy intensity is dictated by road freight. Although mode shift in the freight transportation is not included, this behaviour acts as a pseudo-shift towards a dominant road transport mode in freight transportation. On the other hand, the mode shifting structure in the urban transportation is included which could have a spillover effect on the mode choice for domestic travel. The ever-increasing energy intensity indicates that the transportation system is not sustainable. Thus, a policy intervention is needed.

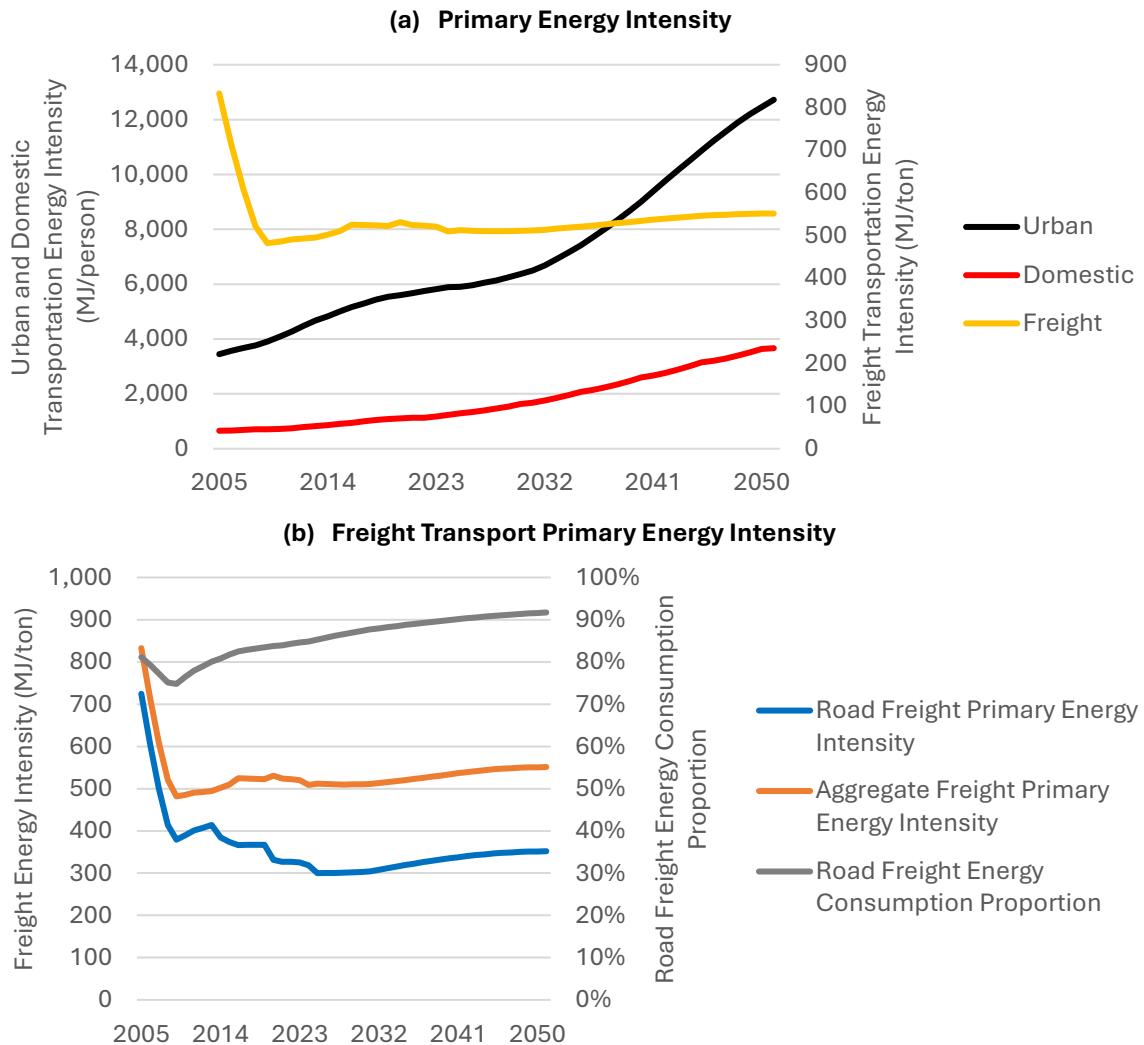


Figure 3.14. Base runs of urban, domestic, and freight transportation, and (b) road freight transportation compared to total freight transportation energy intensity.

3.5. Uncertainty Test

3.5.1. Policy Tests

The relative value of each indicator compared to the base run was used to assess the effects of a policy. The base run value was set as one. If the relative value of a policy in a given year is greater than one, it indicates that the policy increases the indicator while a value less than one shows the opposite. To isolate the effect of a policy, the values of the uncertainties defined in Section 3.3.3 are kept.

3.5.1.1. Public Transportation Network Development

Three public transportation network development plans are investigated: no expansion, moderate, and aggressive expansions. The difference between them is the rate at which the network is developed. The expansion plan in the baseline assumes a 2.5% of the desired level of transportation network is planned to be built in each construction period. The proportion is then doubled for the consecutive expansion plans, 5% for moderate expansion and 10% for aggressive expansion.

As depicted in Figure 3.15, the effect of expansion rate on shift to public transportation is non-linear, where the difference between the baseline and moderate expansion is small, and only when an aggressive expansion plan is implemented the share of public transportation grows significantly. In this case, the share of public transportation users would only be around 14% in 2050. In contrast, the share of public transportation users could drop to 2% in 2050 if there were no further expansion. Figure 3.16 shows most public transport new adopters would be former motorcycle users, and the number would grow with more public transportation network being developed. However, the number of new adopters from motorcycle would reduce naturally since more people would use cars as the economy grows.

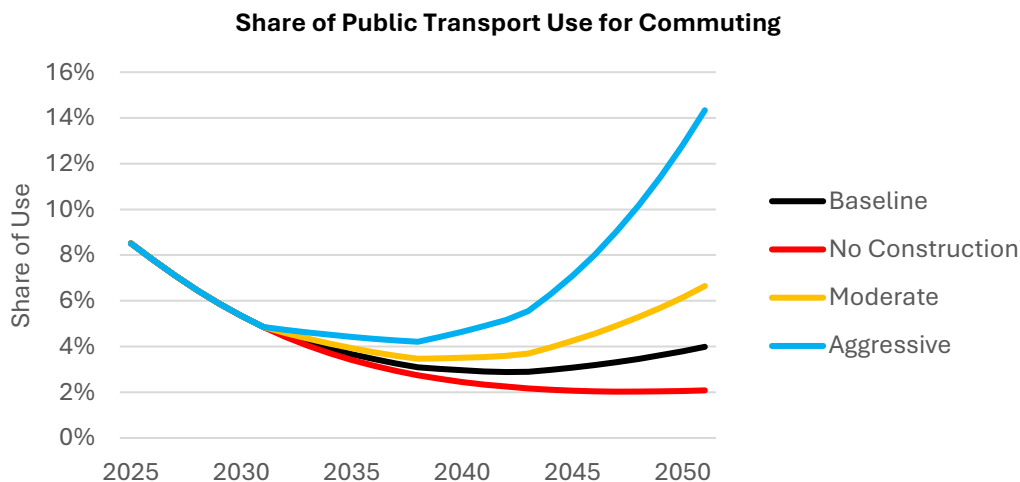


Figure 3.15. The effect of public transportation network development on mode split.

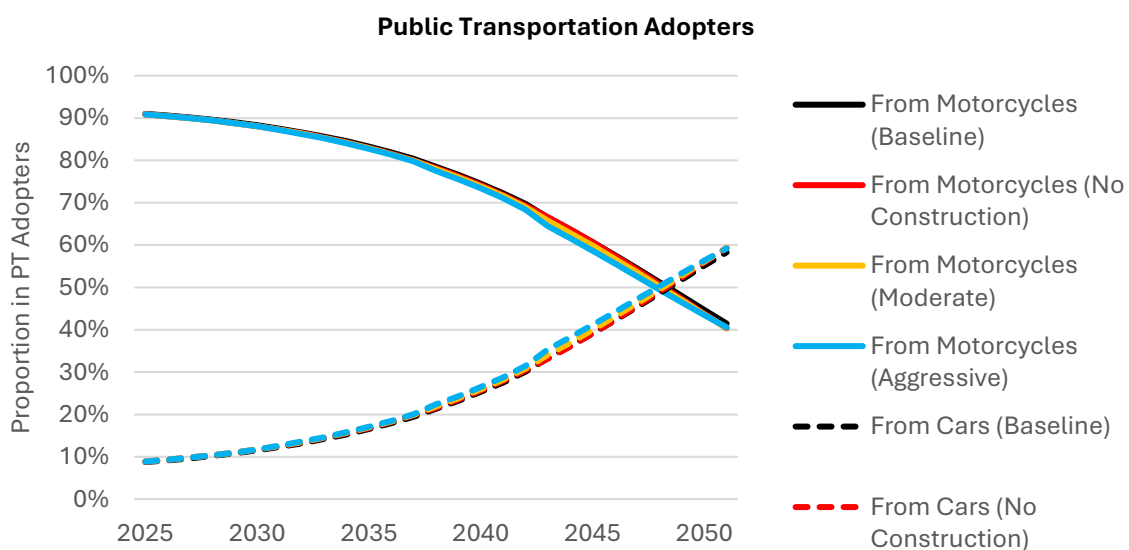


Figure 3.16. Sources of shifts to public transportation (PT).

The rate of expansion has a clear effect on fossil-based fuels consumption, i.e., gasoline and diesel, as well as electricity consumption as shown in Figure 3.17. With moderate expansion, fossil-based fuels demand could be 1.7% lower than the baseline in 2050. Under aggressive expansion plan where the share of public transport is around 14%, fossil-based fuels demand could be 6.6% lower than the baseline in 2050. On the other hand, if there are no further expansion, fossil-based fuel demand could be 1.2% higher than the baseline. Although public transportation network expansion decreases biofuels demand, it is not affected as much as fossil-based fuels since some fleets would still use diesel-engines, especially bus. Despite public transportation includes railway networks which uses electricity, electricity demand decreased the most where it could be 11% lower than the baseline in the aggressive expansion case because EV users shift to public transportation. In contrast, electricity demand could be 1.8% higher than the baseline if there is no further network expansion. Thus, electricity demand is the most affected by the public transportation network expansion policy.

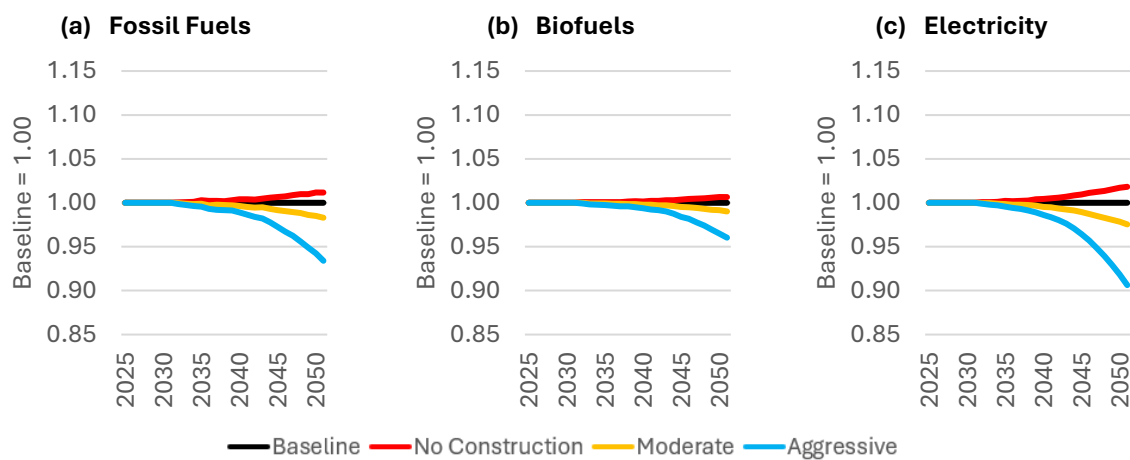


Figure 3.17. The effect of public transportation network development on final energy demand.

The effect of public transportation network development on crude oil, biofuel feedstocks, coal, and natural gas demand mimics the final fuel consumptions in behaviour as shown in Figure 3.18. Similarly, the effect on land requirement would follow the final energy demand as shown in Figure 3.19. Scale-wise, crude oil demand is slightly less impacted by the policy since public transport network development would not have any effect on marine and aviation energy consumption which are increasing and would still be using fossil fuel. On the other hand, biofuel feedstock demand would decrease less since not all vehicles use biodiesel and bioethanol has not been implemented.

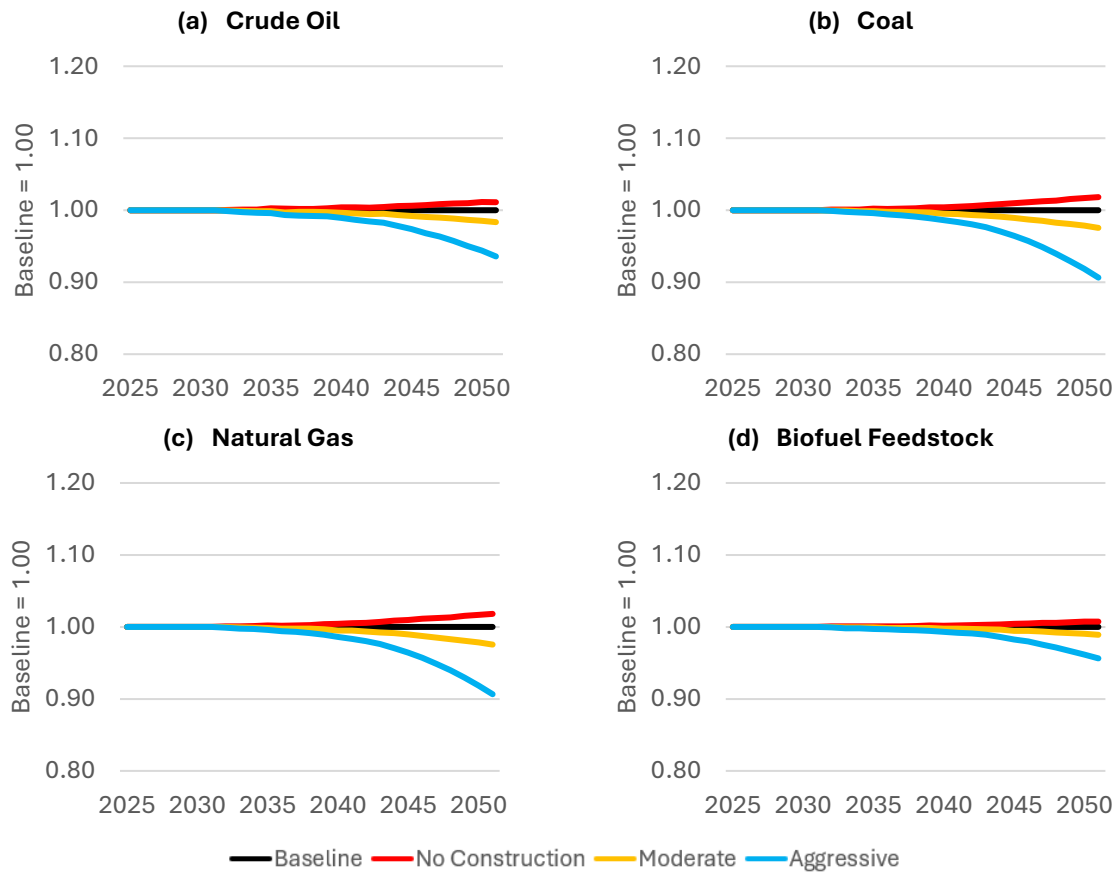


Figure 3.18. The effect of public transportation network development on primary energy demand.

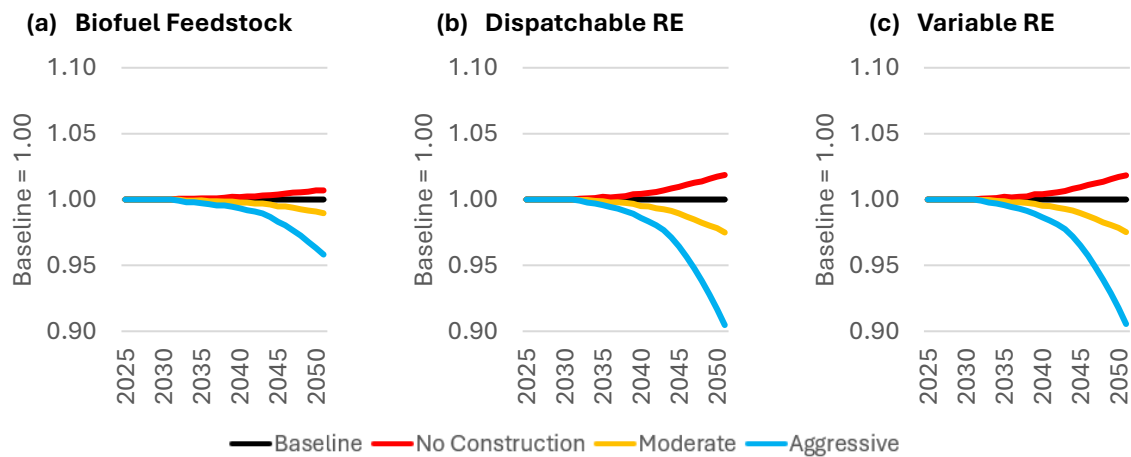


Figure 3.19. The effect of public transportation network development on land requirement.

Somewhat like the effect on final fuel consumption, expanding public transport network under the moderate plan would have a small impact on emissions, while an aggressive plan could reduce them significantly as shown in Figure 3.20. Even so, the emission reduction is less than the reduction in fossil-fuel consumption. This is due to road freight, whose emissions constitutes at least 75% in every pollutant, is only slightly affected by the expansion of public transport network development as an effect of the road congestion relief. The effect of public transportation network development on PM and SO₂ emission reduction is larger than CO₂ and NO_x since the electricity grid is mostly generated from coal which has a high PM and SO₂ emission factor.

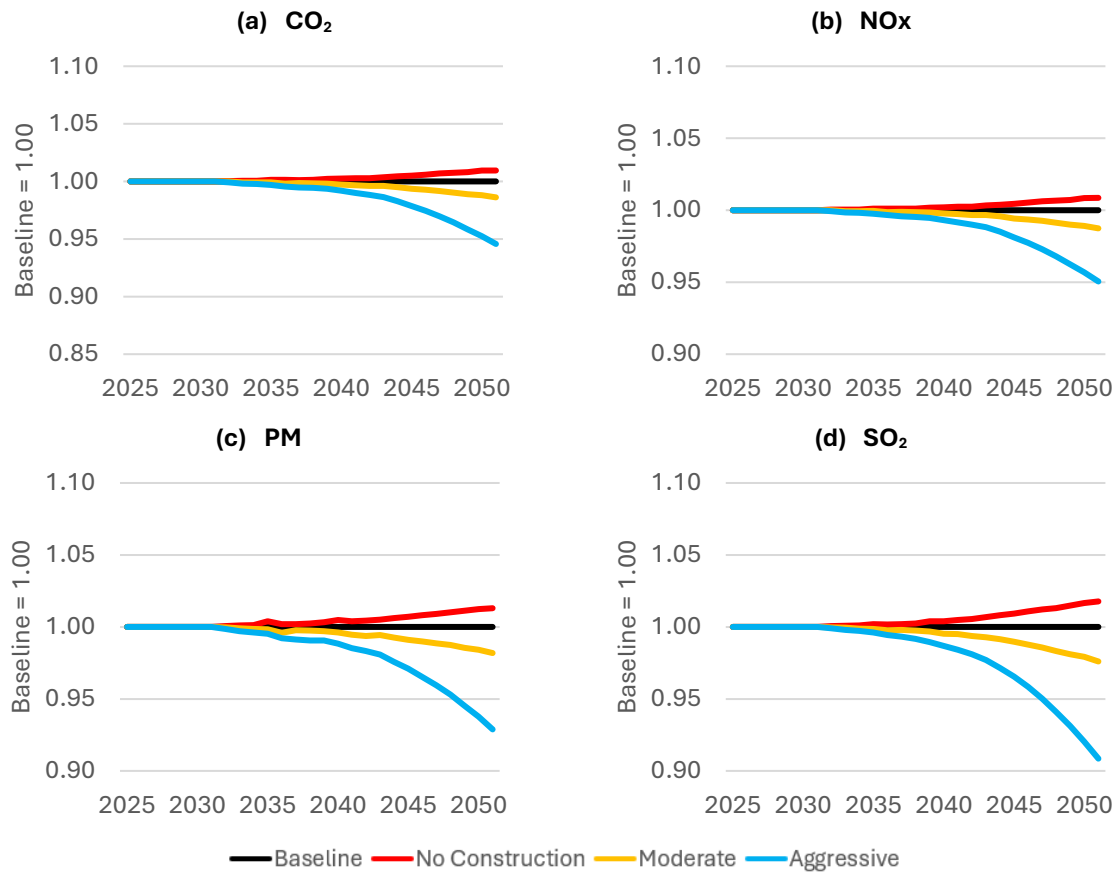


Figure 3.20. The effect of public transportation network development on observed emissions.

As shown in Figure 3.16, developing public transportation network would lead to less private vehicles used, which then reduces the necessity for purchasing them. In turn, Figure 3.21 shows the reduced purchase reduces the demand for minerals to be used in the production of vehicles with batteries, i.e., HEVs and BEVs. Lithium demand would be impacted the most, around 2% lower than the baseline in 2050 if the public transportation expansion was aggressive, while other minerals are affected almost equally.

As can be seen in Figure 3.22, the urban transportation energy intensity can be reduced significantly by aggressively expanding the public transportation network. As commuters use public transportation more, less energy is consumed to transport the same number of people, i.e., less energy consumption per capita. The use of public transportation also has a slightly reducing effect on domestic and freight transportation energy intensity. Promoting the use of public transportation can reduce vehicle ownership, which in turn could reduce the use of private vehicles for domestic travel towards a more mass transport mode. On the other hand, public transportation use alleviates urban traffic congestion, which helps in reducing freight vehicle's fuel consumption.

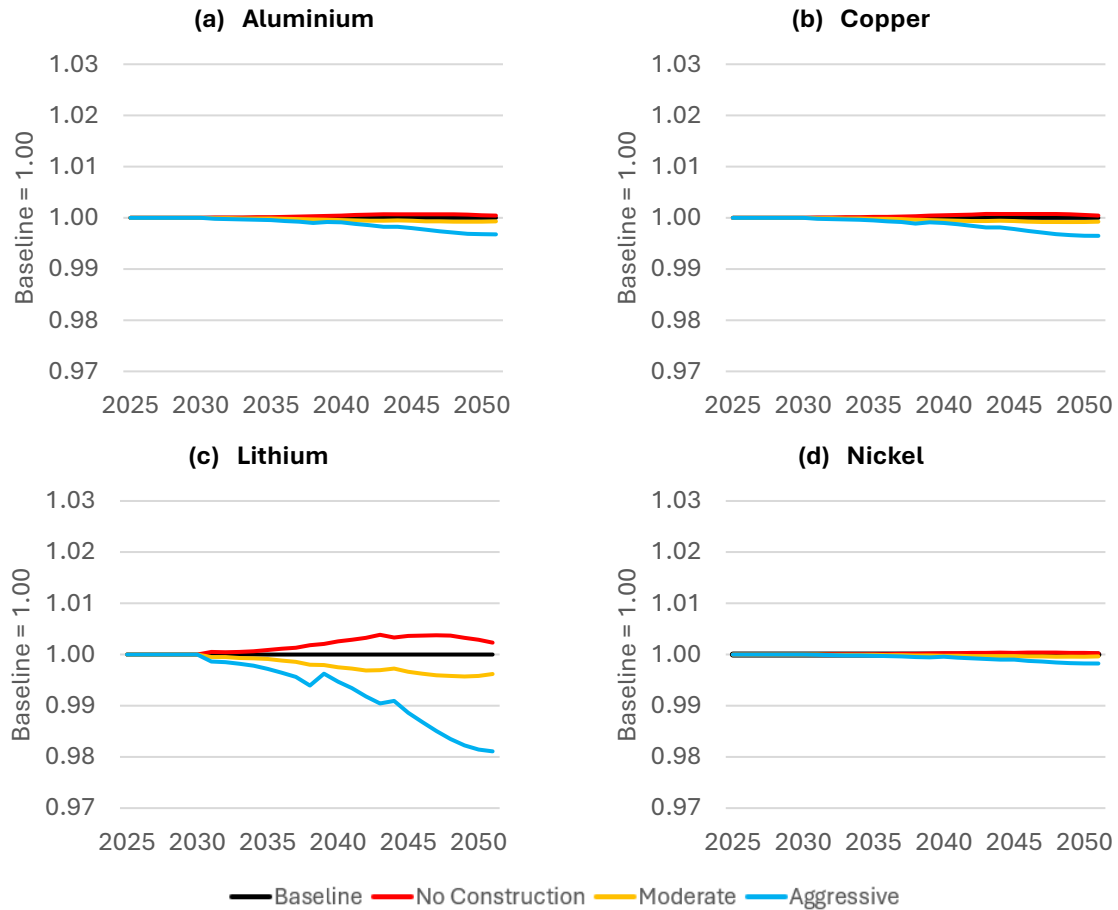


Figure 3.21. The effect of public transportation network development on the observed mineral demands.

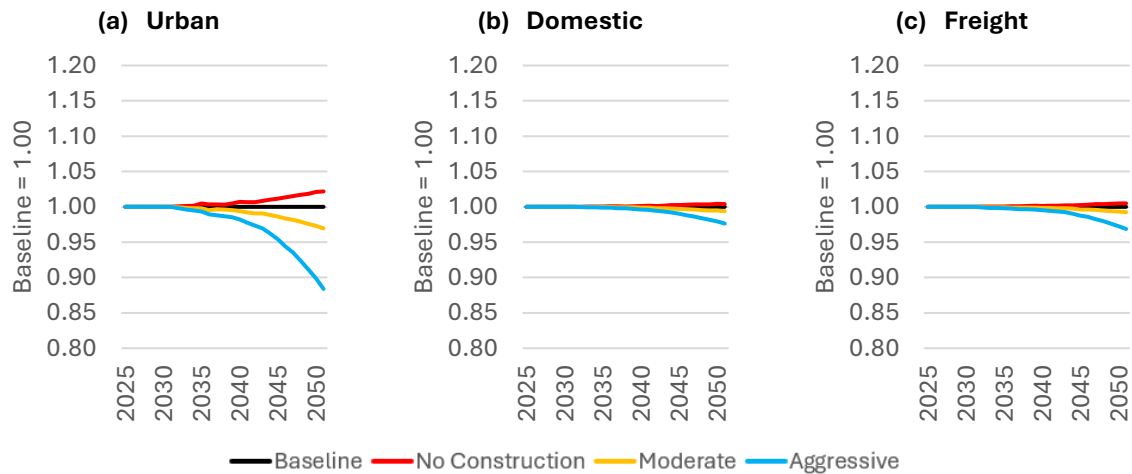


Figure 3.22. The effect of public transportation network development primary energy intensity.

3.5.1.2. Vehicle electrification

We investigated the effectiveness of incentives in promoting BEVs by comparing the market share of BEVs with 50% incentives, 25% incentives and without any purchase tax incentives and ownership tax incentives as opposed to full tax incentives which is currently implemented. The result shows that the incentive has a clear effect in increasing BEV share, although varied between type of vehicles. Figure 3.23 shows that electric car's share would be 44% higher with incentives in 2050 while the other modes would be around 15% to 16% higher compared to without any incentives. This comes down to the relative benefits of each vehicle type. For cars,

potential EV adopters also have the option to purchase HEV while other modes only have either ICEV or BEV. Hence, if there are no incentives, electric cars would have more difficulties in gaining market share. Nonetheless, even without any incentives electric car share is still relatively compared to bus or trucks, while still lower than motorcycles. Electric bus and trucks have a very low driving range compared to their ICEV counterparts which undermine their relative benefit and thus adoption probability. On the other hand, electric cars and motorcycles have a relatively competitive driving range. The sharp increase of electric bus share is related to the bouncing back of public transportation user as shown in Figure 3.7, which could be further amplified with a more aggressive public transportation network development as (see Figure 3.15). This sharp change also indicates the link between the vehicle electrification and public transport network development policies.

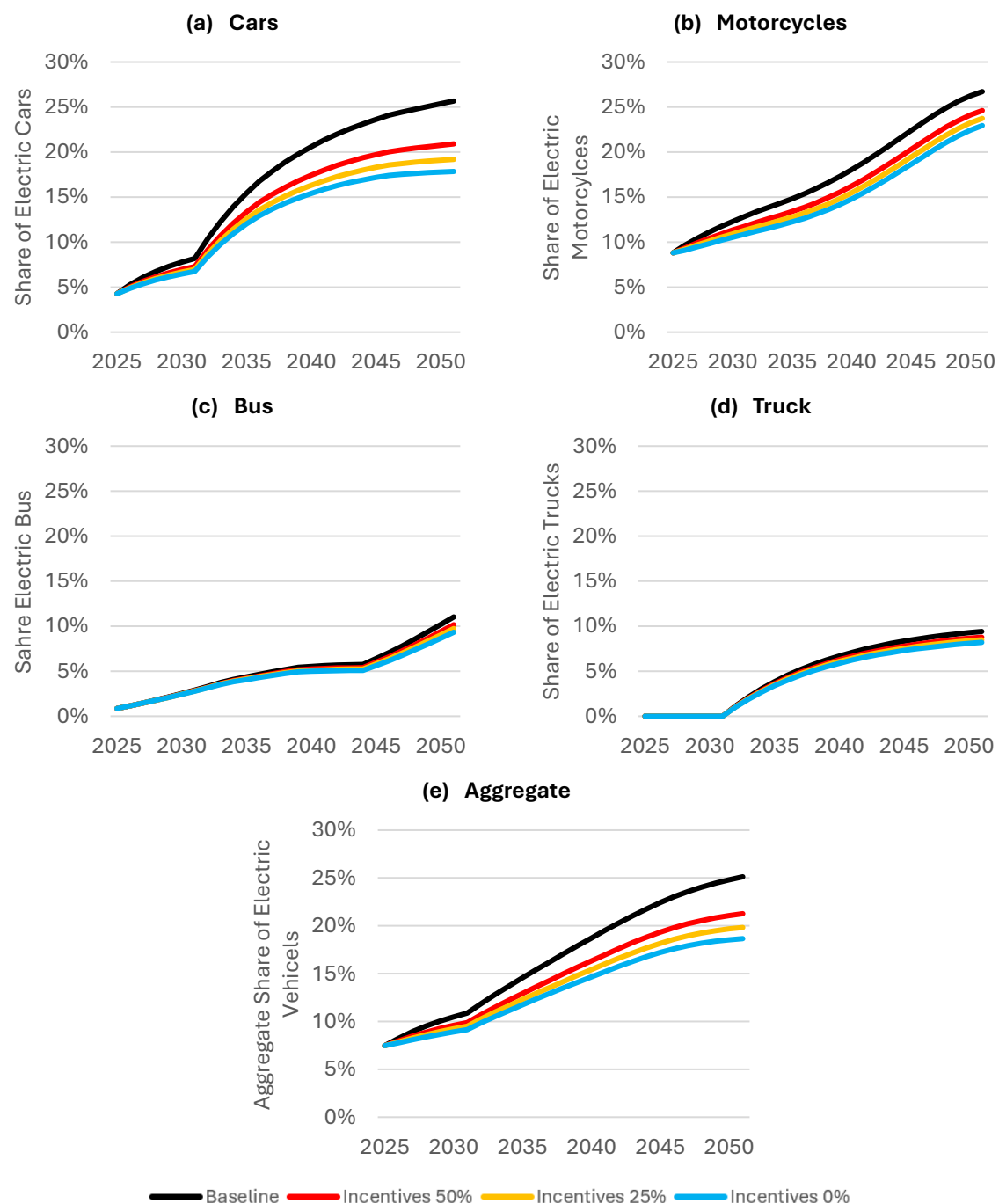


Figure 3.23. The effect of BEV incentives on BEV share.

Figure 3.24 shows that reducing the adoption of BEV would increase fossil-based fuels and bio-based fuels demand which could increase the burden on the environment and land-use. Without any incentives, the demand for fossil fuels could be 4.8% higher than the baseline in 2050 while biofuels 1.8%. Conversely, electricity demand could be lower 27% than the baseline in 2050 if no incentives are applied after 2025. The implication of the final energy demand changes is the proportional changes in primary energy demand as in Figure 3.25 and land use in Figure 3.26, except for biofuel feedstock. Despite direct biofuel feedstock demand for use in vehicles would increase proportionally with the decrease in BEV adoption due to its incentive's reduction, the reduced BEV would also reduce electricity demand and hence the biofuel feedstock used to be blended in diesel power generation, causing the aggregate demand to be slightly lower than the baseline.

Figure 3.27 shows there is very little effect of EV adoptions on CO₂ and NO_x, but significantly on PM and SO₂ due to the grid is still reliant on coal power generation. The effect on emissions varies overtime and Figure 3.28 provides a clearer view of how the changes in EV adoption affects the observed emissions by using CO₂ as the benchmark. The effect can be clearly seen from 2030 to 2035 if it is assumed an electric MPV is introduced to the market earlier stage of the adoption. Since MPV is popular in Indonesia²¹², its introduction would boost EV adoption. Until 2035, the net change in CO₂ emission is positive, meaning the emission reduction from less ICEV is compensated by the grid emission which is still coal-dominated. However, the net CO₂ emission soon drastically becomes negative as the grid's emission factor improves due to thermal efficiency improvements and renewables adoption. This indicates the importance of transitioning to renewables or improving the efficiency of thermal power plants as will be explored further in Chapter 6 of this thesis.

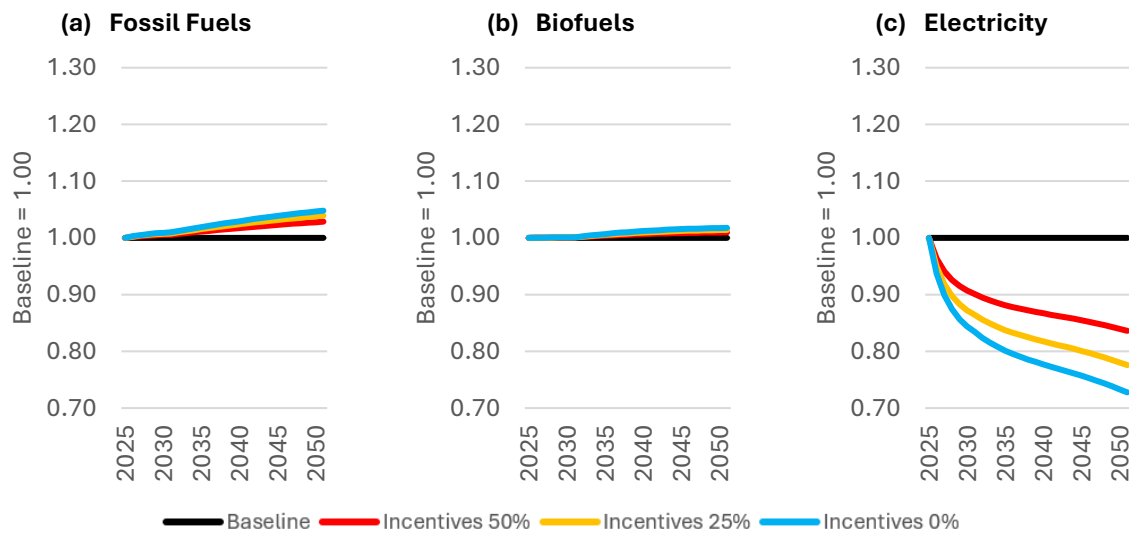


Figure 3.24. The effect of BEV incentives on final energy demand.

The demand for mineral would highly depend on the adoption of BEVs. The key difference with the other indicators is that changes in mineral demands would occur a period earlier since it represents the demand for BEV production in the next period. Figure 3.29 shows the changes in demand for all minerals are the same. If no incentives are given, the demand for all minerals will reduce by 27% – slightly higher than the reduction in the number of EV since the reduction in minerals also includes from the power sector due to less electricity demand.

The effect of changing the BEV adoption rate on urban, domestic, and freight transportation energy intensity is shown in Figure 3.30. In general, more BEV would lead to higher energy intensities due to the grid being less energy efficient compared to ICEVs and HEVs. Comparing to the base run, urban transport energy could be 8% lower when there are no incentives given to BEV. As a result of less BEV, the urban energy intensity increases at 2.7% per year from 6 GJ per capita to 11.7 GJ per capita in 2050. While it is lower than if BEV are given full incentives (3% per year, 12.7 GJ per capita in 2050), it still illustrates an unsustainable transportation sector. The effect of a decreased urban energy intensity from less BEV spilt over to the domestic transportation energy intensity which decreased 2% to 3% from the baseline in 2050 depending on the incentives. The energy to deliver 1 ton of goods would also not significantly change due to the low adoption rate of electric trucks.

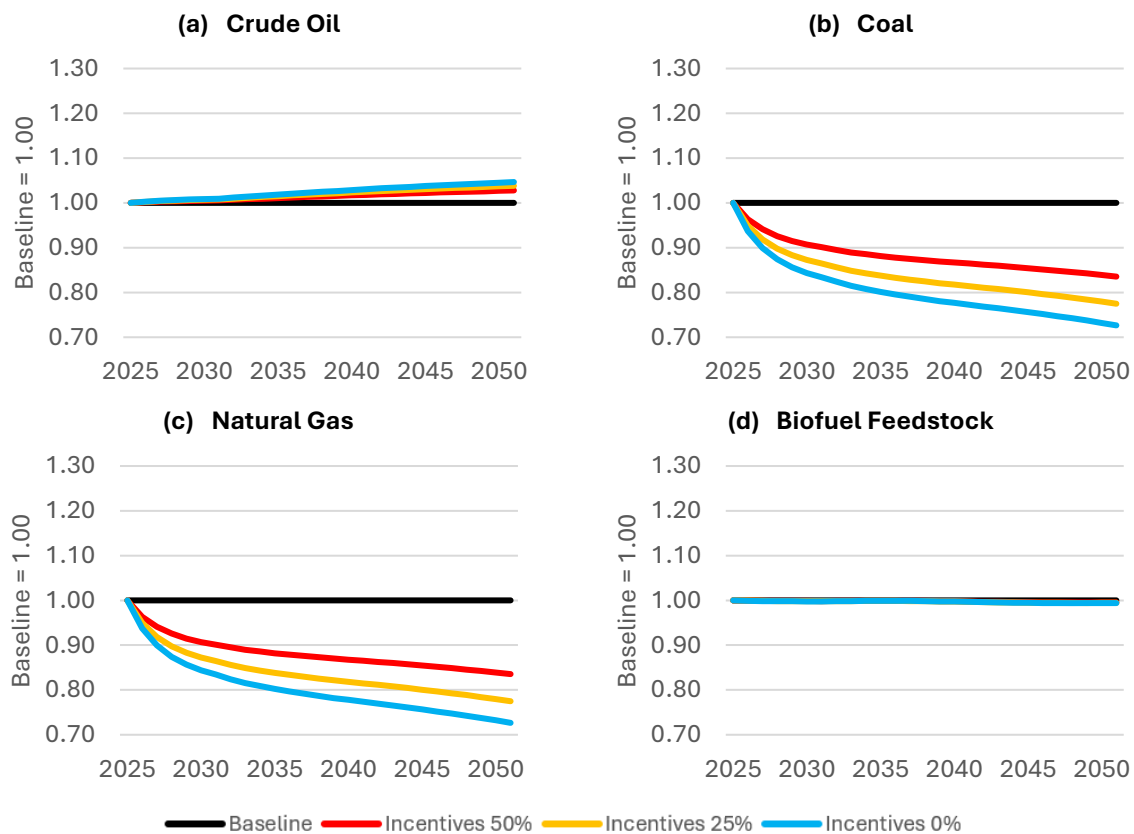


Figure 3.25. The effect of BEV incentives on primary energy demand.

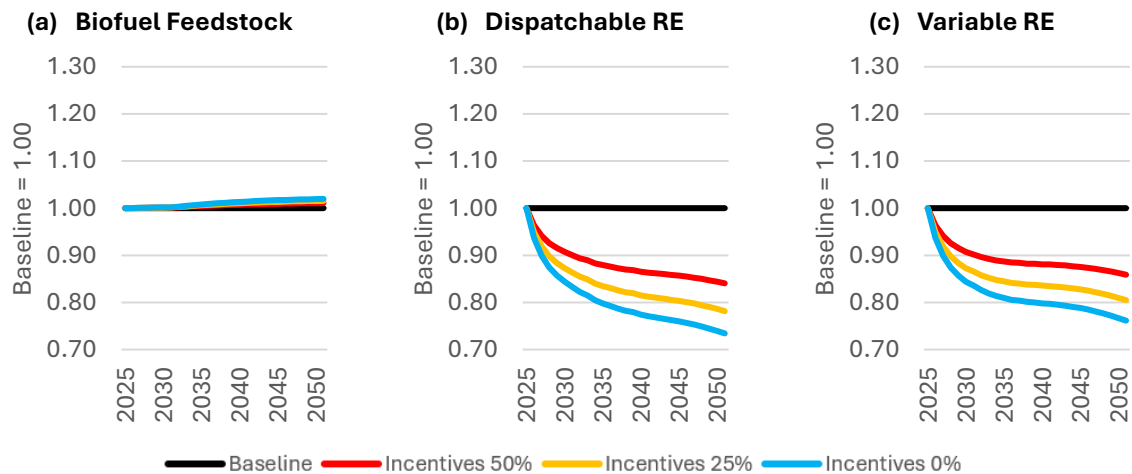


Figure 3.26. The effect of BEV incentives on land requirement.

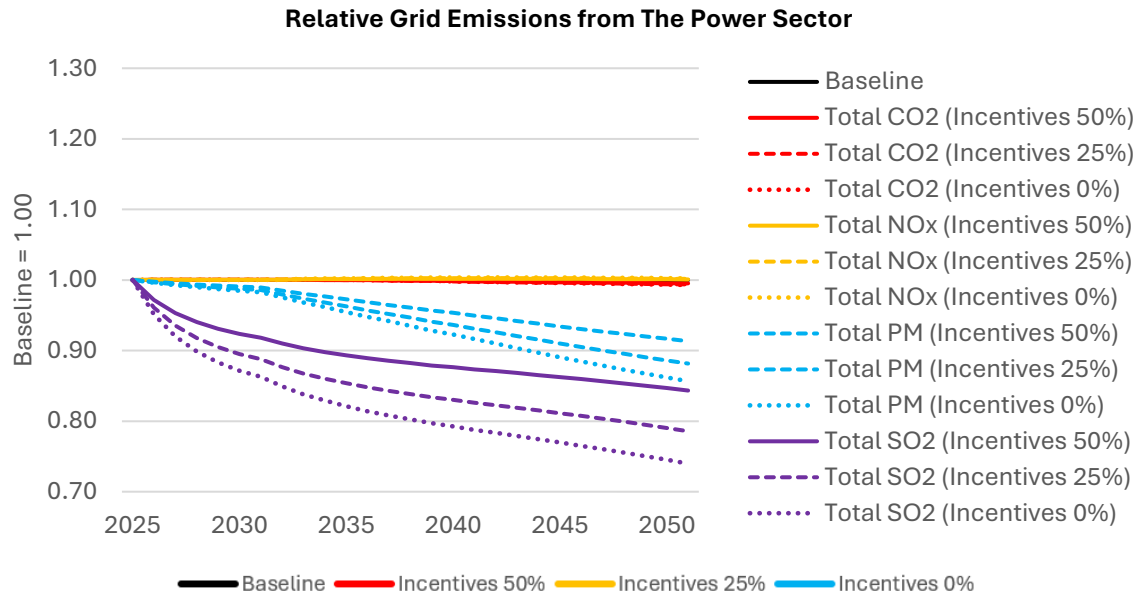


Figure 3.27. The effect of BEV incentives on observed emissions.

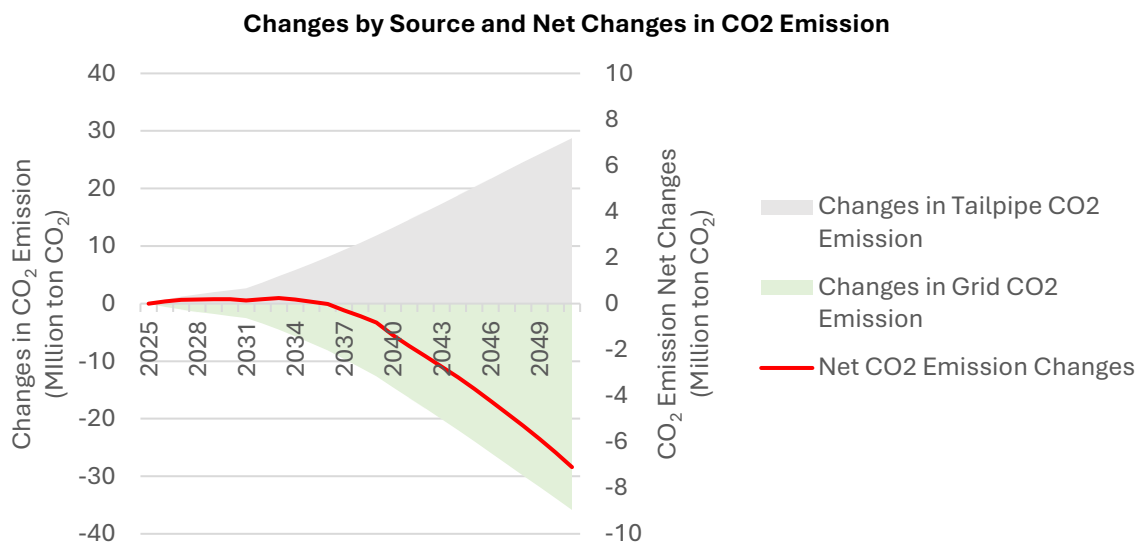


Figure 3.28. The changes in exhaust emissions, grid emissions, and net changes of CO₂ when no EV incentives are given.

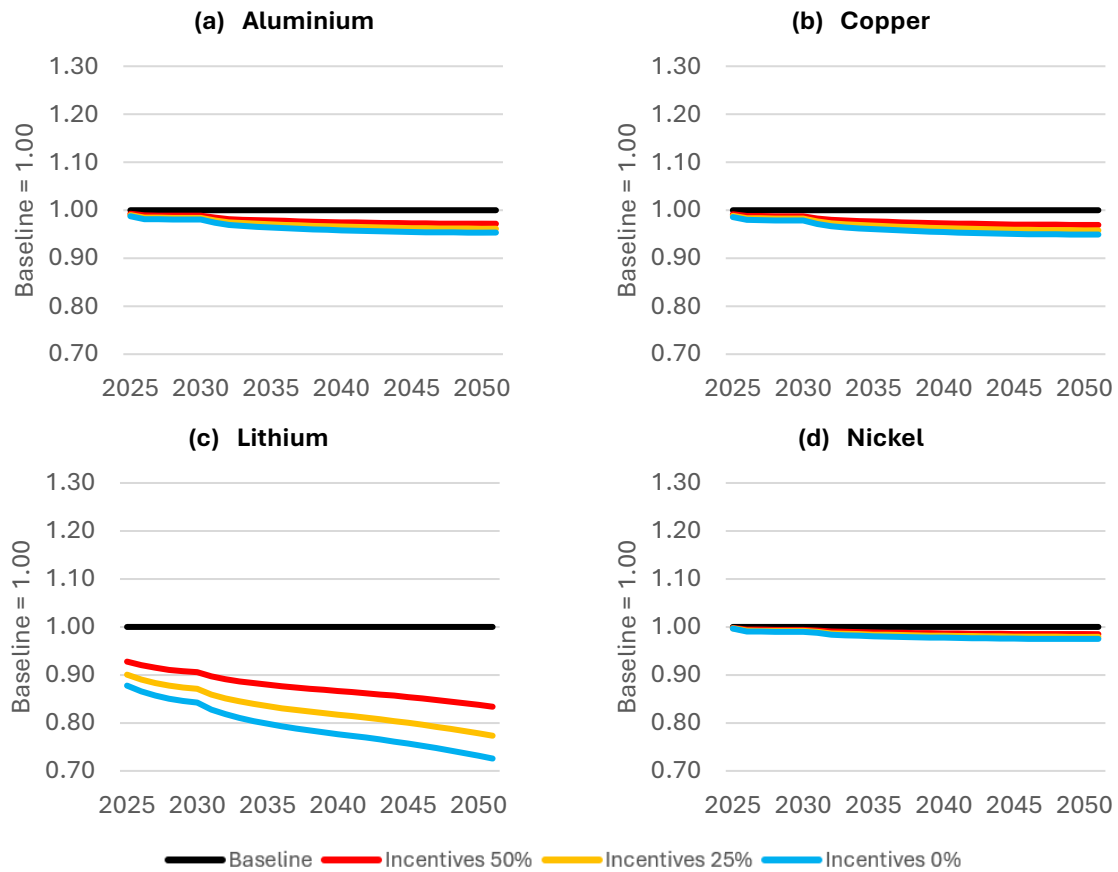


Figure 3.29. The effect of BEV incentives on minerals demand.

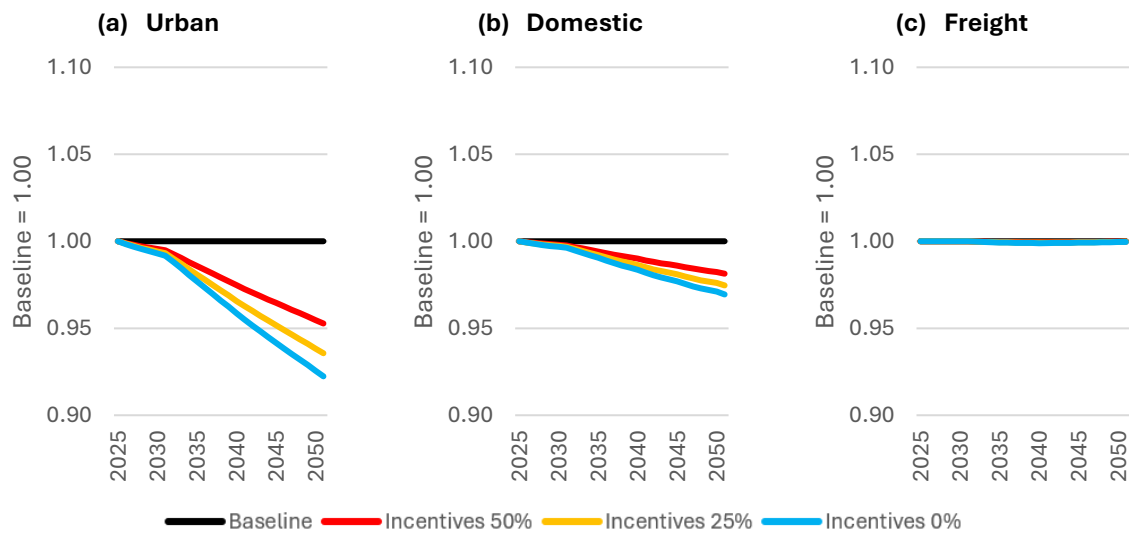


Figure 3.30. The effect of BEV incentives on energy intensity.

3.5.1.3. Biofuel

Biofuels are a blend of the so-called drop-in fuels produced from biomass with conventional fossil fuels. It is usually written in the format of the type of biofuel followed by its blending level, for e.g. B40 corresponds to biodiesel with 40% of drop-in fuel or E20 corresponds to bioethanol with 20% blending level. Biofuels are implemented to road, marine, and air transportation. However, biofuel implementation in marine and air transportation is not included since the focus of this research is the relation between the transportation and power

sector, and vehicle electrification is focused on road transportation. Hence, this chapter does not include the implementation of biodiesel and bioethanol for road transportation and in the power sector for diesel generators.

At the baseline, the blending level for biodiesel is 35% (B35) and for bioethanol is 5% (E5). Historically, the blending level for biodiesel is periodically increased 5 to 10% every 5 years. The nearest goal to reach a B40²¹³ and E20²¹⁴. Further increasing the blending level may pose negative impact on land-use as noted in Section 3.2.3, especially with the obligation to keep at least 30% of the land area for conservation²¹⁵. This study simulates the effect of changing the blending level for both biofuels to the observed indicators in two ways. First, the blending level is increased by 5% every 5 years without any land availability restrictions. Secondly, continuously increasing until the land availability restrictions is reached.

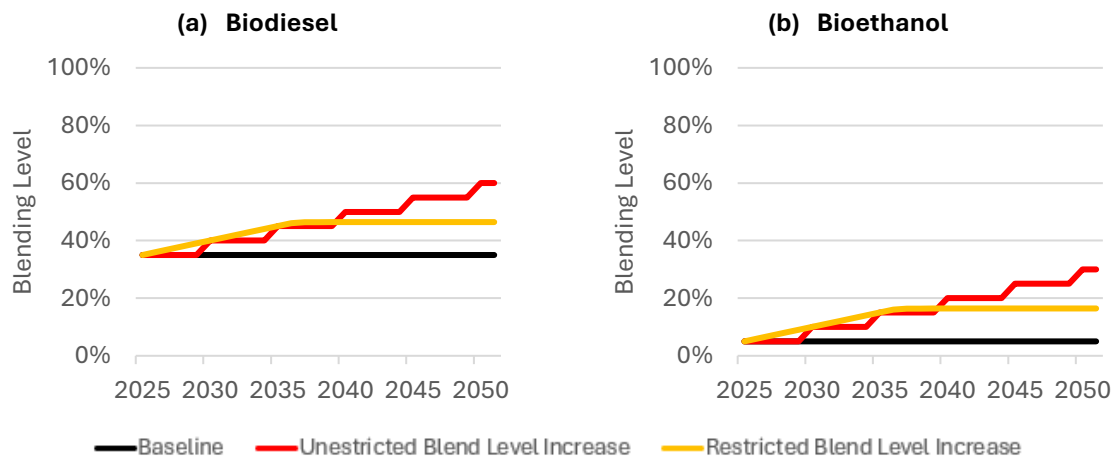


Figure 3.31. Biofuel blending level progression under restricted and unrestricted land availability.

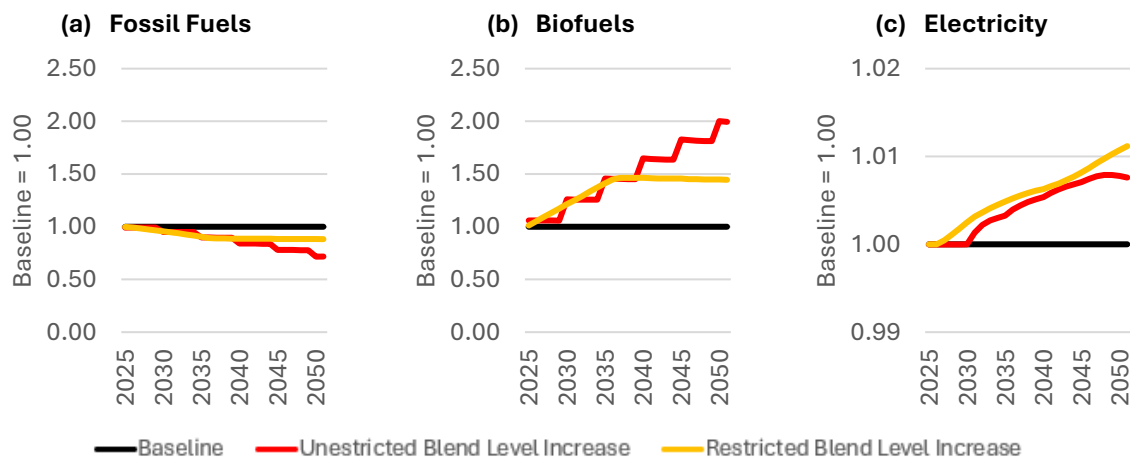


Figure 3.32. The effect of increasing biofuel blending level on final energy consumption.

Implementing biofuel policy would reduce fossil-based fuel consumption. If the blending level is unrestrictedly increased, fossil fuel demand would increase at 1.5% per year from 2025 and reaching 104 billion litres in 2050 which is 29% lower than the baseline. However, when land restriction is included, the demand would only decrease by 12% or to 128 billion litres as shown in Figure 3.32. The large gap between the two simulation results is because the blending level could only reach 46% for biodiesel and 16% for bioethanol by 2050 if land restriction is included but it could reach 60% for biodiesel and 30% for bioethanol if not as shown in Figure 3.31. Interestingly, a higher biofuel blending level would also slightly increase electricity

consumption from the use of more EV. The increased EV adoption is since biofuels led to higher fuel consumption^{183,184}, hence increasing the economic benefit of EV over ICEV.

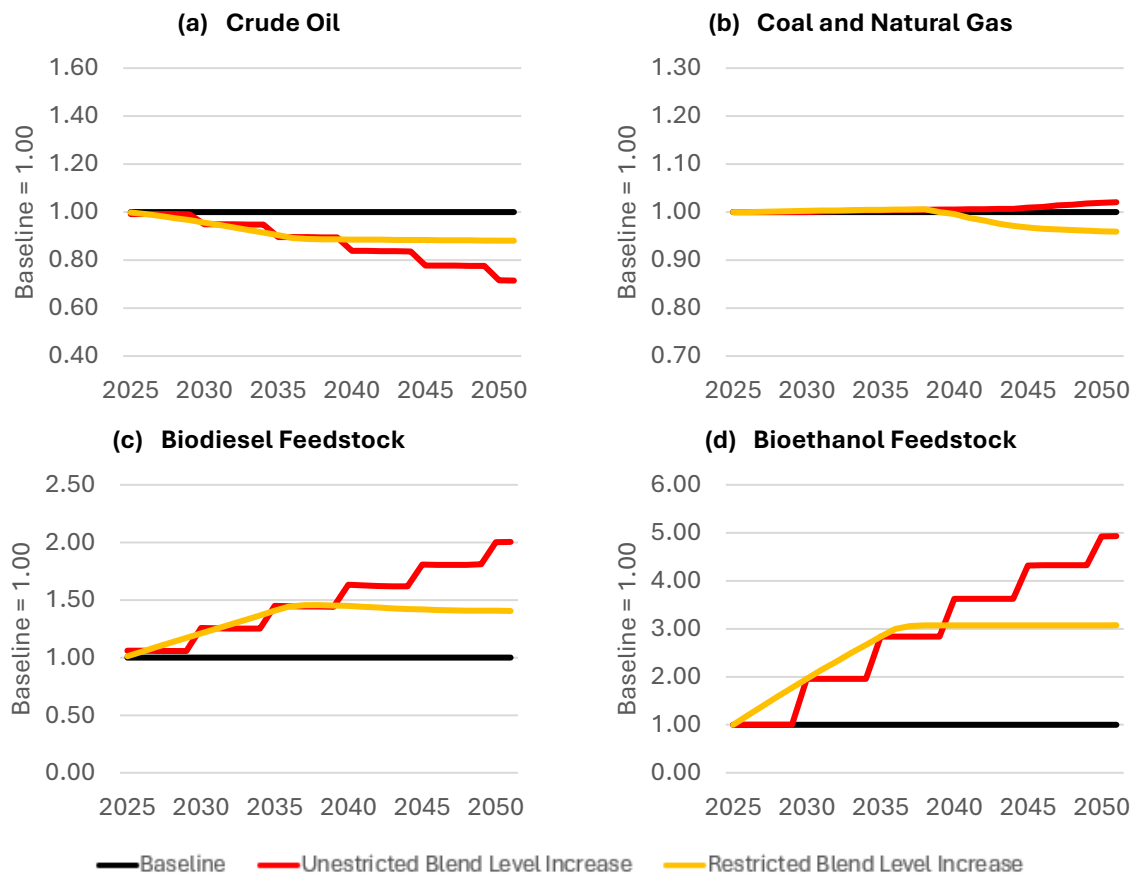


Figure 3.33. The effect of increasing biofuel blending level on primary energy consumption.

The crude oil and biofuel feedstock demand would change proportionately because of the changes in final energy demand. Figure 3.33 shows the demand for biodiesel feedstock would increase 7.1% per year from 2025 if the blending level is unrestrictedly increased and 5.8% per year if restricted. The increase corresponds to a demand for biodiesel feedstock – in this case CPO – of 72 million ton or 4.9 times the current production for biodiesel and 50 million ton or 3.1 times the current production. On the other hand, bioethanol feedstock would increase most significantly by 8.3% or 6.4% whether the land availability restriction is applied, resulting to 7.6 times and 2.7 times the current demand.

The land required to fulfil the production of B60 and E30 could reach 188 million hectares while with the land restriction the land required would be 134 million hectares. Compared to the baseline in 2050, the first requirement is 2.1 times larger while the second is 1.5 times larger as illustrated in Figure 3.34. Figure 3.35 shows that both requirements exceed the land availability, resulting in an insufficient domestic production and hence may result in biofuel feedstock imports. Bioethanol fared better than biodiesel in terms of sufficiency since its blending level is lower and its demand to replace gasoline is lower than biodiesel's demand to replace diesel. Without any improvements in production yield, it is unlikely that increasing biofuel blending rate further from current state would be sustainable. While under the unrestricted case the blend level is lower than the unrestricted case, the continuous blend level increase led to a faster land availability depletion. Eventually it resulted in the halt of power generation expansion, explaining the lower coal and natural gas consumption for power

generation in Figure 3.33. As a result, the share of RE in the power grid could increase and the land requirement for power generation attributed to the transportation sector become higher than the baseline as shown in Figure 3.34.

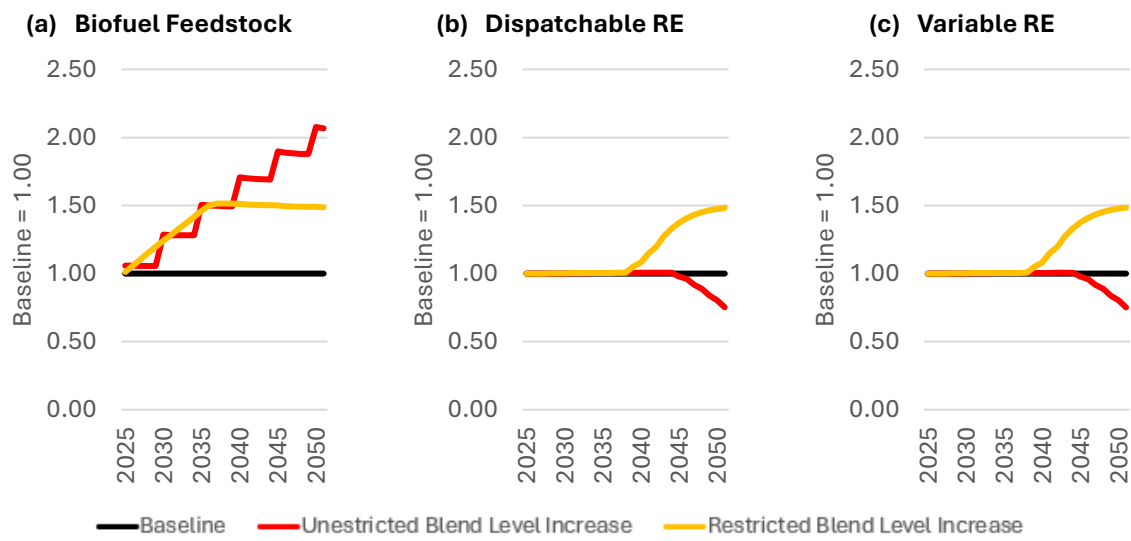


Figure 3.34. The effect of increasing biofuel blending level on land requirements.

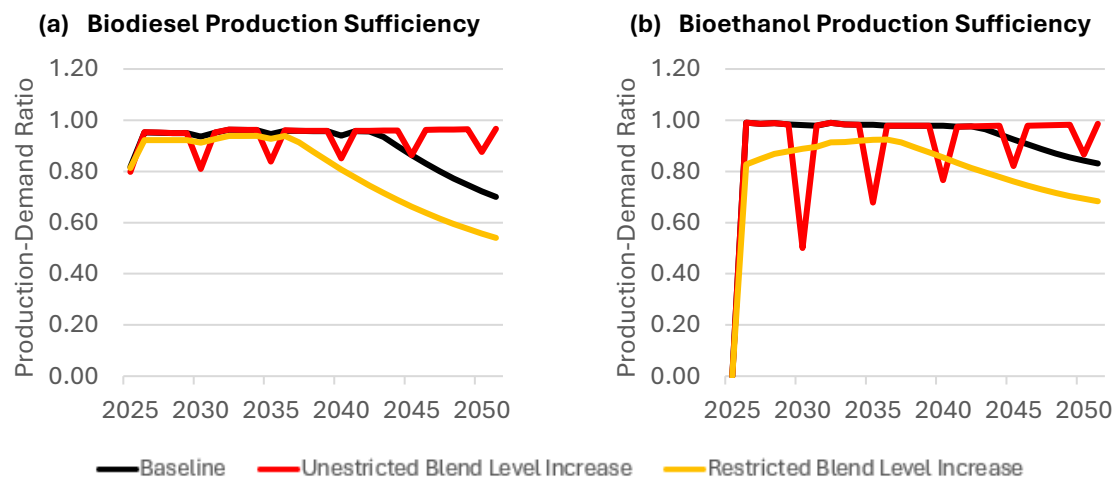


Figure 3.35. Biofuel domestic production sufficiency under restricted and unrestricted land availability.

As reported in several studies, biodiesel and bioethanol have higher CO₂ and NO_x emissions compared to their conventional counterparts^{178,179,216}. On the other hand, they also showed that biofuels have lower PM and SO₂ emissions. However, as noted in Figure 3.32 that increasing biofuel blending rate also result in higher electricity demand from EVs, hence while the tailpipe PM and SO₂ emission may decrease, it may be offset by the increase from power generation. The total emission for the four emission is shown in Figure 3.36 where in the CO₂, NO_x, and PM emissions are consistent with the previous studies. However, the total SO₂ emission approaches the baseline indicating the SO₂ emission from power generation indeed offset the reduction from tailpipe emission. Another characteristic of biofuels is their lower energy density, in particular bioethanol, which led to higher fuel consumption^{178,184}.

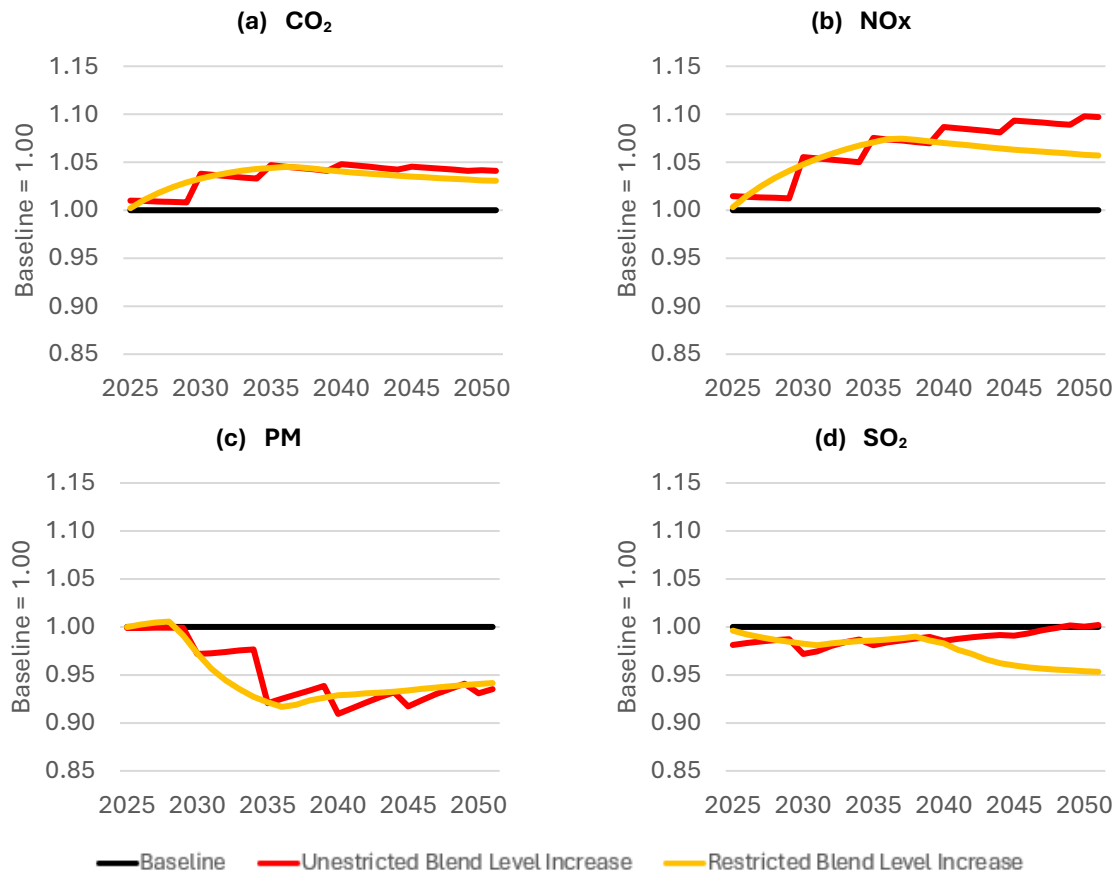


Figure 3.36. The effect of increasing biofuel blending level on emissions.

The lower fuel economy of biofuels increased the attractiveness of a more fuel-efficient vehicles, which includes HEV and BEV. Hence, there would be a slight increase in HEV and BEV adoption and, so, the demand for minerals especially lithium. The changes of the observed minerals showed similar profile but at a different magnitude as shown in Figure 3.37. In addition, a higher fuel consumption led to more energy consumed per capita both for urban and domestic transportation which primarily would use bioethanol as a replacement for gasoline. The result showed that further increasing biofuel blending rate would start to induce a shift to public transportation, particularly from motorcycle users and to more efficient vehicles since it would become costlier to use them. Figure 3.38 showed a higher biofuel blending level led to a reduced urban energy intensity due to the shift. However, the energy intensity for domestic and freight transportation could increase due to the increased fuel consumption.

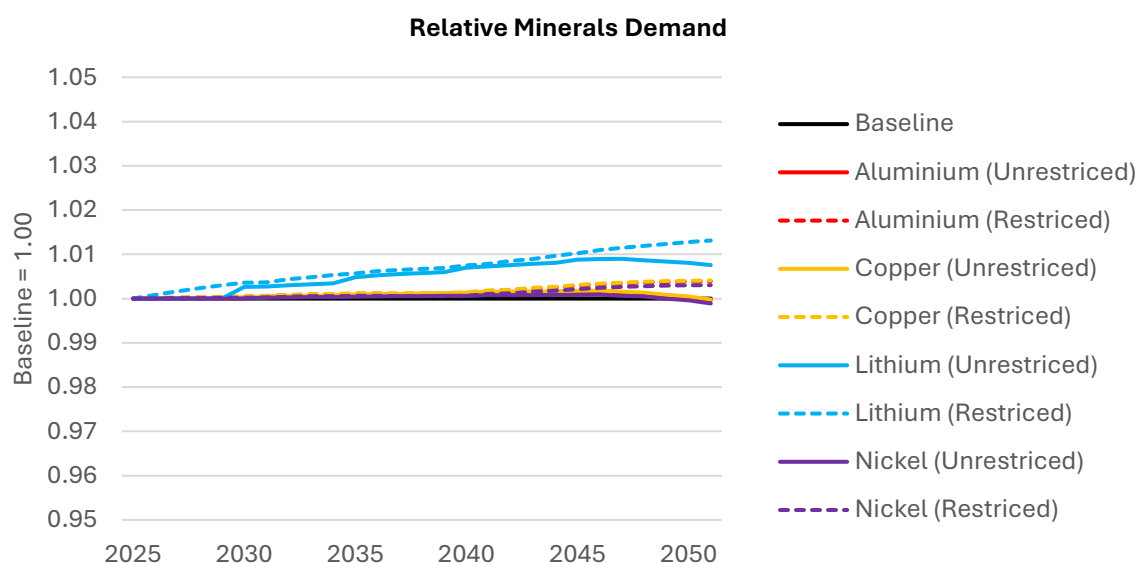


Figure 3.37. The effect of increasing biofuel blending level on the minerals demand.

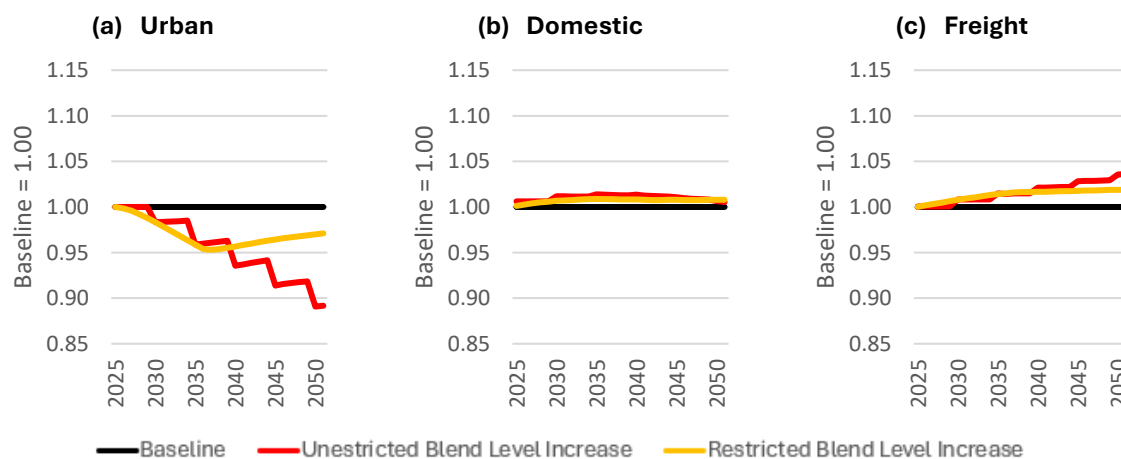


Figure 3.38. The effect of biofuel policy on energy intensities.

3.5.2. Uncertainty Tests

The purpose of these sensitivity tests is to investigate the effect of the uncertainties mentioned in Section 3.3.3 on the indicators.

3.5.2.1. Final Energy Consumption

Fossil-based fuel consumption is most sensitive to tank-to-wheel efficiency improvement, where 1% of improvement leads to 0.5% of fossil fuel consumption. Eliminating delays in public transport network development and improving BEV battery capacity induces a shift to public transportation and BEVs, reducing fossil fuel consumption by 2.3% and 4.3% at most compared to base run, respectively. Oil price is inversely related to gasoline consumption. However, the effect is asymmetrical. A 1% higher oil price compared to the reference leads to 0.02% lower consumption, but a 1% lower oil price leads to a 0.03% increase in consumption.

Biofuel consumption is also highly influenced by tank-to-wheel efficiency improvement, with an elasticity of 0.61. Improving EV battery affects biofuel consumption similarly to fossil fuel, reducing 4.3% of biofuel consumption compared to the base run in 2050. On the other hand,

eliminating public transport development delays reduces biofuel consumption by 1.3% in 2050, less impactful compared to fossil-based fuels since public transport fleet still uses biodiesel.

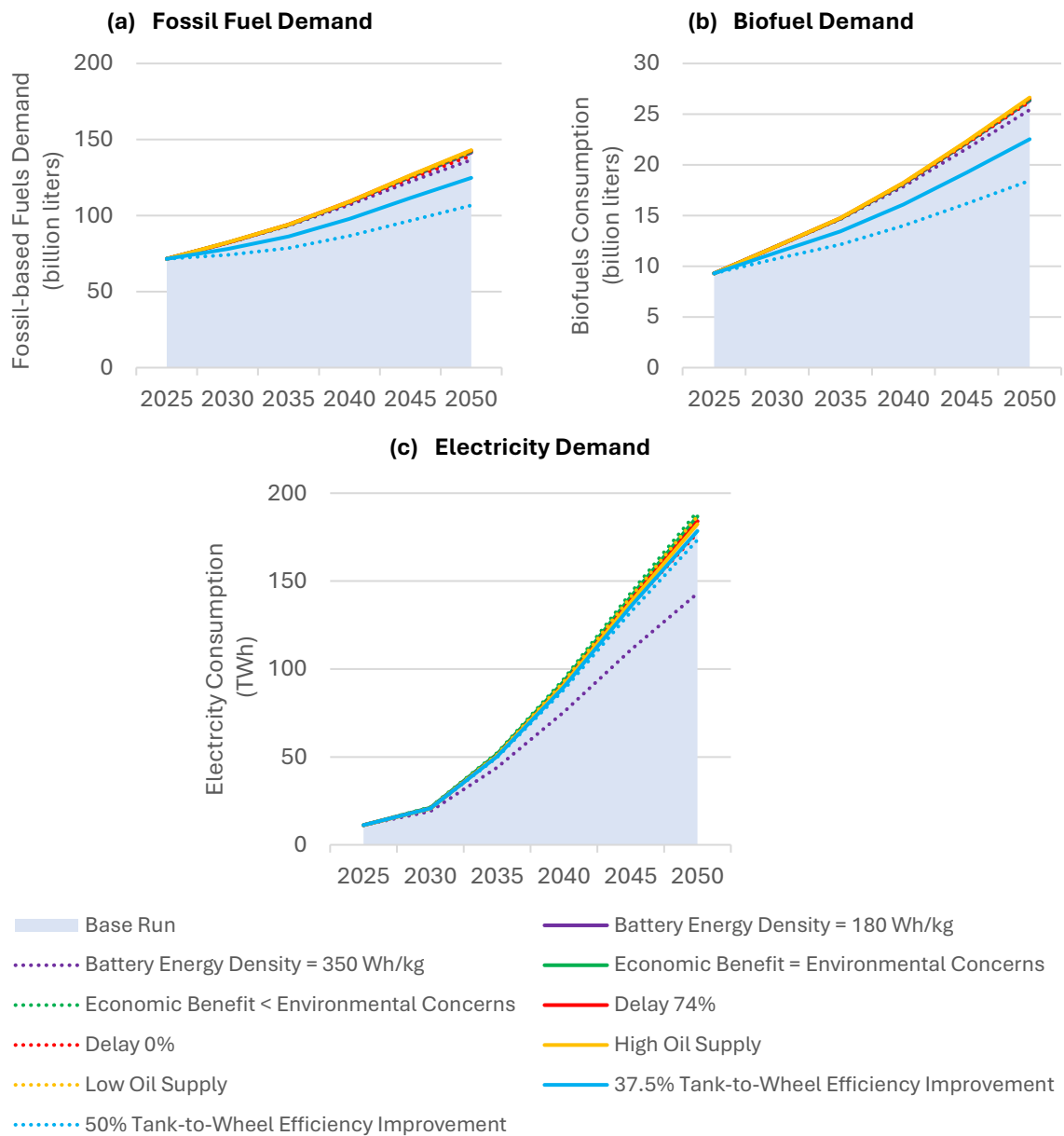


Figure 3.39. Sensitivity test of final energy consumption.

A 1% tank-to-wheel efficiency improvement also reduces electricity consumption by 0.12% since it would make ICEV and HEV more attractive compared to BEV. Battery capacity improvement was shown to have slightly more significant electricity consumption where a 1% improvement reduced electricity consumption by 0.16% at most. As consumers become more aware of the environment, electricity consumption could increase from to higher adoption rate of BEVs. Similarly, higher oil price provides the incentive to use BEVs. The analysis of the two indicators shows that electricity consumption is more uncertain during the transition efforts. The sensitivity test result can be seen in Figure 3.39.

3.5.2.2. Primary Energy Demand

Similar to gasoline consumption, tank-to-wheel efficiency improvement resulted in the highest crude oil consumption reduction, followed by EV battery capacity improvement and public

transportation network delay minimization. The reduction from the baseline is 25%, 4%, and 2% at most, respectively as shown in Figure 3.40. An increase in oil price only slightly reduced the demand for crude oil by 0.2% from the baseline in 2050, while a decrease in price could increase the demand by 0.4%.

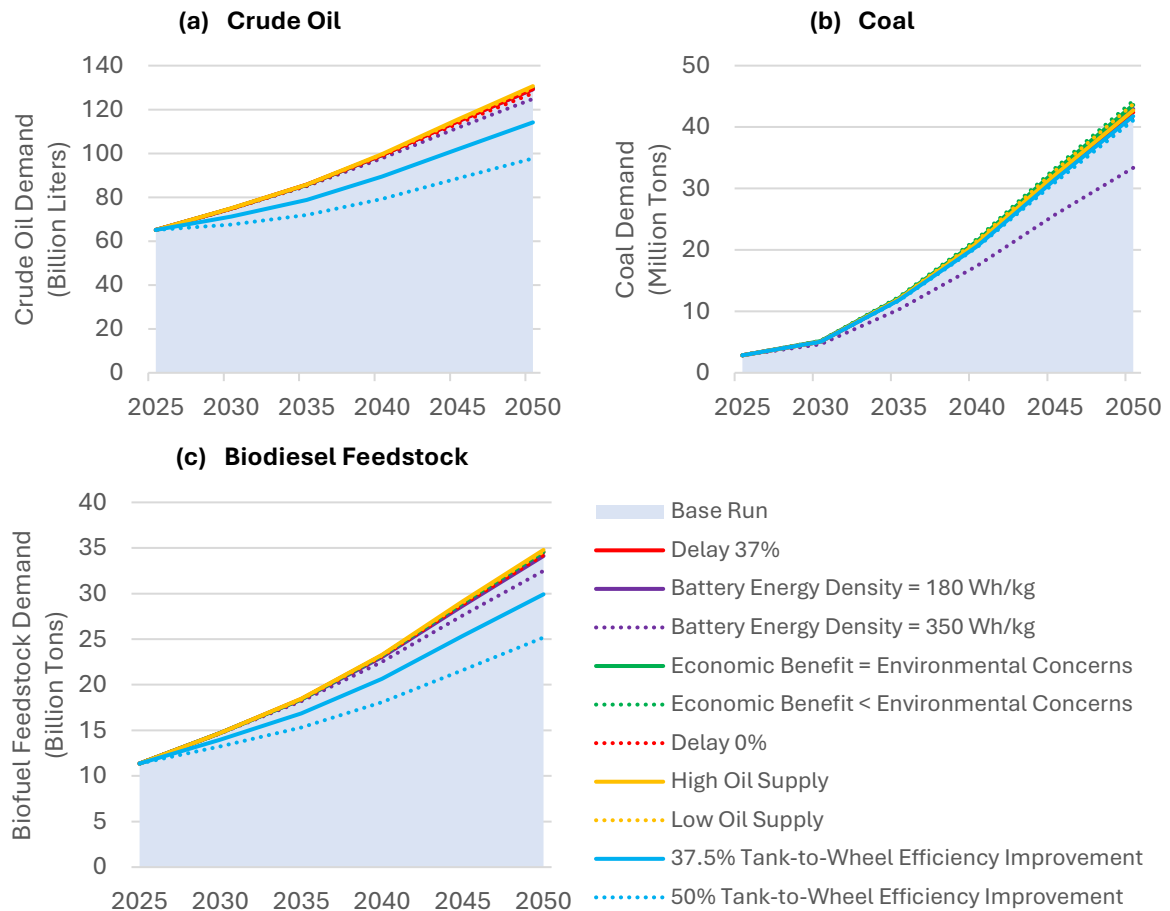


Figure 3.40. Sensitivity test of primary energy consumption.

As with crude oil, biofuel feedstock consumption would also decrease as tank-to-wheel efficiency improved albeit to a greater extent, where it could be reduced by 27% at most. Biofuel feedstock consumption is slightly more sensitive to an increase in BEV adoption than crude oil. When EV battery capacity reached its theoretical limit, biofuel feedstock consumption could drop by 6%.

Coal consumption is proportionate to the number of BEVs and in turn the electricity consumed. If more consumers adopt EVs for their perceived environmental benefit without improving battery capacity, coal consumption could be 3% larger than the base run with the current power mix. On the other hand, the coal demand increase can be greatly countered by improving the battery energy density, where it was shown to be reduced by 22% from the baseline in 2050 if the theoretical limit is achieved.

3.5.2.3. Land Requirement

Figure 3.41 shows that biofuel land requirement follows biofuel consumption, where tank-to-wheel improvements can reduce it significantly. Land requirement could be reduced by 12%, and 25% from the base run in 2050 when the tank-to-wheel efficiency is improved by 37.5% and 50% from 2005 level, respectively. On the other hand, both dispatchable renewable

electricity and variable renewable electricity land requirement follows electricity demand which is negatively affected if EV potential adopters have a higher environmental concern but is positively affected by improvements in battery energy density and delay reduction in public transport development.

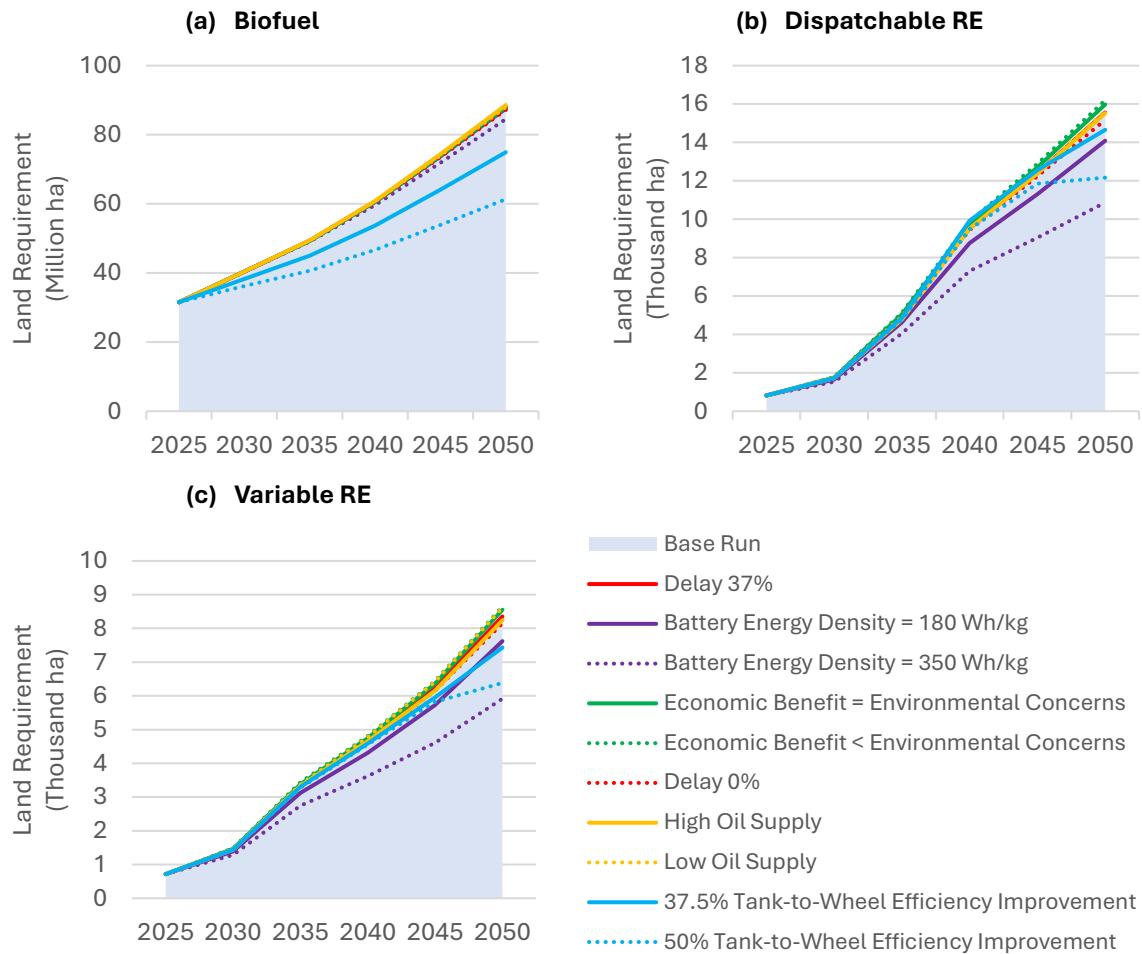


Figure 3.41. Sensitivity test of land requirement.

3.5.2.4. Emissions

Both CO₂ and NO_x emissions are most sensitive to tank-to-wheel efficiency since the main emitters are road vehicles. Battery density improvements could also reduce CO₂ and NO_x emissions since it would lead to longer BEV driving range in with the same battery capacity. On the other hand, as a consequences of BEV adoption increase – without any intervention on the power mix or power plant efficiency – SO₂ and PM emission will increase as shown by the sensitivity tests of adoption weight shifts and oil price. As with CO₂ and NO_x, SO₂ and PM emissions could be significantly reduced by improvements tank-to-wheel efficiency and battery density. While PM emissions can be equally improved by tank-to-wheel efficiency and battery density, SO₂ emissions can only be improved significantly by battery density since the large increase in SO₂ overtime is due to EV adoption which still used coal-dominant power generation – a prominent emitter of SO₂. The sensitivity test results for the observed emissions are presented in Figure 3.42.

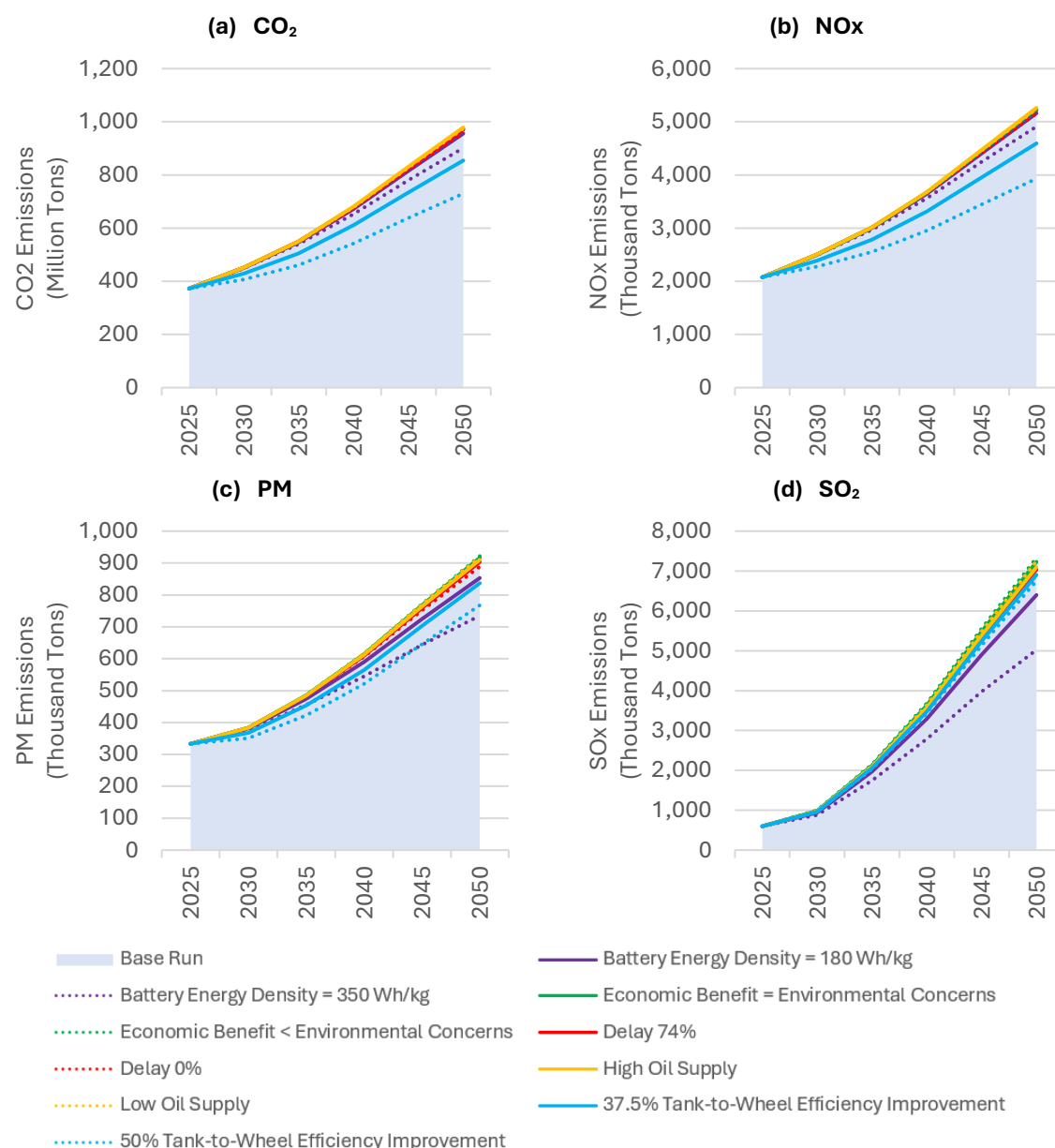


Figure 3.42. Sensitivity test of emissions.

3.5.2.5. Minerals Demand

Mineral demands are most affected by the adoption of BEVs which in turn is most driven by improvements in battery capacity, and slightly by changes in environmental benefit adoption weights. Lithium demand could increase 2.46 times that of base run in 2050 if the battery capacity reaches its theoretical limit. Mineral demand could be reduced with higher tank-to-wheel efficiencies since it would lead to less EV adoptions and more ICEVs or HEVs. Lithium demand would be the most affected If the tank-to-wheel efficiency of internal combustion engines is improved 50% from the 2005 level, which could be reduced by 6% in 2050 from the baseline.

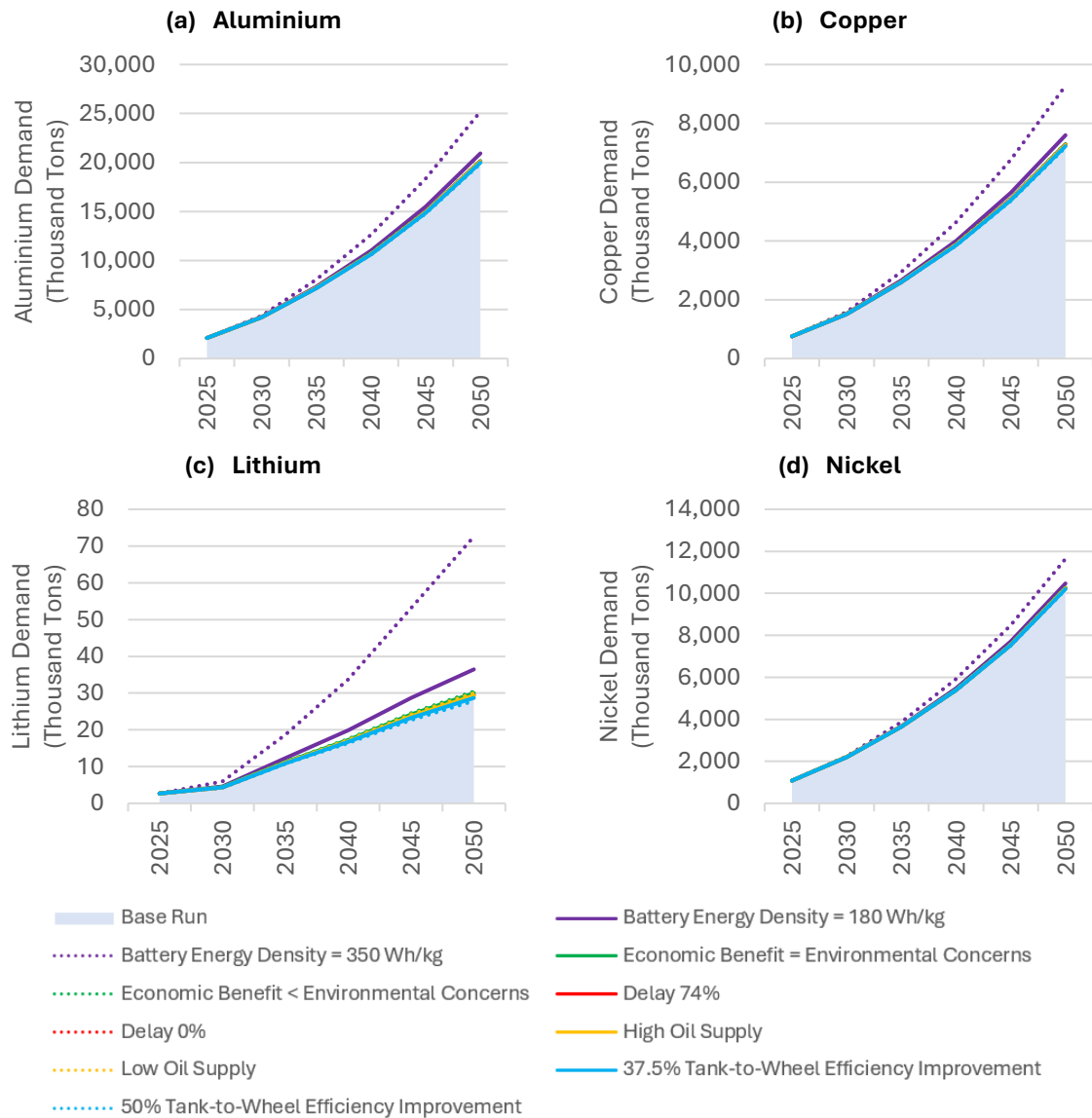


Figure 3.43. Sensitivity test of minerals demand.

3.5.2.6. Primary Energy Intensity

As previously shown in earlier sensitivity tests, tank-to-wheel efficiency is also pivotal in reducing energy intensity, where if it could be increased by 50% then energy intensity could be reduced 20%, 7%, and 27% for urban, domestic, and freight transportation, respectively. Like the sensitivity result on emissions, increase in BEV adoption by an increased environmental awareness without improvements in battery density would lead to an increased primary energy intensity by 0.2%. Improving battery density to its maximum limit as elaborated in Section 3.3.3 could reduce primary energy intensity significantly by 18% from the baseline in 2050 as shown in Figure 3.44.

Nevertheless, only shifts to public transportation can provide a sustainable energy intensity since it reduces urban VKT and energy consumption while carrying the same amount of transportation demand. Figure 3.45 shows that the urban energy intensity would be reduced in the baseline due to improvements in energy efficiency improvements. However, when looking at the uncertainties individually, only eliminating public transportation development delays could the annual changes in energy intensity be constantly reduced.

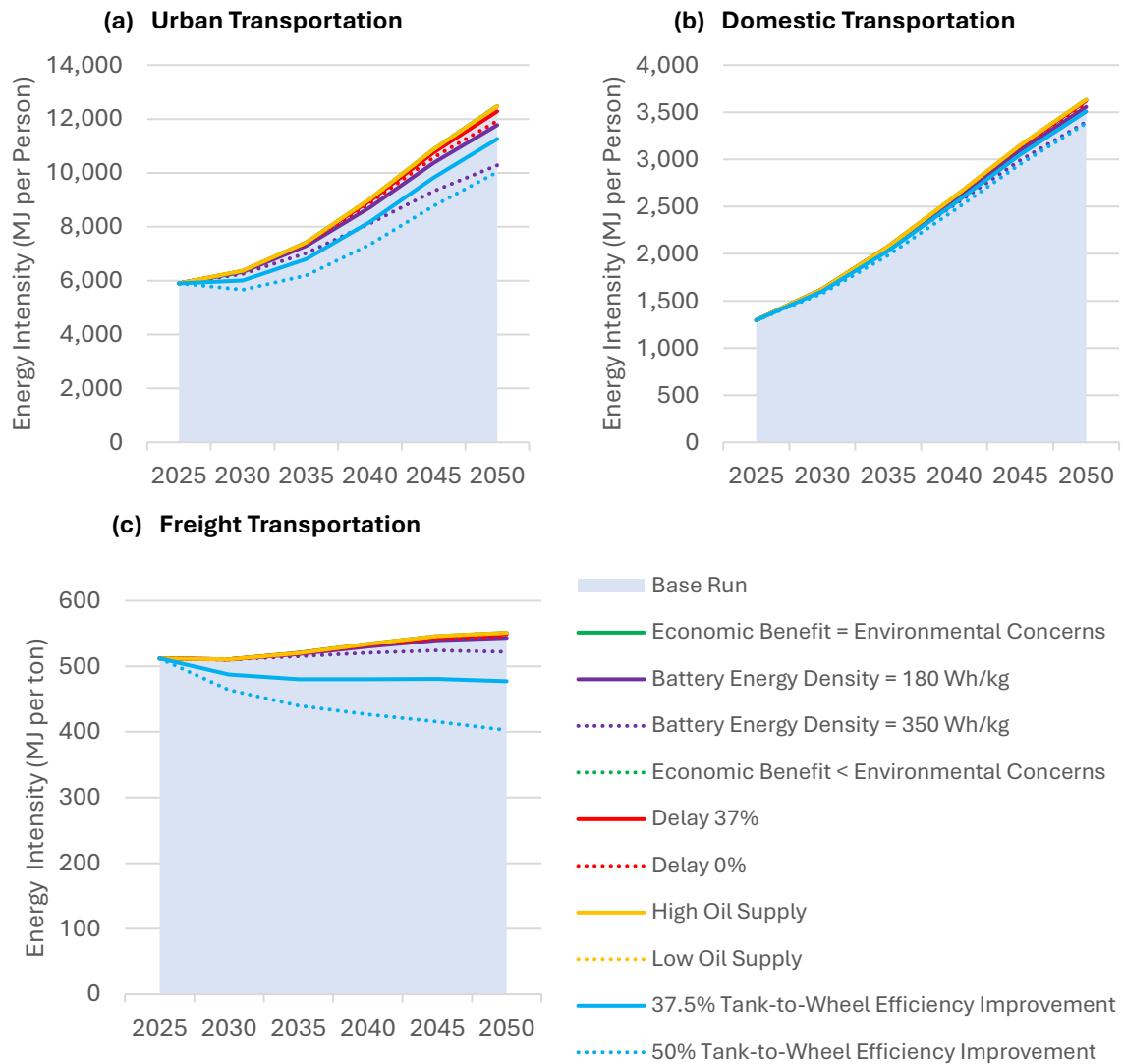


Figure 3.44. Sensitivity test of primary energy intensity.

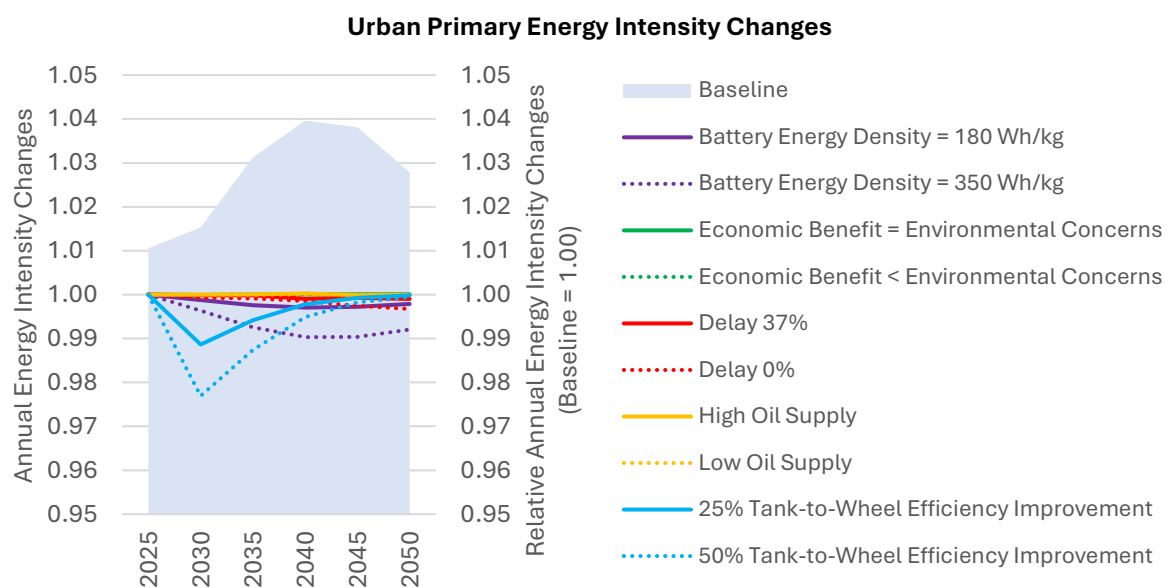


Figure 3.45. Annual changes of urban transportation primary energy intensity and the effects of uncertainties

3.6. Scenario Analysis

Scenario Analysis was used to identify a range of potential future paths, and the influence of alternative policies. This section explores what could happen to the indicators of interest when the policies listed in Section 3.2 are implemented under the uncertainties in Section 3.3.3. Four policy alternatives were developed: Conservative, Improve-focused, Shift-focused, and Aggressive, presented in Table 3.2.

Furthermore, two uncertainty setups were formulated – Disadvantageous and Advantageous – which correspond to the extreme points in the sensitivity tests (including baseline) in Section 3.5.2 and summarized in Table 3.3. Advantageous uncertainty indicates the situation that most supports the achievement of policy goals, and disadvantageous is the least supportive.

Table 3.2. Policy sets used in the scenario analysis.

Policy	Parameters	Conservative (C)	Improve-Focused (I)	Shift-Focused (S)	Aggressive (A)
Public Transport Development	Expansion factor (of desired network length per period of development)	0.025	0.025	0.1	0.1
	Expansion frequency	Every 8 years	Every 8 years	Every 4 years	Every 4 years
Vehicle Electrification	Fiscal incentives	25%	100%	25%	100%
Biofuel	Land Availability Restriction	30%	0%	30%	0%

Table 3.3. Uncertainty setup for scenario analysis

Uncertainties	Disadvantageous (D)	Advantageous (V)
Project Delay	74%	0%
Battery Energy Density Limit	144 Wh/kg	350 Wh/kg
Adoption Weights	Economic benefit > environmental benefit	Economic benefit < environmental benefit
Oil Supply	High	Low
Tank-to-Wheel Efficiency Improvement	25%	50%

3.6.1. Final energy consumption

In the conservative policy and under a disadvantageous situation (C-D scenario), the rate of increase of fossil-based fuel demand was 2.5% annually which is already lower than the base run 2.8%. On the other hand, biofuel as the substitutes to fossil fuel would increase considerably by 5% per year in the C-D scenario and resulting in a 27% higher cumulative demand than the baseline. The cumulative demand is further increased to 33% in the improve-focused policy in a disadvantageous situation (I-D scenario), the highest among all scenarios. However, biofuel demand could be lowered significantly with the conservative policy and improve-focused policy if the situation is advantageous (C-V scenario and I-V scenario,

respectively). Under these scenarios, the increase in blending level can be countered by the tank-to-fuel efficiency is greatly improved, resulting in an almost the same biofuel demand as the baseline.

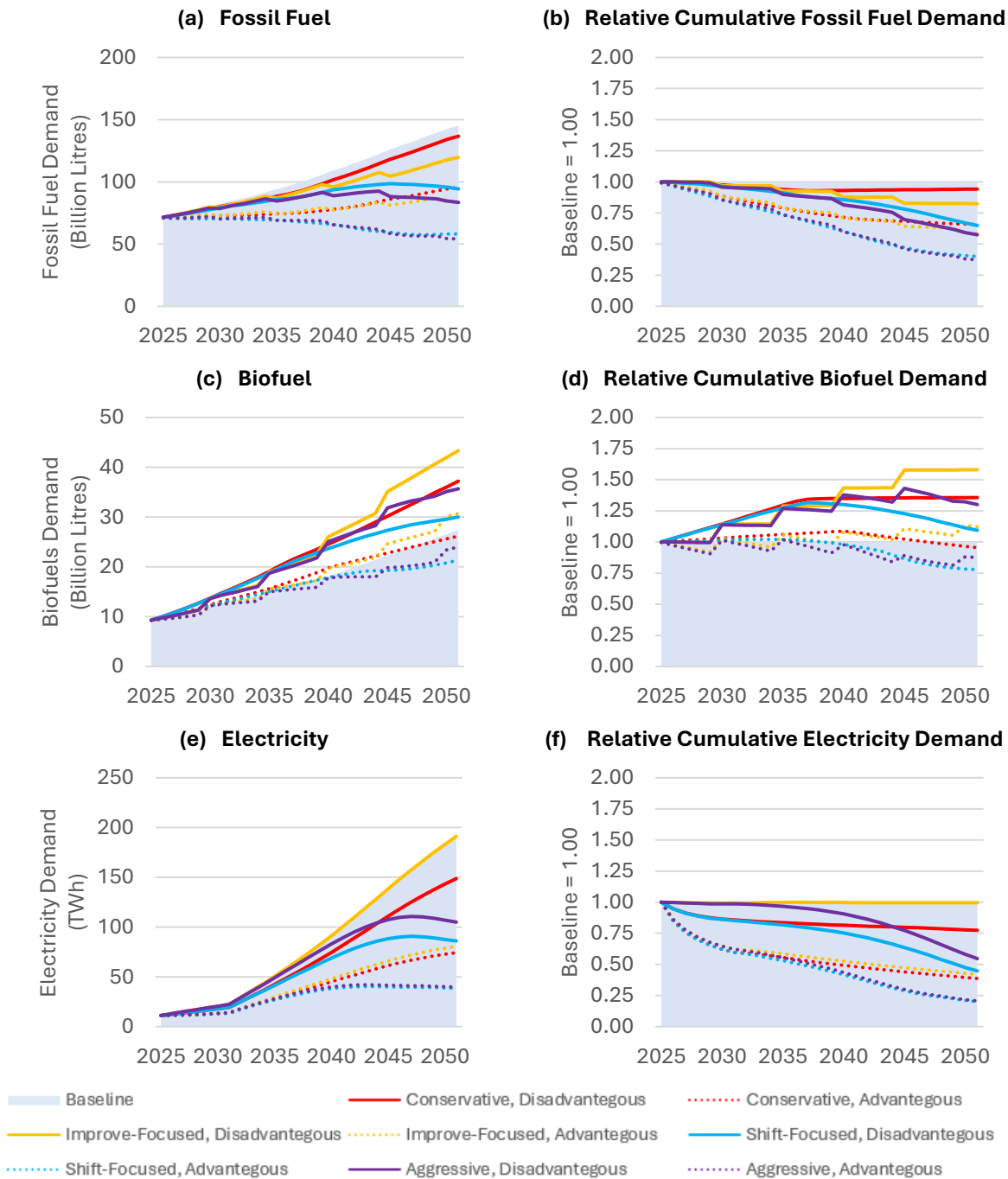


Figure 3.46. Final energies demand under the defined scenarios.

The consumption of electricity in the C-D scenario increased at a lower rate than the baseline – 10% per year compared 12% per year – which resulted in a 23% lower demand than the baseline in 2050. The C-D scenario entails a lower fiscal incentive for EV which resulted in the decrease of EV share from the baseline 25% to 20%. In contrast, the electricity demands in the I-D scenario where EV incentives are kept at 100%, is almost the same with the baseline. The C-V scenario and I-V scenario resulted in an almost equal electricity demand. The decreased electricity demand in both scenarios was due to the improvement of EV battery

capacity which was shown to greatly affect electricity demand in Figure 3.39. The cumulative electricity demand between 2025-2050 in the C-V scenario was reduced by 43% from the baseline, while the reduction is 50% in the I-V scenario.

Focusing on shift policies was shown to have a balanced result, reducing fossil fuel, biofuel, and electricity demand simultaneously. Even under the disadvantageous situation, the shift-focused policy (S-D scenario) was able to deflect fossil fuel demand – a feat the improved-focused policy cannot provide. The similar effect can also be seen for biofuel demand and electricity demand which indicates the more sustainable policy for the transportation sector energy demand. The cumulative demand for fossil fuel and electricity demand in the S-D scenario is 12% and 35% lower than the baseline, while the cumulative biofuel demand is still 18% higher because most public road transport fleets would still be consuming biodiesel. However, if the situation is advantageous (S-V scenario), the cumulative biofuel demand could be 7% lower than the baseline.

Applying both improve and shift policies, resulted in a lower fossil fuel demand than the shift-focused policies but higher biofuel and electricity demand due to the higher biofuel blending level and higher EV adoption. In the disadvantageous situation (A-D scenario), the cumulative fossil fuel demand is 14% lower than the baseline but the biofuel demand is 24% higher. While the electricity demand is 22% lower than the baseline, it was 20% higher than the S-D scenario. In the advantageous situation, the aggressive policy (A-V scenario) resulted in a 27%, 8%, and 64% lower fossil fuel, biofuel, and electricity demand than the baseline, respectively.

From the scenario simulation result, while all policy resulted in a reduced electricity demand, it was shown to be the most uncertain where the reduction ranges from below 1% to 65%, compared to fossil fuel which reduction ranges from 4% to 27% or biofuel which could increase by 33% or reduce by 8% at the extreme. Hence, the transportation sector would be increasingly become an important sector to watch for the power sector while developing their capacity planning in the future.

3.6.2. Primary energy demand

Like the fossil fuel final consumption, crude oil demand would still be increasing even when both shift and improve policies are implemented. However, the increase rate would differ as shown in Figure 3.47 where the demand increase trend was able to be reversed when a shift to public transportation is pushed. Nonetheless, the cumulative demand for crude oil can be reduced between 4% to 27%, around the same number with the reduction in its refined products.

The changes in electricity demand directly translates to the demand for coal and natural gas as the primary energies in power generation. In the I-D scenario the demand for coal and natural gas does not differ significantly from the baseline since the electricity demand is almost the same. When the battery capacity reaches its theoretical limit (I-V scenario) which would greatly improve EV driving range, the demand for coal could be 49% lower than the baseline. While the reduction is significant, a shift-focused policy could reduce the demand of both primary energies even further in line with the result in Figure 3.46. In the S-D scenario, coal and natural gas demand could be 36% lower than the baseline and 65% lower in the S-V scenario.

The demand for biofuel feedstocks, namely crude palm oil (CPO) for biodiesel and sugarcane for bioethanol, would increase. However, the demand increase for sugarcane would much larger than CPO since the increase in blending level is higher. As discussed in Section 3.3.3,

the biodiesel blending level increased from the current level 35% to 46% or 60% depending on the land restriction policy. However, bioethanol blending level would increase from 5% to 16% or 30%. As the result, the cumulative demand for CPO could decrease by 10% or increase by 34%. On the other hand, sugarcane demand would increase regardless of the scenario, between 37% to 205% from the baseline in 2050.

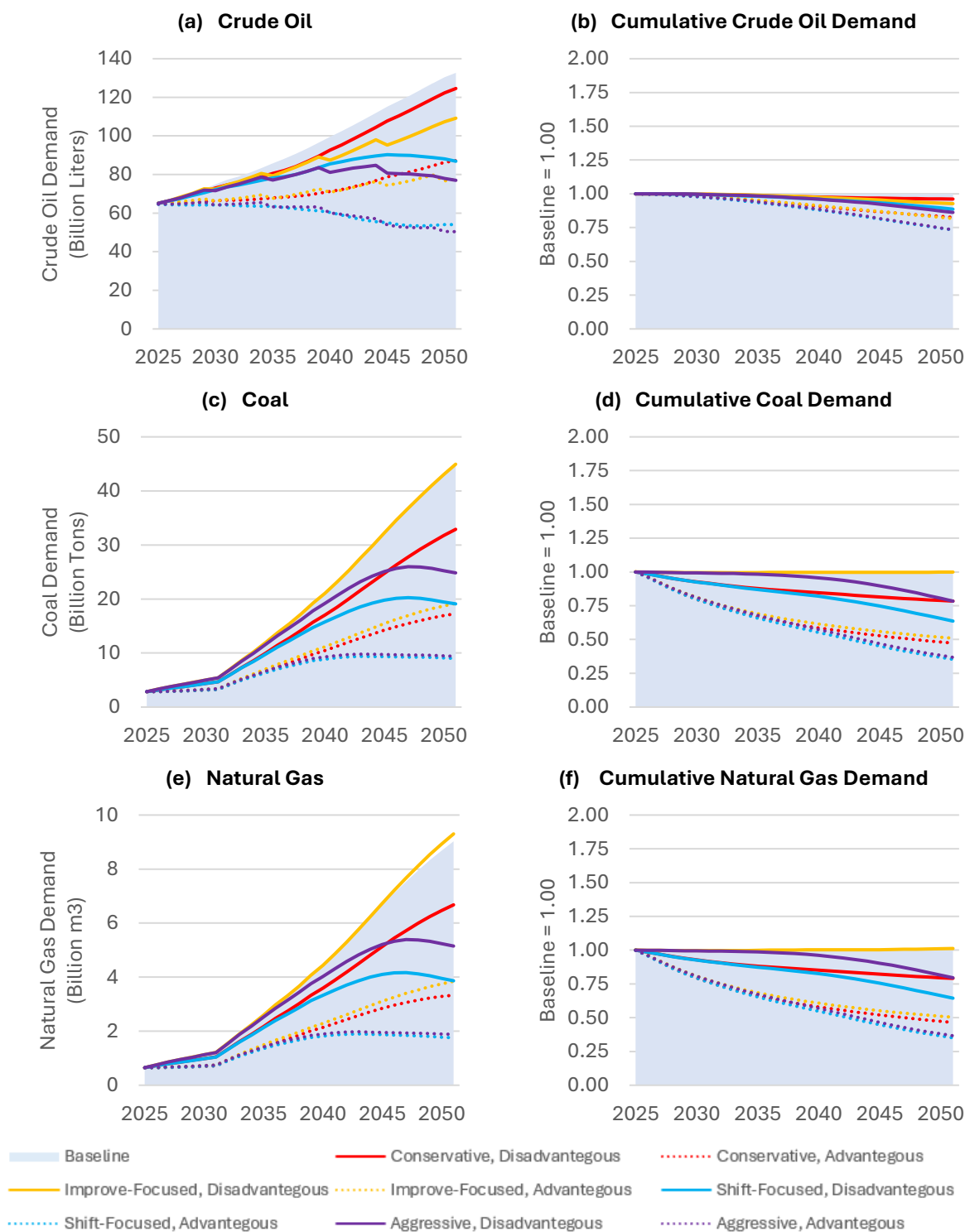


Figure 3.47. Comparisons of demand for fossil resources under different scenarios.

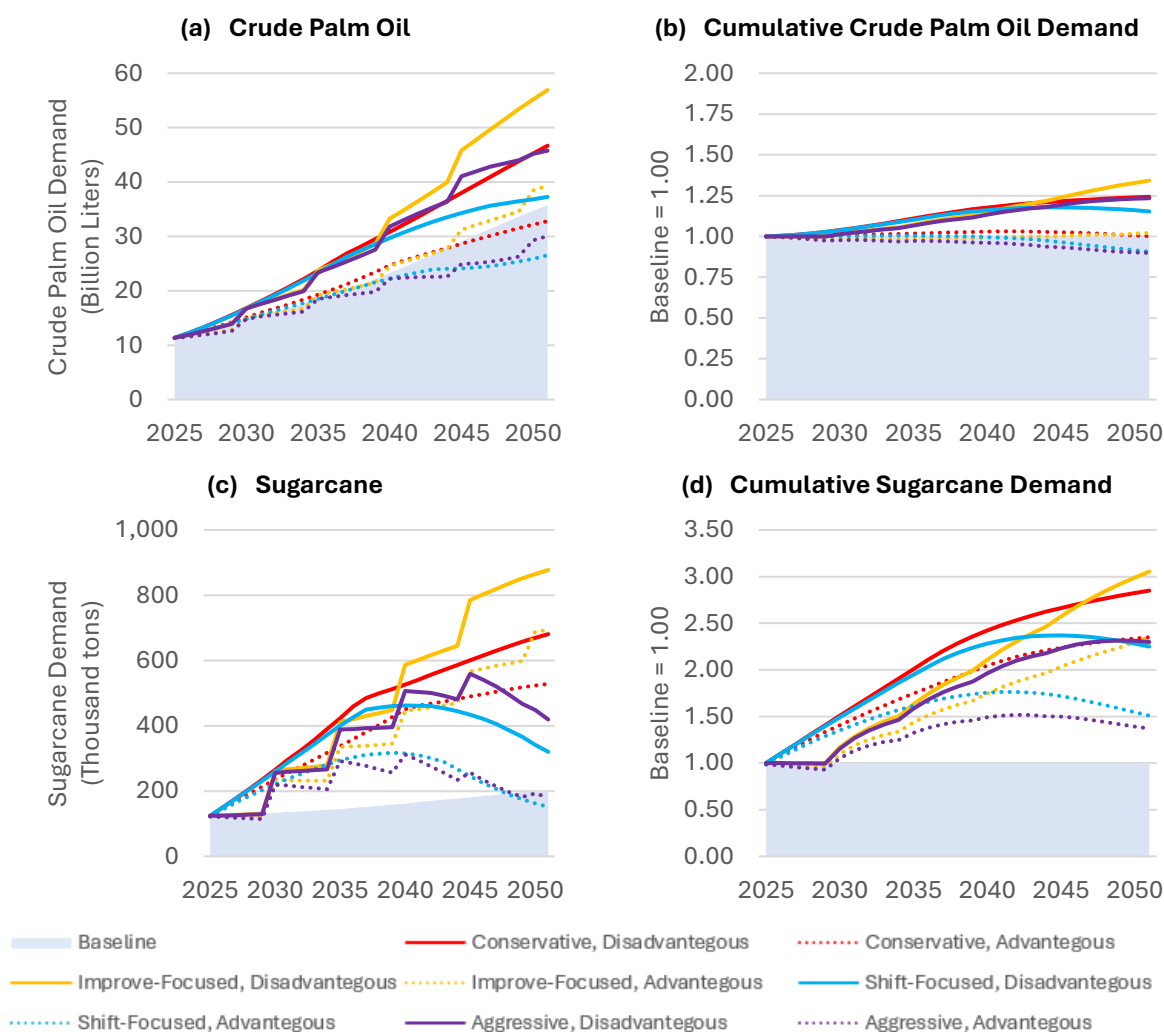


Figure 3.48. Comparisons of demand for biomass resources under different scenarios.

3.6.3. Land requirements

Figure 3.49 shows the land requirement for each of the scenarios. In line with the biofuel and electricity consumption, the land requirement is the largest when improve-focused policies are implemented (I-D scenario), reaching around 150 million hectares combined, mostly to grow biofuel feedstocks. Under this scenario, the land requirement for CPO for transportation alone would reach 140 million hectares in 2050. This land requirement far exceeds the land availability even without any land conservation constraint, which indicates that the blending level cannot be sustained with domestic production.

The land required to provide clean electricity was also the largest under the same scenario, which reached more than 21 thousand hectares in 2050. However, the impact of uncertainty on electricity land requirement is more accentuated compared to the land requirements for biofuels, which mimics the final energy demand. In general, the increasing land requirements shows the same trend between dispatchable and variable renewables and led to a lower requirement than the baseline by 2050. However, land requirement for dispatchable RE is slightly higher because a higher electricity demand forced the power sector to invest in a more reliable power generation. The characteristics of power generation adoption will be discussed in detail in Chapter 6.

In the S-D scenario, it is shown that a shift-focused policy would require 33% less land relative to the improve-focused policies which have a more extensive BEV adoption and higher biofuel blending level. Furthermore, among all scenarios, the shift-focused policy required the least land for clean electricity.

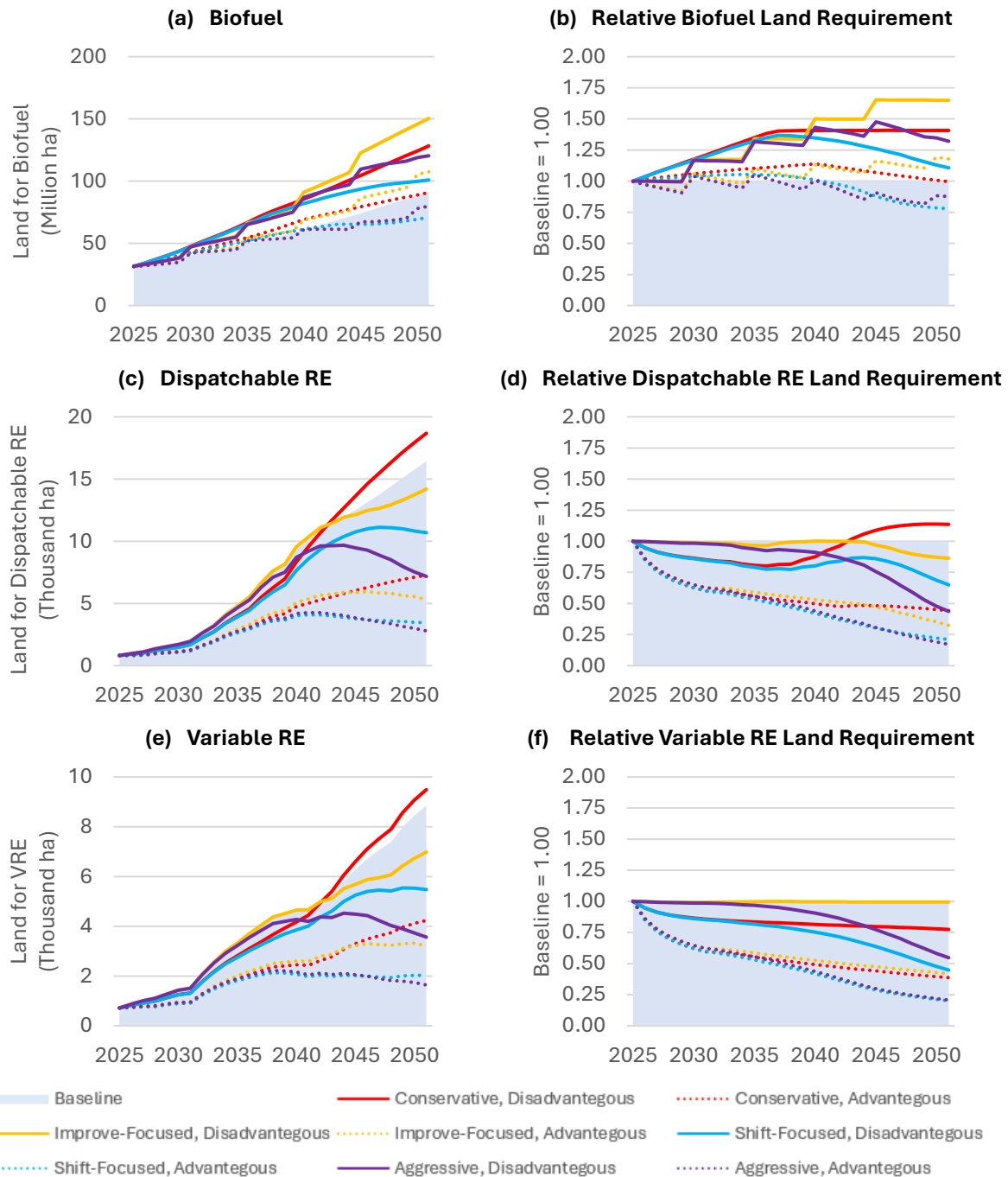


Figure 3.49. Land requirements under the defined scenarios.

3.6.4. Emissions

The emission result under the defined scenario shown in Figure 3.50. The C-D scenario shows an increase in CO₂ emission due to the increased biofuel blending level which has a higher CO₂ emission factor compared to fossil fuel due to its more complete combustion¹⁸¹. The CO₂ emission is even higher in the I-D scenario with even higher blending level and the addition from the increased EV adoption. Cumulatively, the CO₂ emission is 2.5% higher than the

baseline in the C-D scenario and 2.8% higher in the I-D scenario. When the policy is switched to a shift-focused policy, the CO₂ emission can be gradually decreased. In the S-D scenario, the cumulative emission is 6% lower than the baseline.

The effect of the scenarios on the NO_x emission is similar to its effect on CO₂ emission. The NO_x emission was shown to be higher than the baseline under the C-D and I-D scenario because both the biofuel and grid have a higher emission factor compared to conventional internal combustion engines^{101,181}. Hence it is important to improve the tank-to-wheel efficiency and battery capacity should biofuel blending level and EV are to be pushed as can be seen in the C-V and I-V scenario result. The most reliable policy to reduce NO_x emission (and other emissions) is to push for public transportation adoption instead since it was shown to effectively reduce the emission even under a disadvantageous situation.

The negative effect of focusing on Improve policies can be seen in the PM and SO₂ emissions result where only under the I-D scenario both emission is much higher than the C-D scenario. The high PM emission is again the result of the higher PM emission factor of the coal-dominated power grid compared to internal combustion engine. The difference in emission factor is further accentuated in the SO₂ emission where the cumulative emission in 2050 could remain the same with the baseline despite changes in the power mix as will be explained in Chapter 6. Unlike the CO₂ and NO_x emission result, the PM and SO₂ emission under the C-D scenario was shown to be lower than the baseline because of the lower emission factors in biofuels.

On the other hand, the positive effect of focusing on public transportation development can be seen in the SO₂ emission result where the gap between the I-D and S-D scenario result is the largest among all emissions. Furthermore, even when the EV adoption and biofuel blending level increase is paired with public transport development (A-D scenario), the emission for CO₂, NO_x, PM, and SO₂ is still higher compared to only focusing on Shift policies – signifying the importance of the shift to public transportation.

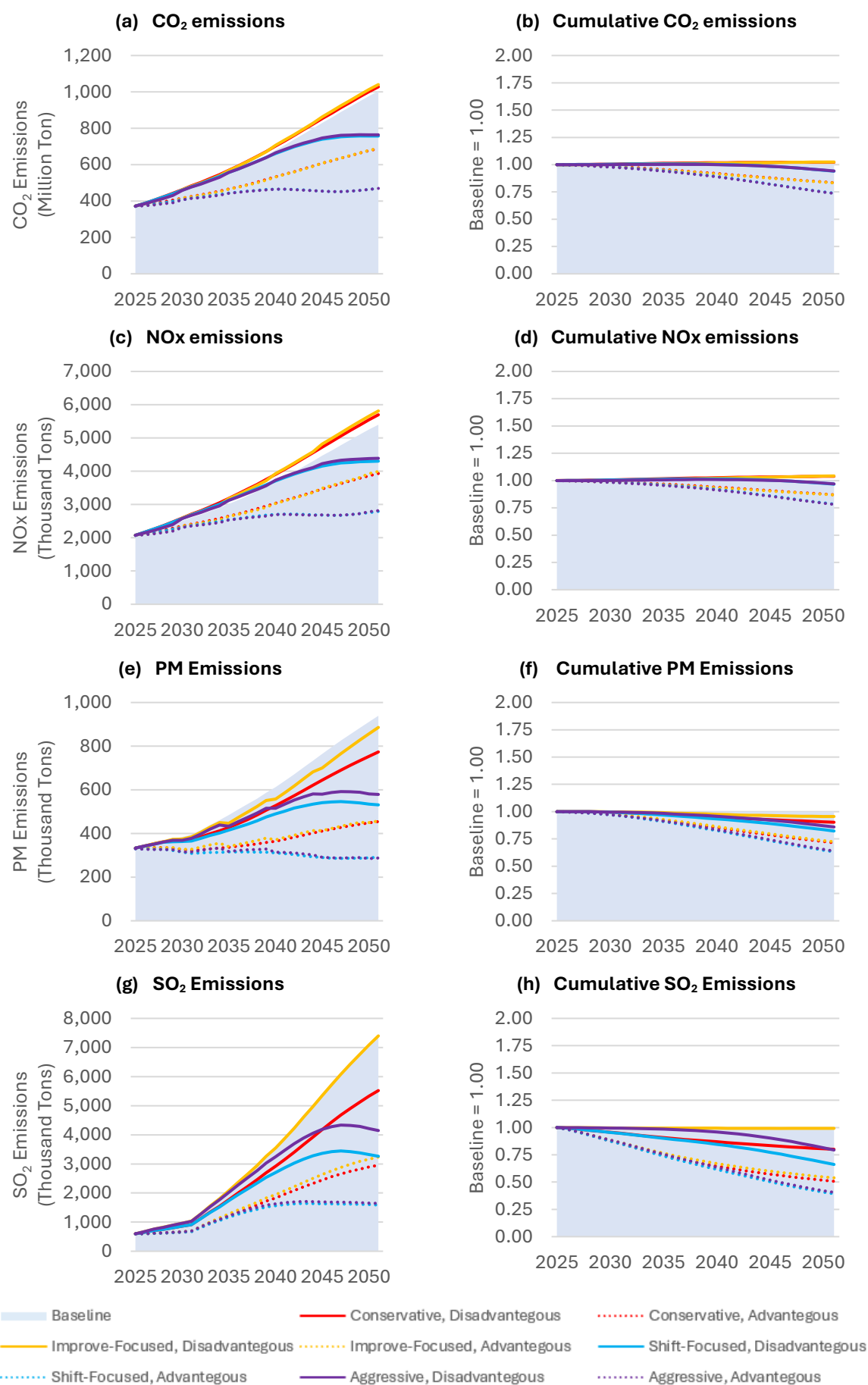


Figure 3.50. Emission result under the defined scenarios.

3.6.5. Minerals demand

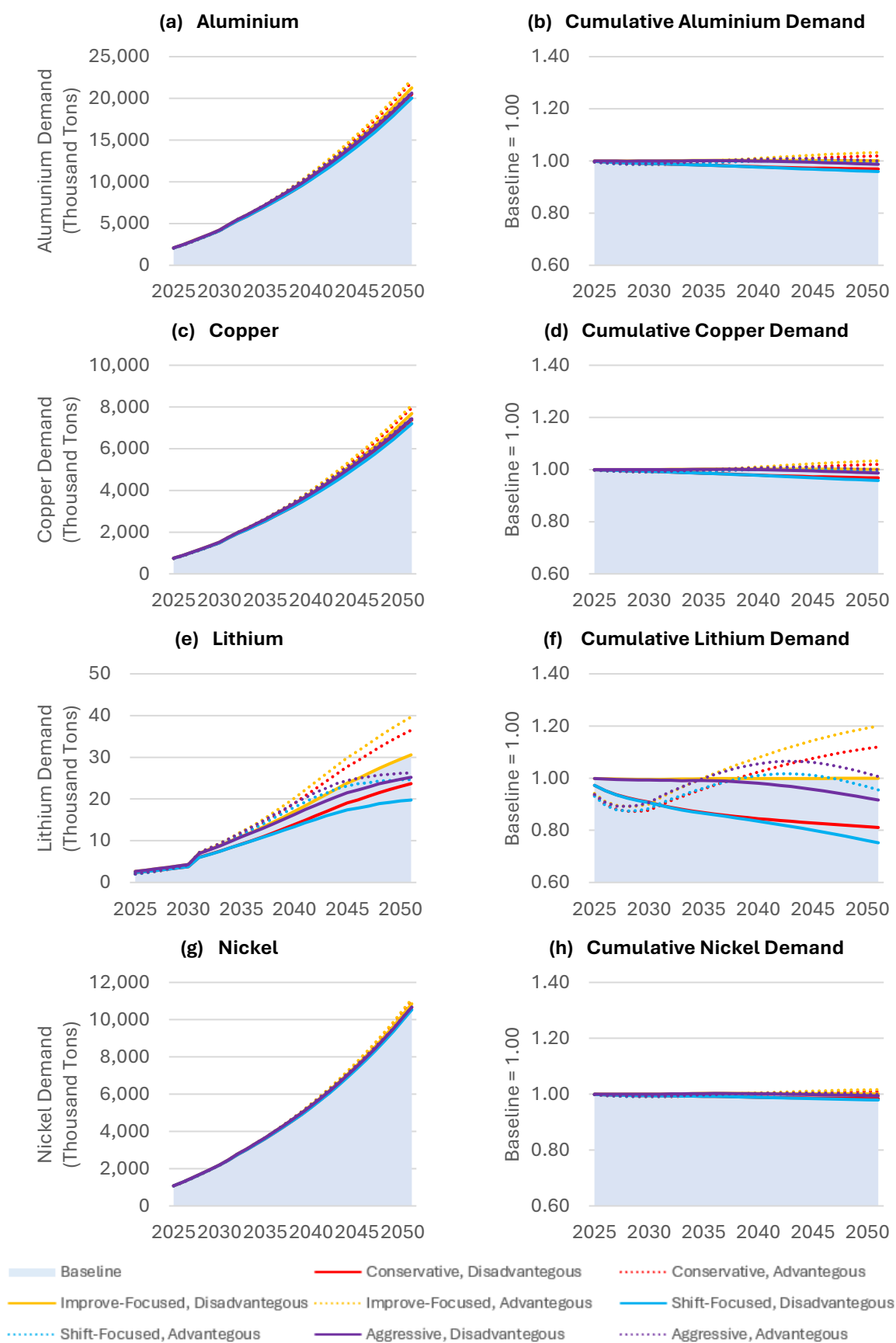


Figure 3.51. Demands of observed minerals under the defined scenarios.

As shown in Figure 3.51, mineral demands are highest whenever EV adoption is promoted but particularly lithium which is only used in EV. On the other hand, minerals demand is lowest when policies emphasized shifting to public transportation.

The demand for minerals in the C-D scenario is lower than the baseline since incentives for EVs are cut from 100% to 25%. Cumulatively, lithium demand could be 19% lower than the baseline when the share of BEV drops from 25% to 20% in 2050, while other minerals which are also used in the power sector decreased by 3%. The demand could be lowered even more if the shift to public transportation is pushed as can be seen in the S-D scenario result in Figure 3.51. On the other hand, the I-D scenario resulted in a 0.1% lower cumulative mineral demand compared to the baseline even though the incentives for EVs are kept at 100%. This slight decrease is the result of the higher supply of oil in the scenario which leads to a lower fuel price²¹⁷ and hence lower EV adoption. Under this disadvantageous situation, the mineral demand can be reduced when paired with shift to public transportation (A-D scenario).

Unlike the results in other indicators, an advantageous situation led to a higher demand for minerals as the result of higher EV adoption, specifically in the C-V and I-V scenarios where public transportation development is not the focus in the transportation policy. In the I-V scenario, the cumulative demand for minerals could be 20% higher than the baseline while in the C-V scenario it could be 12%. The effect of the push for EV under an advantageous situation can almost be negated by shifting to public transportation as shown by the A-V scenario where the cumulative mineral demand only increased 1% from the baseline.

3.6.6. Primary energy intensity

The result of primary energy intensity evolution under the defined scenarios are presented in Figure 3.52. Primary energy intensity (EI) in the transportation sector under the defined scenarios.. A similar increase in the urban transportation energy intensity can be seen under the C-D and I-D scenarios. The minor differences between the scenarios are the result of higher EV adoption in the I-D scenario compared to C-D scenario. On both scenario sets, electricity consumption increased dramatically compared to the Shift-focused or the Aggressive policies. Unfortunately, and as indicated in Section 3.6.2, the electricity grid mostly consumes coal which has a lower heat content compared to gasoline or diesel used in ICEVs or HEV. This is exacerbated by the lower efficiency of the coal-fired power plants than internal combustion engines. Even when uncertainties are favourable, the urban transportation primary energy intensity under the conservative policy and Improve-focused showed a tendency to increase after the decrease in the first half of the simulation. In contrast, urban energy intensity falls in the S-D scenario. The effectiveness of the shift to public transportation is shown how the intensity under the A-D scenario is even still higher than S-D scenario.

The primary energy intensity for domestic travel under the C-D and I-D scenario is almost equal to the baseline. Like urban transport energy intensity, the Shift-focused and the Aggressive policy sets have lower domestic energy intensity due to the less vehicle ownership. Under the S-D scenario, the public transportation share increased dramatically as demonstrated in Section 3.5.1.1, and the number vehicles went down by 20% in 2050. The lack of vehicle ownership could push travellers to use public transports for domestic travels also which resulted in a lower energy intensity.

The freight transport is the only one that showed noticeable increase in primary energy intensity. In the C-D and I-D scenario, the energy intensity to transport one ton of goods could increase

by 2% and 3%, respectively. The increase in the C-D scenario is due to the higher blending level of biofuel which increased fuel consumption, while the increase in the I-D scenario is due to the higher number of EV fleets and the power grid is less efficient. As with the domestic travel, pushing for public transportation use for urban transportation would also benefit the freight transportation since it would alleviate congestion and improve fuel efficiency.

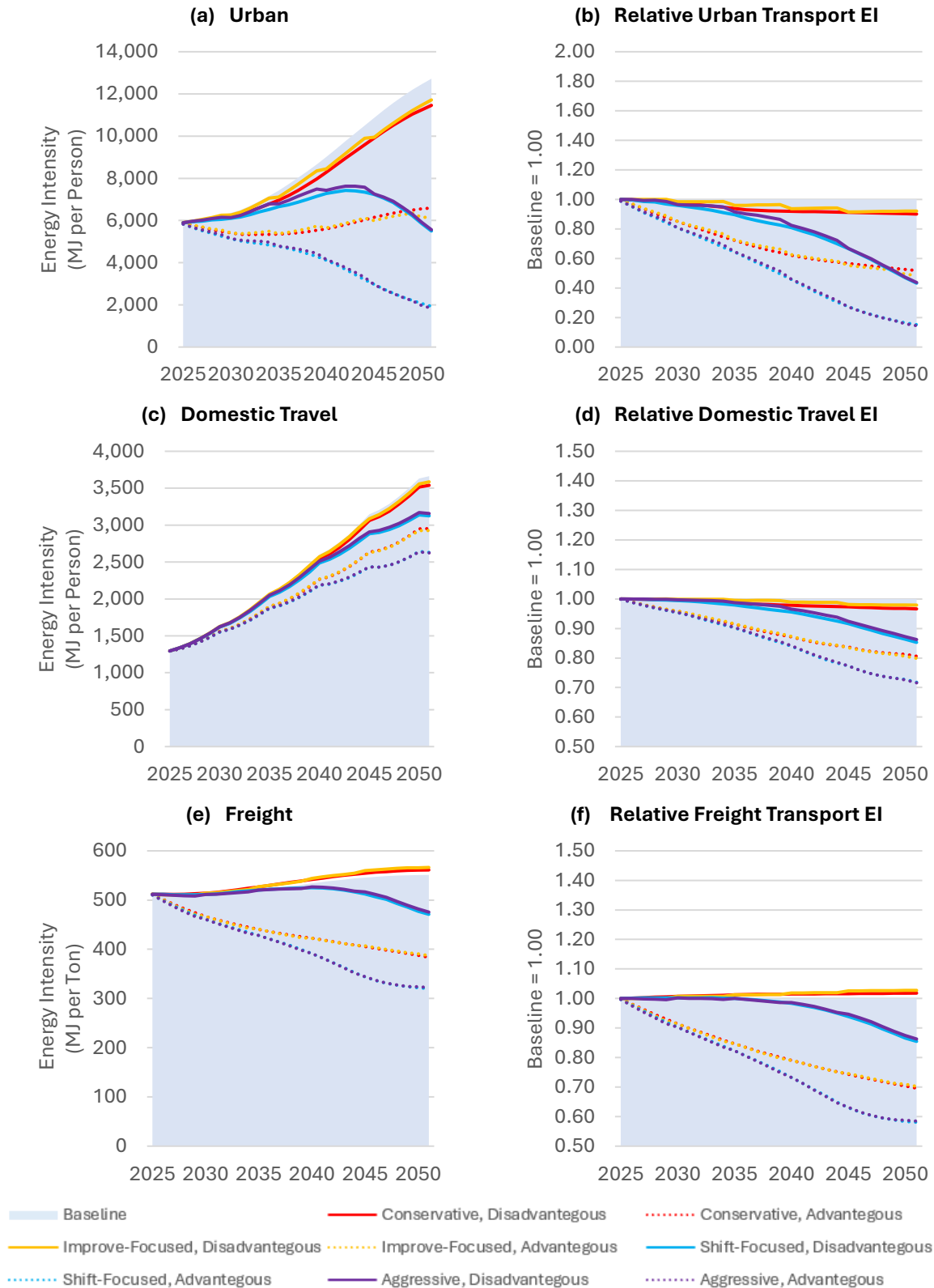


Figure 3.52. Primary energy intensity (EI) in the transportation sector under the defined scenarios.

3.6.7. Comparisons of scenarios

The scenario runs from Sections 3.6.1 through 3.6.6 is summarised in Figure 3.53 which shows the relative resources demand and environmental impacts of the policy sets used in the scenario analysis. The relative value of a policy set is the value of an indicator when the policy set is applied, divided by the maximum value between all the policy sets on that indicator including the baseline, i.e. when no policy changes is being implemented. The emissions are divided into carbon emissions which would have a nation-wide impact, and local emissions which includes NO_x, PM₁₀, and SO₂ emissions.

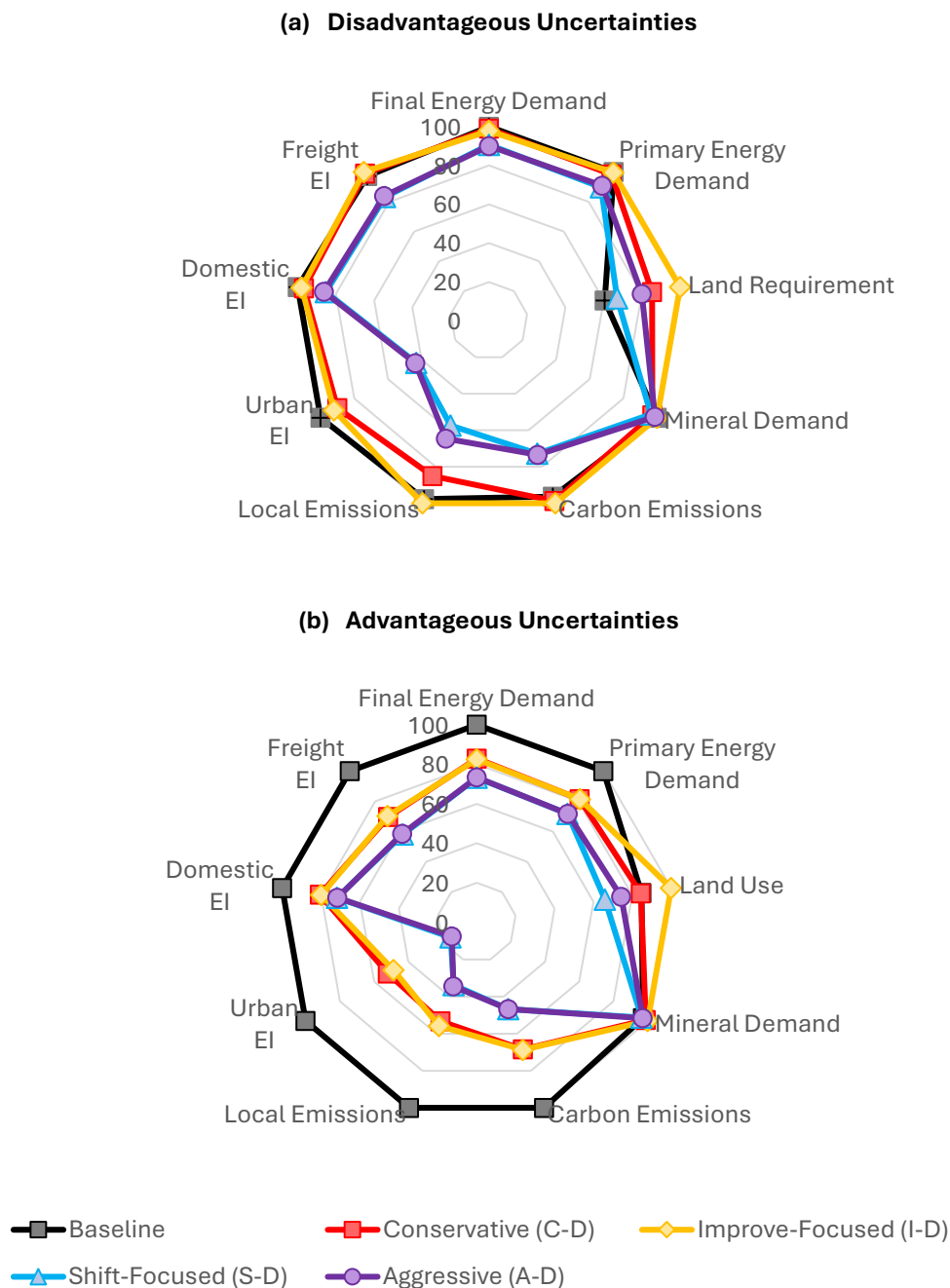


Figure 3.53. Relative resources demand and environmental impacts of the policy sets under the disadvantageous and advantageous uncertainties.

The Improve-focused policy set has a slightly lower final energy demand, mineral demand, urban transport energy intensity compared to the baseline. However, this scenario led to the

highest primary energy demand, land requirement, CO₂ emission, local emission, domestic, and freight energy intensity than the baseline if the uncertainty is unfavourable as shown in Figure 3.53(a). However, the result significantly improved when the uncertainty is advantageous as shown in Figure 3.53(b), except for land requirement and mineral demand which now is the highest among all scenarios including the baseline.

The Shift-focused policies performed better in all indicators compared to the Improve-focused policy set. Furthermore, focusing on shifting to public transportation provided the least resources demand compared to all scenarios, except for land requirement in the disadvantageous uncertainty (S-D scenario). A combination of both policies led to a superior result in terms of final energy demand in the as demonstrated by the A-D scenario and A-V scenario results in Figure 3.53(a) and Figure 3.53(b), respectively.

3.7. Economic implication of the transportation sector policy

The policies that are implemented requires a substantial amount of state expenditure. Using the same scenario set defined in Table 3.2 and Table 3.3

Table 3.3, the total cost required for fuel subsidy, EV purchase incentives and electricity subsidy, and the expansion of public transportation network are compared.

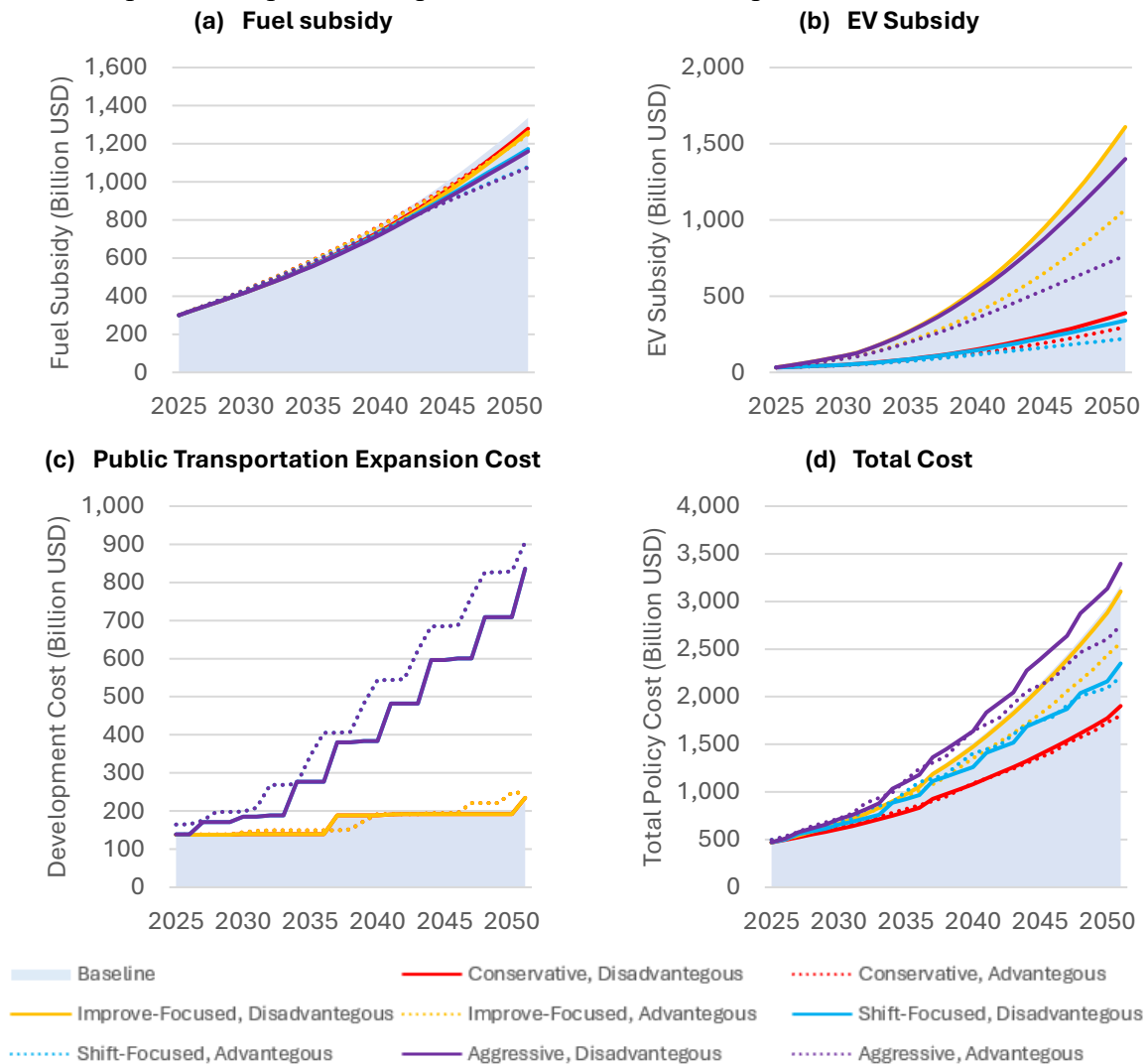


Figure 3.54. Total cost of sustainability transition in the transportation sector

Figure 3.54 shows the result of the scenario simulation, and the cumulative subsidy for EV between 2005 to 2050 may exceed the cumulative fuel subsidy on the same period. Although it is generally the case that EV incentives are commonly gradually phased out, but such policy resulted in a decelerating EV adoption²¹⁸. Hence, the incentives were applied until the end of simulation to explore the extent of its effect. The cumulative subsidy for EV may amount to 1.6 trillion USD by 2050 should the incentives are given continuously, while the fuel subsidy up to that point in time would be 1.3 billion USD. Under the I-D scenario, the cumulative incentives for EV would increase slightly but the fuel subsidy would be decreased 6%. Indeed, the high cost of the defined Improve policy would burden the state budget as will be discussed more detail in Chapter 6.

On the other hand, when policy is focused on shifting to public transportation, the fuel and EV incentives can be halved. Even when including the costs of developing the public transportation network, pushing the public transportation development would result in a substantially lower total cost with the benefits summarised in Section 3.6.7. Furthermore, when comparing the total cost and benefits of the Aggressive policy and the Shift-focused policy, Shift-focused policy is the most cost-effective policy in attaining a sustainable transportation system.

3.8. Conclusion

The transportation sector is a key subject in decarbonisation. The ASI framework aims to transform the current system into a sustainable transportation system. Being a large consumer of energy and resources, drastic changes in the transportation sector could disrupt the supply and demand balance of resources. Hence, while previous studies have discussed the social and environmental benefit of the framework, the study examines the impact of the ASI framework on resources demand as well. This study proposed the use of primary energy intensity as a sustainability indicator when assessing the ASI framework. Furthermore, since the framework involves shifts in behaviour and technology, it is fitting to apply system dynamics which can accommodate explanations of structural changes in a system.

The results from final energy demand scenario analysis show that total electricity demand in the transportation sector would grow significantly, but also the most uncertain – ranging between 5% to 12% annual increase compared to fossil fuel -1% to 3% or biofuel 3% to 6%. This leads the demand for fossil fuels to continue to increase since it would still be used as primary energy for electricity. While the demand for crude oil in the transportation sector may decrease through shifts to public transportation and improvements in fuel efficiency, the transportation is likely to be more dependent on coal and natural gas instead. Biofuel feedstocks, where CPO and sugarcane are used in this study, would also be a dominant primary energy for the transportation sector.

The increasing demand for biofuel brings to the total land requirement to support energy demand for the transportation sector. This study found the total requirement could exceed the land availability should the blending level be aimed to be higher than the current level, which may lead Indonesia to import biofuel feedstock to meet the demand. Electrifying the fleets may reduce biodiesel consumption, although it may result in an increase in electricity demand. Alternatively, fleets may instead adopt hybrid technology which could greatly improve fuel efficiency and thus reducing biodiesel consumption without increasing electricity demand. Another way is to keep the blending level but limit the supply to be allocated for certain purposes.

Emissions results showed vehicle electrification is only effective in achieving a sustainable transportation system if, and only if, paired with a clear decarbonisation effort in the power sector. From the minerals demand results, while Indonesia could utilize domestic copper and nickel potential, they would be entirely reliant on imports for lithium, rendering them vulnerable to critical mineral supply.

In light of the work's finding, the government should prioritize "Shift" strategies since these can create a structural change in resource demand and environmental impacts leading to a sustainable transportation system, unlike "Improve" strategies which could only provide reduction effects.

This work could be useful for policy makers in selecting the appropriate policy with respect to specific resources and environmental constraints. For example, countries or regions with limited land availability may want to avoid massive vehicle electrification since it could lead to the highest land requirement, while countries with enough land might not consider this to be a significant limiting factor. From the emissions results, heavily promoting BEVs, increasing renewables in the power mix, and pursuing pure biofuels would have a minor effect on CO₂ emissions growth. While the policies led to a 17% lower CO₂ compared to the base run under the advantageous uncertainty, this study estimated that the total amount of tax incentives and subsidies for BEVs alone would reach almost \$1.1 trillion dollars across the timespan. Thus, the cost may outweigh the benefit it provided.

Up to this point, this chapter has not discussed the implications of renewable energy adoption in the power sector to BEV adoption. Chapter 6 shall continue this discussion in detail, along with the scenario and uncertainty analysis.

Chapter 4

Assessments of the Energy Security Impacts of Two Energy Transition Technologies in the Residential Sector in Indonesia

4.1. Introduction

The Indonesian residential sector is the largest consumers of liquid petroleum gas (LPG) in the country¹. The LPG consumption has been increasing rapidly with a consumption of 8.2 million ton in 2022, almost double the consumption in 2012¹. This growth was driven by the cooking fuel transition from biomass, explained by the increasing number of middle-income households as described by Sovacool as climbing “energy service ladder”, where low-income households tend to use more traditional fuels²¹⁹. In parallel to the increase in LPG consumption, electricity consumption has also increased from 65 TWh to 116 TWh in the same period, making the residential sector also the largest electricity consumer in Indonesia¹.

The shift to LPG has been beneficial, primarily in terms of health since the use of biomass for cooking is attributed to increased harmful emissions including ultra fine-particulate matters²²⁰. However, it also exposed Indonesia to energy security risks since almost all the LPG is imported¹. In addition, the Government of Indonesia (GOI) subsidise these LPG to encourage this transition away, costing the government US\$ 4.9 billion in 2021¹⁹.

To improve energy security and to reduce the burden on the state budget, the GOI is pushing for the introduction of electric stoves for household use¹⁹. However, electric stoves have higher initial costs than gas stoves (among other barriers for its adoption)¹⁹. While the operating cost if electric stoves is lower than gas stoves¹⁹, the electricity tariff – which is also subsidized – has been increasing at around 6% annually in the last decade¹, making its impact on household energy expenditure uncertain. In parallel, the GOI is also pushing for the installation of rooftop solar in households with the lure of reducing electricity expenditure and selling excess electricity to the grid³³. While the adoption of rooftop solar power systems might mitigate the increase in household electricity bills as the result of electric stove adoption, rooftop solar has an even higher adoption barrier for households than electric stoves due to its high initial cost³³, which could limit its overall benefit for the sector.

Turning to the consideration of national energy security, one of the commonly used frameworks for energy security evaluation is the 4As – availability, accessibility, affordability, and acceptability – which was introduced by the Asia Pacific Energy Research Centre (APERC)^{221,222}. Cherp and Jewell further explains the importance of adding the subject (for whom) when discussing energy security²²². For example, the affordability dimension of the 4As could be interpreted differently depending on the subject of the energy security assessment. From the perspective of the government affordability could be measured by the energy import costs, while for households it could be measured as the proportion of energy expenditure proportion to household income.

There have been several studies discussing energy security at the household level. For example, Motz developed a discrete choice model to assess the willingness-to-accept (WTA) blackouts

as an impact of energy transition in Swiss households²²³. Similarly, Praktiknjo et al. discussed the outage cost for residential consumers in Germany²²⁴. Shupler et al. studied the affordability component of energy security by assessing the impact of COVID-19 on energy cost in households²²⁵. One study in India discussed the availability and affordability of clean energy fuels²²⁶, while a study in China explores the effect of smart home adoption on CO₂ emissions which is a part of the acceptability dimension²²⁷. However, these studies have not discussed the full extent of the 4As of energy security, focusing only on one or two dimensions. In addition, the adoption of electric stove and rooftop solar is driven by the dimensions of energy security, particularly affordability, and yet they feedback to energy costs through the subsidy mechanism as will be elaborated further in Section 4.2.2 – a discussion that has not been explored in previous literatures.

To this end, this research aims to investigate the adoption process of both electric stoves and rooftop solar technologies and assess its impacts on households' energy security based on the availability, accessibility, affordability, and acceptability. To achieve this, the method used must be able to model the adoption process (which is a dynamic process involving feedback within the system) is required. Thus, this study uses system dynamics to model the transition process from gas stoves to electric stoves and the adoption of rooftop solar. This chapter assess the energy security at both household and national level using indicators which are selected in Section 4.2.4.

The next section shall discuss the system dynamics model building. The result of the simulation will be disseminated in Section 4.3. A deeper discussion on energy security is presented in Section 4.4. Finally, Section 4.5 concludes the findings in this study and draw practical implications.

4.2. Model Building

The model is built using the bottom-up approach by incorporating the energy consumed by appliances used in households. The Bass diffusion model is then applied to model the adoption of two technologies discussed in this study, namely the electric stove and solar rooftop. The indicators used to assess the technology adoption as well as the model structure is also presented in this section.

4.2.1. Residential energy consumption in Indonesia

Sovacool (2011) identified five residential energy consumption purposes or services, namely cooking, lighting, space temperature conditioning, water heating, and appliances²¹⁹. Since water is commonly withdrawn individually in each household instead of a centralized supply in Indonesia, added electricity consumption for water withdrawals is added on top of water heating.

Out of the energy services, cooking consumes the largest amount of energy in Indonesia, at around 60% of the total household energy consumption¹. The two fuels used for cooking in Indonesia are biomass and liquid petroleum gas (LPG), with the latter being more dominant recently¹. The energy consumed is related to the time required to cook which in turn is subject to income level, household size, habitual and cultural factors^{19,228}. Income level was particularly found to be a strong driver for energy consumption, where houses with the highest installed electric power capacity consumes almost 4 times the LPG consumption in houses with the lowest installed electricity power capacity¹⁹.

Lighting can be considered as an essential energy service along with cooking, indicated by how it is considered as one of the highest priority energy services in low-income households²¹⁹. Lighting is provided almost 100% using electricity with only a small portion of the population still using kerosene¹. The energy consumption for lighting was found to be strongly associated with floor space²²⁹. In addition, the energy consumption is also determined by the type of room. As recommended by the Illuminating Engineering Society (IES), the lighting level may range from 30 Lumens per square meters of floor area for living rooms to 500 Lumens per square meters for kitchens²³⁰. The efficiency of lightbulbs also plays a major role in energy consumption, where there has been a significant improvement in the lighting level per watt. A halogen lamp can produce 15 lumens per watt, but an efficient LED bulb can produce more than 200 lumens per watt²³¹.

As a tropical country, air conditioning is a high priority energy service in Indonesian households. Research has found that household income and residential building floor space significantly affect energy consumption for air conditioning purposes²³². The research concludes that the direct effect of income is up to 84%, while floor space acts as a strong intermediary variable, along with the amount of equipment. Income level can be explained as the key determinant, since households with higher incomes can afford higher costs for air conditioning. It also amplifies the energy consumption since income level has a positive correlation with floor space and the number of air conditioners²³². This conclusion is supported by findings from other research, adding household size into the list of air conditioning energy consumption determinants²³³.

Unlike in many developed countries, most households in Indonesia draw their own water from the ground using water pumps despite the availability of a public piped system. By 2022, only 20% households used the public water supply services^{234,235}. Among the reasons for self-supplying water in households are reliability, convenience, safety, and the lack of trust in the quality of the public piped system²³⁶. When self-supplied water availability is declining, households tend to dig wells to deeper boreholes²³⁶. The energy consumed for water withdrawal would depend on the household's water consumption. The average water consumption per household is 144 litres per person per day as reported by the government, however more recent research found the consumption to be between 231 to 249 litres per person per day^{237,238}. The resulting electricity consumption for water withdrawal would then depend on the capacity and the power rate of the water pump. In addition to water withdrawal, electricity is also consumed to heat water for bathing, which was found to be the largest use of withdrawn water²³⁷.

The use of electronic devices was shown to have a strong relationship with income level also. As stated by Sovacool, while the use of electronic devices is perceived as non-essential in low-income households, it is considered as such by the middle-income and high-income households²¹⁹. Typical home appliance includes refrigerators, washing machine, television set, personal computers, and – more recently – mobile devices²¹⁹. While most of these devices have seen improvements in power rate, the energy demand for mobile devices could increase as their battery capacity have increased over the years²³⁹ and heavy users tend to need more battery capacity²⁴⁰.

4.2.2. Conceptual Model of technology adoptions

Energy consumption in a household is positively driven by the income level of the respective household where households with higher income requires more energy to support a higher living standard²⁴¹. In addition, income level is shown to have a positive relation to the use of

electricity in the household energy mix, since it enables households to have access to electricity, install higher power capacity, and use more electrified appliances²¹⁹. To incorporate the changes of energy-consumption behaviour, the household income-level ladder dynamics into the model is included, driven by changes in the Gross Domestic Production (GDP) per capita.

The technology adoption model is based on the Bass Diffusion Model²⁴² which has been used to study the adoption process of various technologies including electric vehicle²⁴³ and rooftop solar³³. The model illustrates how potential technology adopters' innovative and imitative behaviour in adopting a new technology. In this study, income level also serves as an enabling factor for technology adoption in households – in this case adoption of electric stove and rooftop solar – due to them having high initial costs³³, limiting the number of potential adopters.

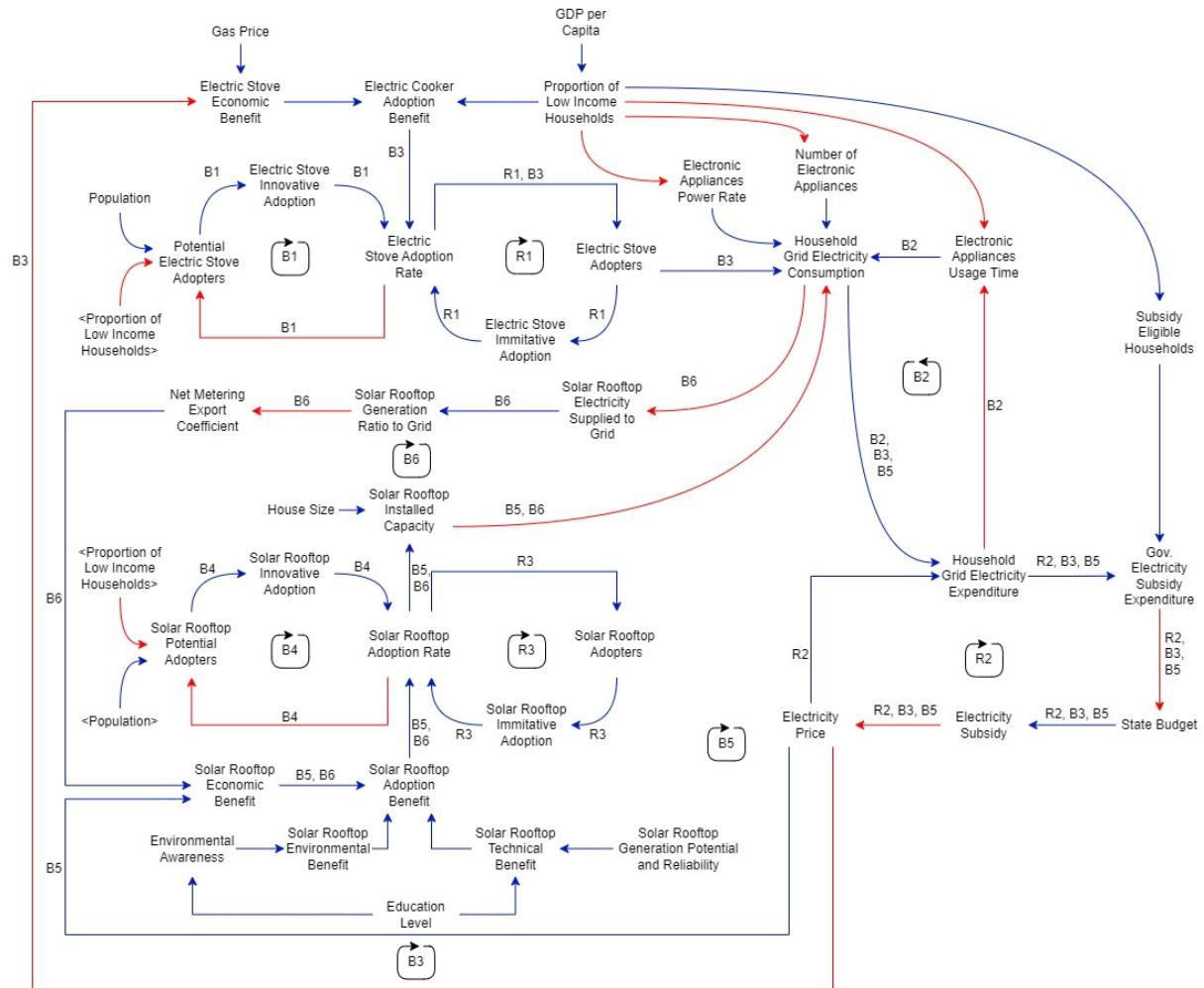
A fraction of the potential adopters would become initial adopters of the new technologies. As their number grow, they could start influencing the larger mass and initiating the imitative adoption of the new technologies as represented as the reinforcing loops R1 and R3 in Figure 4.1. These reinforcing loops would accelerate the adoption rate, increasing the number of adopters exponentially. At the same time, the adoption rate would decrease the number of potential adopters which then decelerate the adoption rate (balancing loops B1 and B4). In the end, the number of adopters would follow an s-curve. In addition to the number of potential and actual adopters, the adoption rate is also determined by the benefit of adopting the two technologies which is quantified using their respective adoption factors. The adoption factors of electric stove and rooftop solar are explained thoroughly in Section 4.2.3.1 and Section 4.2.3.2, respectively.

The adoption of both technologies would have contradicting implication for residential sector electricity consumption. The increased use of electric stoves would increase the demand for grid electricity, while increased rooftop solar installation will reduce it. In turn, this would also have an impact on the government budget since electricity is still subsidized in Indonesia. An increase in household expenditure for electricity would also increase the required subsidy, which would reduce the state budget. The restricted government budget could have an impact on the allocation for electricity subsidies which would increase electricity price and increase the household expenditure if the consumption is maintained (Reinforcing Loop R2). Indeed, the increase in electricity price would send a negative signal to electronic appliances usage which could balance the overall electricity expenditure (Balancing Loop B2).

An increase in electricity price would also feedback to the adoption benefit of both technologies. In the case of electric stoves, electricity price serves as negative feedback, reducing the economic benefit of adopting the technology, creating balancing loop B3. On the other hand, electricity price serves as positive feedback to rooftop solar adoption since it would mean a potentially higher economic savings from its installation. Nonetheless, the increased adoption of rooftop solar due to higher electricity price would reduce grid electricity consumption which would pressure for an electricity price decrease through the subsidy mechanism as shown as the balancing loop B5 in Figure 4.1.

In pushing for rooftop solar installation, the Indonesian Ministry of Energy and Mineral Resources (MEMR) issued Regulation No. 49/2018 regarding the Net Billing policy, allowing for electricity bill deductions in case of net electricity exported to the grid than consumed. In calculating the excess electricity, the exported electricity is multiplied by a coefficient factor

of 0.65, which limits the electricity deduction. The coefficient was increased to 1 through the MEMR Regulation No. 26/2021. However, this policy was ultimately lifted by MEMR Regulation No. 2/2024, eliminating the possibility to sell excess electricity to the grid. Hence the economic benefit of installing rooftop solar is now solely dependent on the avoided grid electricity consumption. Nonetheless, the Net Billing policy is still included in the model to illustrate its impact should it be reimplemented.



Note:

Blue arrows ($\rightarrow +$) indicate a positive relationship between two variables, while red arrows ($\rightarrow -$) indicate a negative relationship. Loops – a circular relationship between variables – are highlighted in blue and yellow. The two types of loop R and B refers to reinforcing loops (positive feedback) and balancing loops (negative feedback), respectively. The loops can be identified by tracing the loop names indicated on the lines connecting the variables.

Figure 4.1. Conceptual model of the energy transition dynamics in the residential sector.

When this policy is implemented, the export coefficient is dependent on the ratio of the supplied rooftop solar generation to the electricity grid to maintain grid integrity³³. If the ratio is lower than 0.05, an export coefficient of 1 is used as stated in the MEMR Regulation No. 26/2021, but the coefficient will be lowered if the ratio exceeds the threshold³³. The economic benefit of rooftop solar would increase with export coefficient which increased its adoption, in turn reducing grid electricity consumption, increasing exported electricity to the grid, ultimately reducing the export coefficient (Balancing Loop B6).

4.2.3. Adoption Factors

4.2.3.1. Adoption factors for electric cooker

Indonesian households have seen a drastic change in fuel mix for cooking purposes, from biomass to liquid LPG. Various research has studied the drivers to this change. For example, Astuti et al. revealed it was favourable for households to shift to LPG due to its competitive price as the result of subsidies and incentives²²⁰. Similarly, a systematic review studying various fuels for cooking in lower-middle income countries found economic factors as the main driver to shift to less polluting fuels. In addition, education level was found to be a supporting factor²⁴⁴. These findings are in line with the energy ladder theory which follows the notion of the rational utility-maximiser, energy choice is determined by economic rationality²⁴⁵.

There are other arguments, however, that fuel adoption is not determined only by economic aspects. Astuti et al. continued their findings by adding aesthetics, cooking time, and fuel accessibility drove the shift to LPG. On the other hand, they identified safety concerns and cooking preferences as factors to not transition to LPG²²⁰. Other research agrees with these findings. For example, a systematic review covering multiple continents puts food and taste demand as the main adoption factor, followed by design features, and ease of use²⁴⁶. A study in India, another developing country, found convenience and cleanliness in addition to cost adoption factors²⁴⁷.

While the previously mentioned study discussed the transition to gas, Al Irsyad et al. investigated the willingness to adopt electric stove in Indonesia¹⁹. They surveyed 160 respondents and found that most do not believe electric stove have significant benefit, mostly due to their cost. The respondents also perceived electric stove to perform worse than gas stoves in terms of convenience, safety, and aesthetics. In addition, the use of electric stove would also require a high installed power capacity, with the recommended capacity no lower than 2000 Watt¹⁹ – further limiting the potential adopters of the technology. The adoption factors for cooking fuel are summarized in Table 4.1.

Table 4.1. Summary of fuel transition for cooking in households

	Gas				Electric
	Astuti et al. (2019) ²²⁰	Gill-Wiehl et al. (2021) ²⁴⁶	Gould and Urpelainen (2018) ²⁴⁷	Guta et al. (2022) ²⁴⁴	Al Irsyad et al. (2022) ¹⁹
Cost	○		○	○	○
Convenience (Ease of use, cooking time, etc.)	○	○		○	○
Fuel Accessibility	○		○	○	
Safety	○	○	○	○	○
Aesthetics	○	○			○
Habitual, social, and cultural factors (taste preference, cooking practice, etc.)	○	○	○	○	

4.2.3.2. Adoption factors of rooftop solar

Shakeel et al. conducted a systematic literature review of 146 articles regarding the rooftop solar adoption factors in households in various countries. Since the study is recent, the result of the review is used as the basis of the rooftop solar adoption factors used in this research. In

conclusion, the study found that economic factors outweigh other adoption factors including environmental, technical, social, and personal factors²⁴⁸.

They found that 72% of included factors were economic which includes financing, return on investment, income level, and cost. Other factors were almost equal in their frequency of occurrence in the literature, for example environmental 33% and technical 32%²⁴⁸. They also include personal, market, demographic, and regulatory factors. However, upon close inspection these factors are more suitable as supporting factors to either economic, environmental, technical, or social factors instead of decision variables. For example, within the regulatory factors are subsidies, which would affect economic benefits of adopting rooftop solar.

Most of the studies cited conclude that income level was positively associated with the adoption of rooftop solar. The most prominent economic factor – 60% of economic factors – was found to be investment related, namely cost and return on investment. Installation cost was found to be negatively affecting adoption. While this may not be an issue for higher income households, they would still consider the investment benefit which is measured by return on investment indicators, such as payback period. This would mean that the economic benefit is largely affected by the savings compared to purchasing grid electricity.

Individuals with high awareness of environmental issue and concern for climate issues were reported to be more likely to adopt rooftop solar. However, prioritizing environmental factors is considered less in developing countries where accessibility and availability to affordable and reliable electricity is more important. Several studies confirm environmental awareness is positively related with education level which is one of the components of the personal factors.

Technical factors were also found to be frequently mentioned in previous studies. Shakeel et al. found familiarity with the technology as the most discussed barriers among the technical factors. If the technology is perceived as complex, then adoption would be low. Indeed, familiarity with the technology can alleviate this perception. Reliability was also found to be one of the main concerns when purchasing a technology in general in addition to the performance of the technology itself. In case of rooftop solar, performance is measured by the actual generation potential.

Personal factors were explained as factors that describe the individual characteristics of the potential rooftop solar adopters. This includes education and psychological factors such as innovativeness of the potential adopters – the tendency to adopt a new technology at its early introduction, i.e. becoming an early adopter – or attitude towards the technology itself. In addition to supporting environmental awareness as noted earlier, education level could also support technology familiarity which were both shown to have positive impact on rooftop solar adoption. Since the described personal factors were found to be more secondary supporting factor, they were not included among the primary determinants for adoption. Furthermore, innovativeness behaviour is automatically included in the adoption model since the adoption process uses the Bass-Diffusion model, while attitude towards the technology is determined by economic, social, and environmental factors – the primary determinants for the adoption.

The systematic literature review identified peer-effect and social pressure as social factors. These are modelled as the word-of-mouth effect in the Bass diffusion model. Other social factors that were mentioned in the review was social status and individual affinity towards environment. However, social status was described in a similar way as income level which is already accounted for in the economic drivers. Households with higher social status were found

to have higher likelihood for rooftop solar adoption – a very similar relationship with income level. On the other hand, individual affinity towards the environment is described like environmental awareness which is already represented in the environmental driver. Based on these judgments, social factors were considered as supporting factors in this research.

Hence, the adoption drivers or primary determinants for rooftop solar were narrowed down to the economic, environmental, and technical factors, and the corresponding indicators are summarized in Table 4.2.

Table 4.2. Adoption drivers and indicators for rooftop solar

Adoption drivers	Indicators
Economic	Payback Period
Environmental	Environmental issue awareness
Technical	Technology familiarity, generation potential, reliability

4.2.4. National and household level energy security indicators

As mentioned earlier, this study assesses the energy security at household and national level. The indicators used are summarised in Table 4.3. At the household level, this study adopts the indicators used by Jain in the study on energy security issues at household level in India²²⁶. Dependence on traditional energy sources and access to clean fuels were used for the availability dimension, while expenditure on energy and affordability of clean fuels were used for the affordability dimension²²⁶. The study includes the health impacts of energy use to represent the acceptability dimension²²⁶. Despite shifting to LPG from solid fuel being found to have a beneficial impact on health, it still emits harmful emissions although at a much lower rate. Moving to electric stoves could further reduce health risks from cooking²⁴⁹, where NOx emissions have been found to trigger respiratory issues¹⁰⁴. However, it is the concentration of NOx that leads to health issue instead of the emission itself¹⁰⁴. Thus, the emission is converted to concentration by incorporating ventilation factor and the kitchen space^{104,250}.

Table 4.3. Indicators of energy security used in this study

Level of Assessment	Availability	Accessibility	Affordability	Acceptability
Households	Dependence on traditional and conventional energy sources for cooking	Access to clean and zero local emission fuels for cooking	Household expenditure proportion on energy	Health impacts of energy use
National	Primary energy domestic reserves and Remaining renewables potential	Energy import ratio to total energy demand in residential sector	LPG imports ratio to GDP	Residential sector consumption CO ₂ emission

At the national level, energy availability is often measured in terms of the reserves relative to the production of primary energy (oil, natural gas, coal, hydro, etc.)²²¹. However, since production is dependent on the economic benefit of producing said primary energy, reserves relative to the demand is used instead. In the context of energy transition, this study also includes the remaining potential for renewables in the availability dimension to illustrate the physical limitations of renewable energy. Energy import dependence is also an important energy security indicator which is applied by APERC²²¹. It is particularly relevant to the topic being studied since most of the LPG is imported and costs the government a large amount in

subsidies, thus becoming a central observation for the accessibility and affordability dimensions. For the acceptability dimension, the residential sector electricity CO₂ emissions are used to capture the effect of the transition in the residential sector at national level²²⁷.

4.2.5. Simulation Model

The simulation model is divided into seven sub-models shown in Figure 4.2. The first sub-model describes the household income shift which models the movement from one income class to another, either climbing or moving down the socio-economic ladder. The number of households in each income class is paramount in determining energy consumption since income was found to have a positive correlation with energy-use behaviour¹⁹.

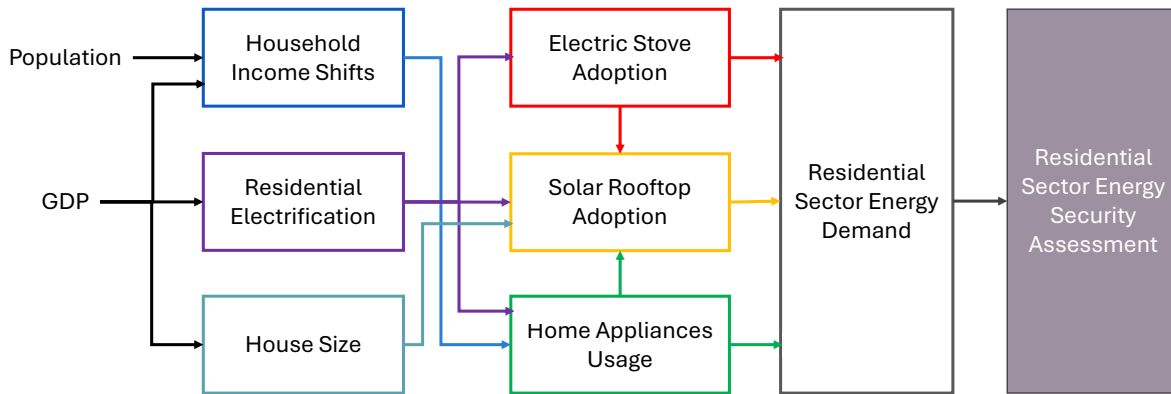


Figure 4.2. Sub-models and the relationship used in this study

In transitioning to electric stoves, households must be electrified and have enough power installed to accommodate the power consumption. Thus, the second sub-model handles the proportion of households that are electrified. Using the outputs from the first and second sub-model, the adoption of electric stoves can be simulated in the third sub-model. The proportion of electrified households also dictates the ability for households to use electronic appliances and, in turn, their electricity consumption which is described by the fourth sub-model.

The fifth sub-model describes the change in housing size which is relevant to the rooftop solar adoption sub-model which is the sixth sub-model. As elaborated in Section 4.2.3.2, the potential power generation from rooftop solar affects the benefit of its adoption, and it is proportionate to the available roof area of the houses.

The adoption of both electric stove and solar power would result in changes in energy consumption in the residential sector. The final sub-model calculates the energy consumption and the energy security indicators for the residential sector. The detailed simulation model is presented in Appendix C.

4.2.6. Model Testing

The model testing method is the same as in Chapter 3, namely MAPE and Theil's statistics. Due to data limitations, only the final energy consumption can be tested here. The model testing result for traditional biomass, LPG, and electricity are shown in Figure 4.3. The R² for the three final energies are 0.99, 0.99, and 0.96, while the MAPE are 0.04, 0.05, and 0.04, respectively. The Theil's inequality statistics for the variable validations shows the errors are not systematic since the contribution of bias errors are small, at 0.01, 0.19, and 0.00, respectively.

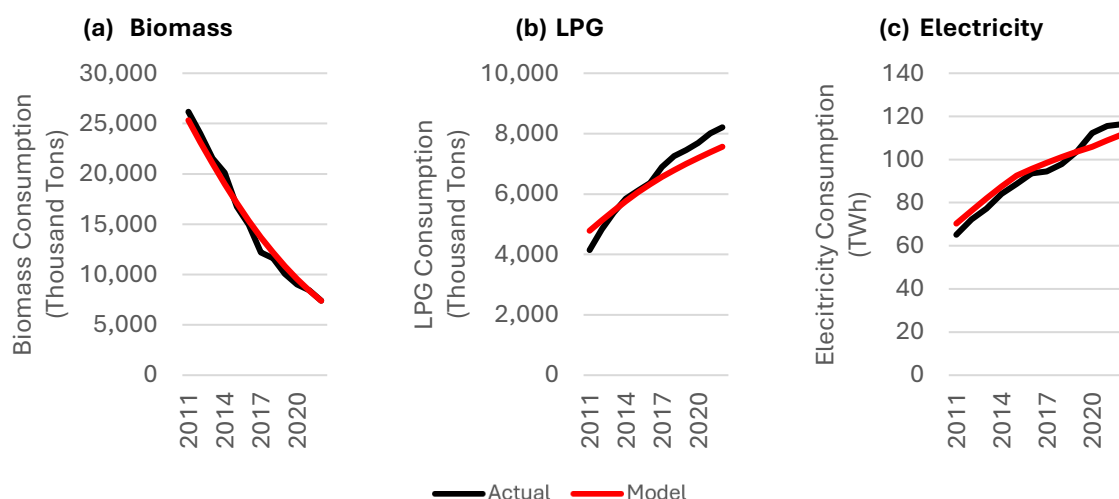


Figure 4.3. Validation of (a) biomass, (b) LPG, and (c) electricity consumption of residential sector.

4.3. Results

4.3.1. Household income shifts

The World Bank classifies households based on their daily expenditure into poor, vulnerable, aspiring middle-income, middle-income, and high-income households²⁵¹. However, poor and vulnerable is replaced with low-income according to the classification by the Indonesian Bureau of Statistics²⁵². Following economic growth, the number of low-income households would naturally decrease, while middle-income and high-income households would increase. The number of aspiring middle-income households would increase up to a certain point but then they would climb the socioeconomic ladder becoming middle-income households. The elasticity of change in GDP per capita to the respective number of households is based on the economic mobility data and GDP from the World Bank^{251,253}. The evolution of the number of households by income group is shown in Figure 4.4.

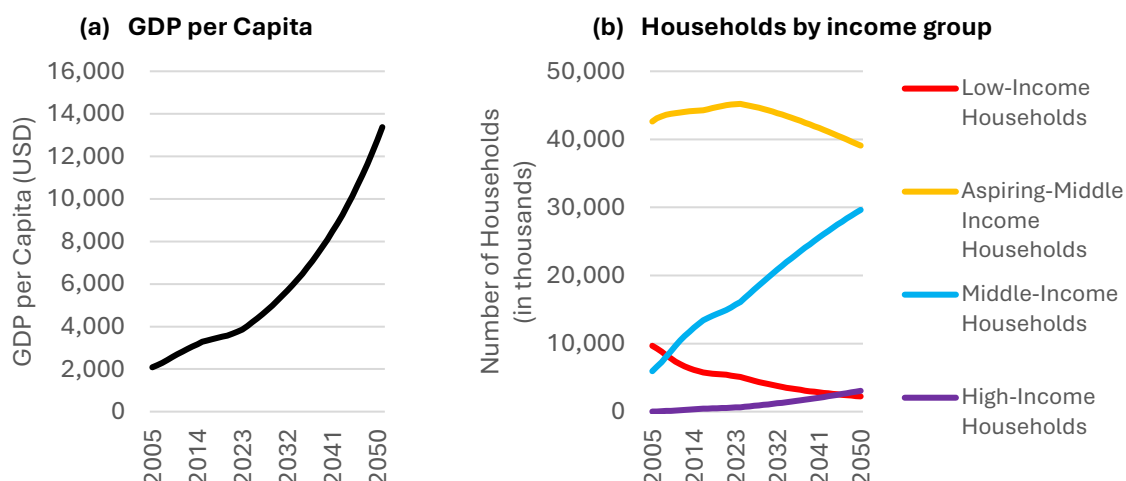


Figure 4.4. GDP per Capita and the number of households by income group.

4.3.2. Electrified residences

The electrification ratio in Indonesia has been increasing rapidly from 45% in 2005 to almost 100% in 2022¹. The electrification ratio is expected to continue to increase with economic growth as shown in Figure 4.5(a). However, the electrification is not distributed equally across all household income groups where energy poverty is most prevalent in low-income households²⁵⁴. The electricity access is assumed to be first enjoyed by higher-income

households, hence aspiring-middle-income households would benefit the most from the increase in the electrification ratio as shown in Figure 4.5(b).

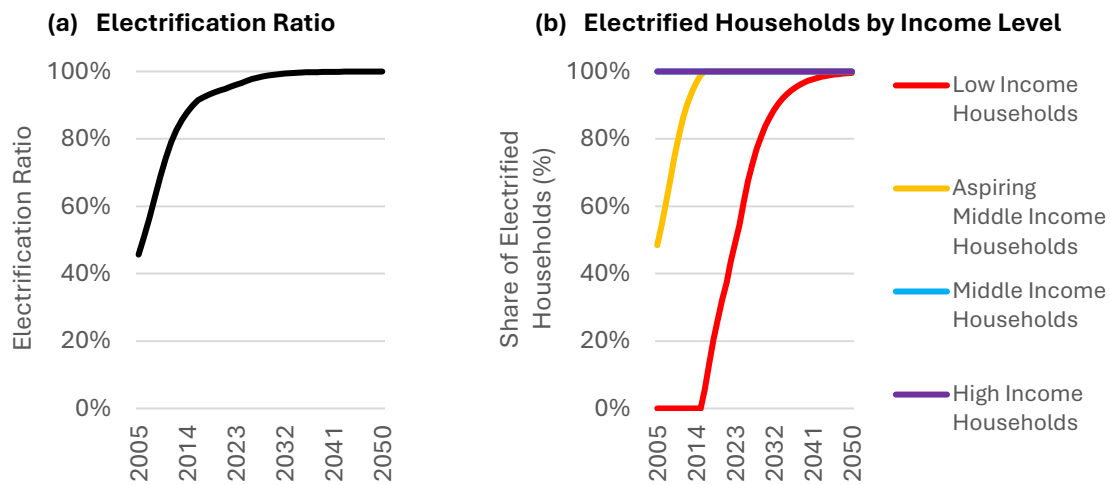


Figure 4.5. Progression of electrification ratio and the resulting electrified households.

4.3.3. Housing sizes

House prices have been increasing in the last two decades²⁵⁵, and the price is highly correlated with GDP (Figure 4.6). The Bank of Indonesia classifies property into small, medium, and large²⁵⁵. The correlation with GDP²⁵³ for each category is 0.972, 0.964, and 0.968.

Research found that property price negatively affects building size both from the supply-side and demand-side. An increase in property value may push developers to build smaller but more plentiful properties²⁵⁶. On the other hand, consumers would need to settle for smaller houses which are affordable, and lower-income households are affected the most²⁵⁷. Since affordability is a central factor in purchasing a certain house, the changes in property price should be compared to changes in household income.

Based on previous research^{256,257}, this study negatively relates the increase in property price to small, medium, and large houses differently – affecting small houses more prominently than the larger ones. However, a minimum floor space per person for decent living is added which was found to be around 28 m² to 52m² for a household of 4 person²⁵⁸, hence limiting the reduction of building size due to price increase. The resulting changes in house size is shown in Figure 4.7 where large houses could reduce in size around 13% from 2005 to 2050, while medium and small houses sizes could reduce around 37% and 55%, respectively.

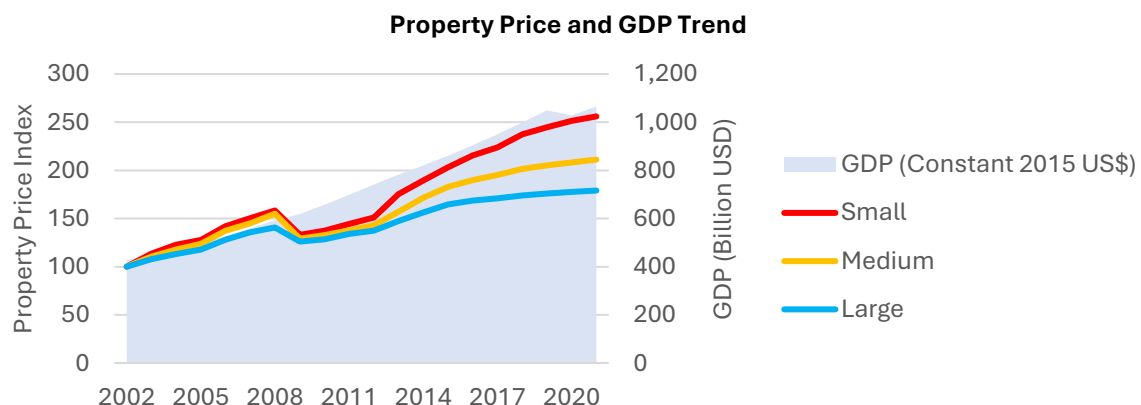


Figure 4.6. Correlation between Property price and GDP.

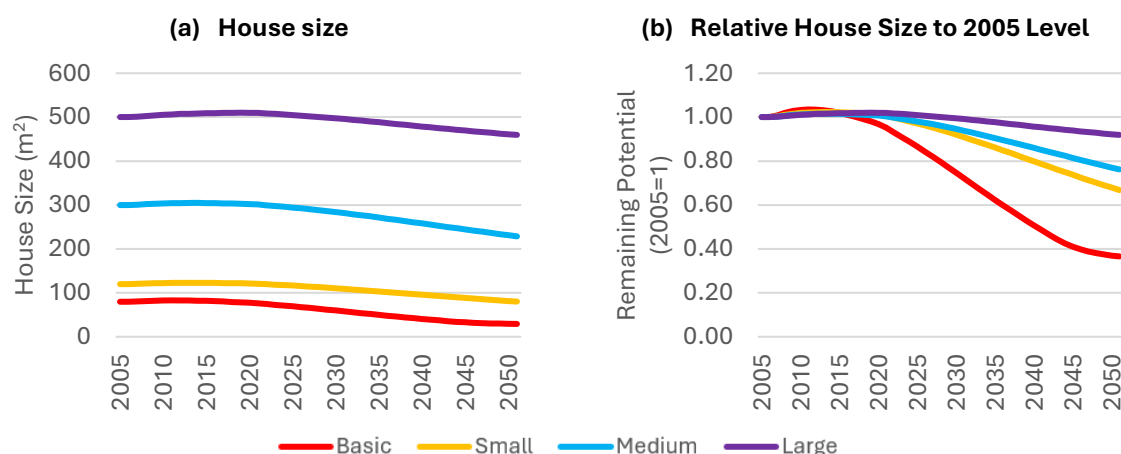


Figure 4.7. Average house size by size-class and the relative size compared to 2005 level.

In addition to the changes in house sizes, it is assumed that households do not move into a smaller house (e.g. from medium to basic-size property) despite negative changes in their household income. Only new households or those who have climbed the socio-economic ladder will occupy houses with the economy-adjusted size; hence the aggregate size of a property class does not change immediately with the changes in property-class size. The resulting aggregate house size in each household group are shown in Figure 4.8, where middle and high-income household house size decreased the most. On the other hand, low-income households house size increased due to some of the previously aspiring middle-income households – who initially lived in larger properties – becoming low-income households but not moving to smaller houses.

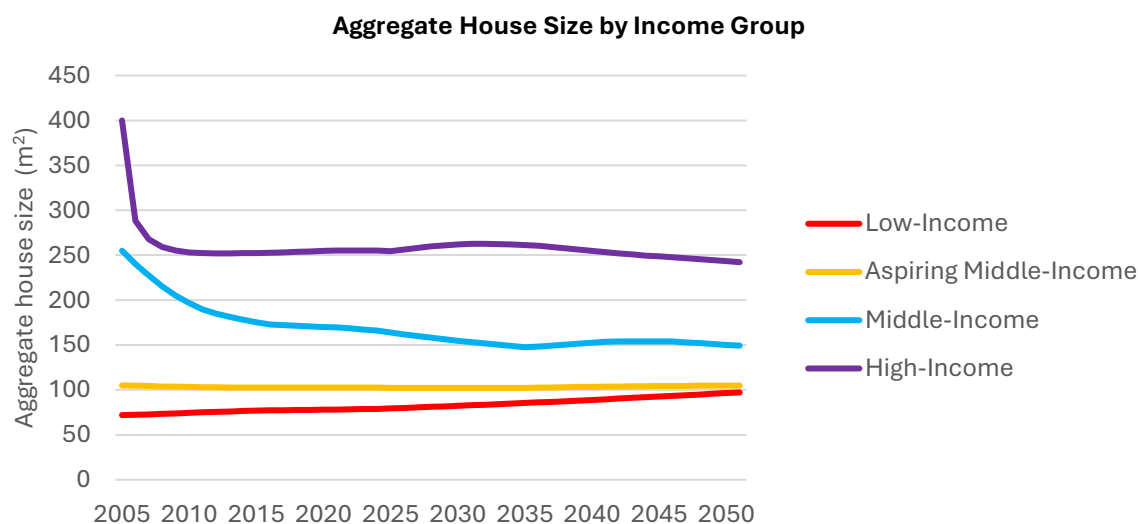


Figure 4.8. Aggregate house size in each household group.

4.3.4. Electric stove adoption

Using the Bass diffusion model, the transition to electric stoves would follow an s-shaped curve²⁴². As illustrated in Figure 4.1 and explained in Section 4.2, innovative adoption of electric stoves would initiate a reinforcing word-of-mouth effect which accelerates the adoption rate, but the adoption rate would slow down following the decrease in potential adopters. However, the transition to electric stoves does not happen directly.

Biomass was still the dominant fuel for cooking more than a decade ago¹. Based on the energy service ladder, biomass is used in the lower income households²¹⁹ in this case the low-income and aspiring middle-income households. Thus, these households would mainly transition to gas stoves first before moving to electric stove although there are also a portion of them directly adopting them as shown in Figure 4.9(a) and Figure 4.9(b). However, middle-income and high-income households who have fully adopted gas stoves will move to electric stoves directly, hence the proportion of households using electric stoves is higher in these households as depicted in Figure 4.9(c) and Figure 4.9(d).

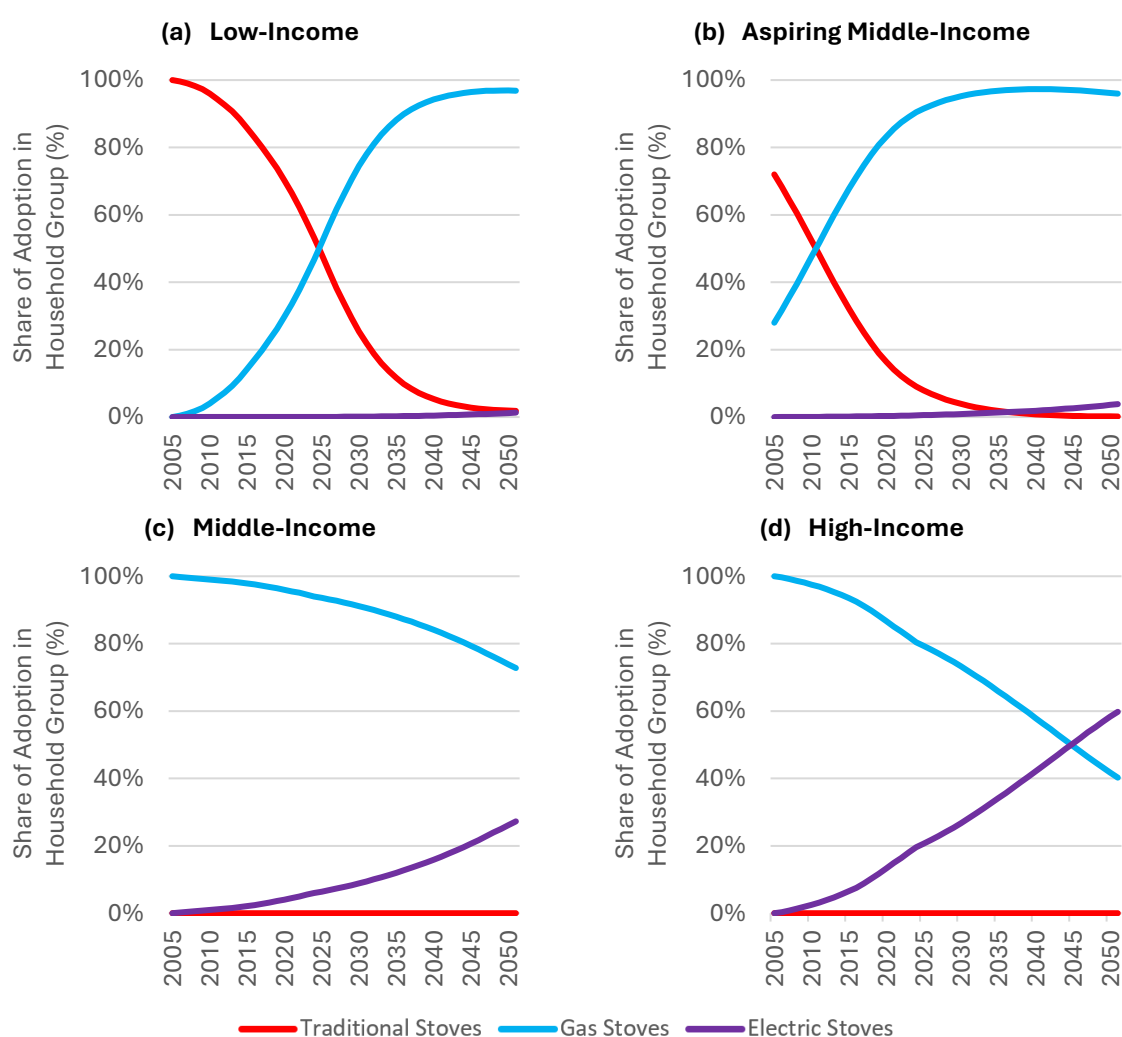


Figure 4.9. Stove transition in each household income group.

Electric stove adoption is most prevalent in high-income households as the result of high convenience and aesthetic benefits relative to gas stoves, for this income group¹⁹. By 2050, the share of electric stove in each of the household income groups are 0.1%, 0.4%, 7%, and 49%. While they have a higher purchasing power, they do not put much weight on economic benefits¹⁹. Middle income households also put more emphasis on convenience benefits, but they are also concerned about economic and safety benefit of electric stoves. Since electric stoves have a higher initial cost, the adoption benefit of electric stoves in middle-income households is lower than high-income households.

Despite the high adoption in high-income households, the overall electric stove adoption remains low since they comprise a very small proportion of the total households as shown in

Figure 4.4(b). Overall, the share of electric stoves in 2050 is around 16% or 11.7 million units. Nonetheless, electric stoves start to reduce the share of gas stoves due to the increase in the number of middle-income households and the accelerating adoption in this income group. The comparison between the traditional, gas, and electric stoves is shown in Figure 4.10.

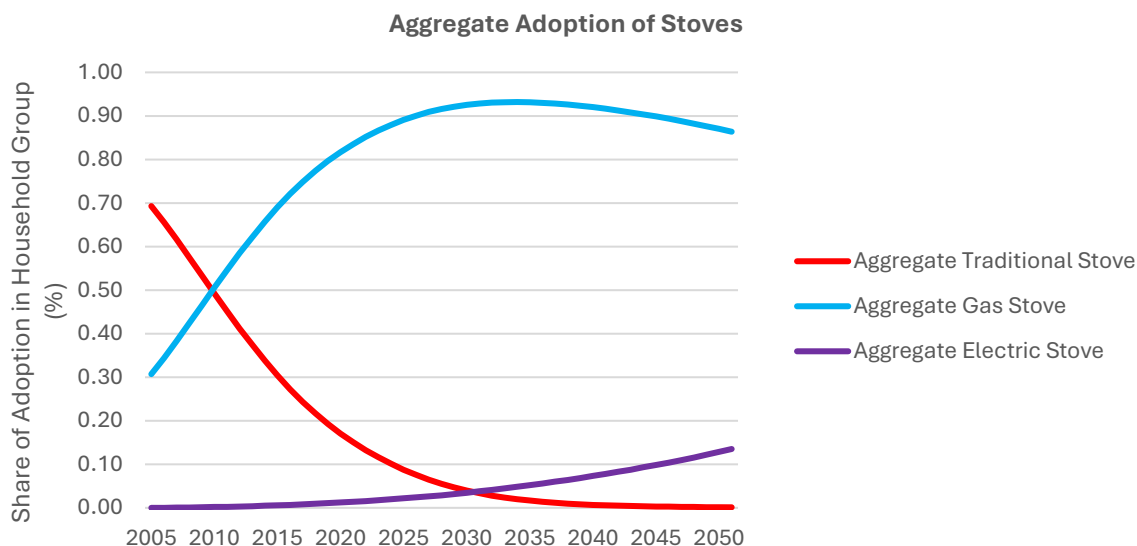


Figure 4.10. Stove transition in all households.

4.3.5. Household home appliances electricity consumption

As elaborated in Section 4.2.1, household energy consumption is positively related to household income level. Figure 4.11 depicts how the electricity consumption for home appliances increases with the increase in number of middle-income and high-income households. More than half of the household electricity consumption is from middle-income households, who are both large in number as shown in Figure 4.4 and have a high energy consumption intensity¹⁹.

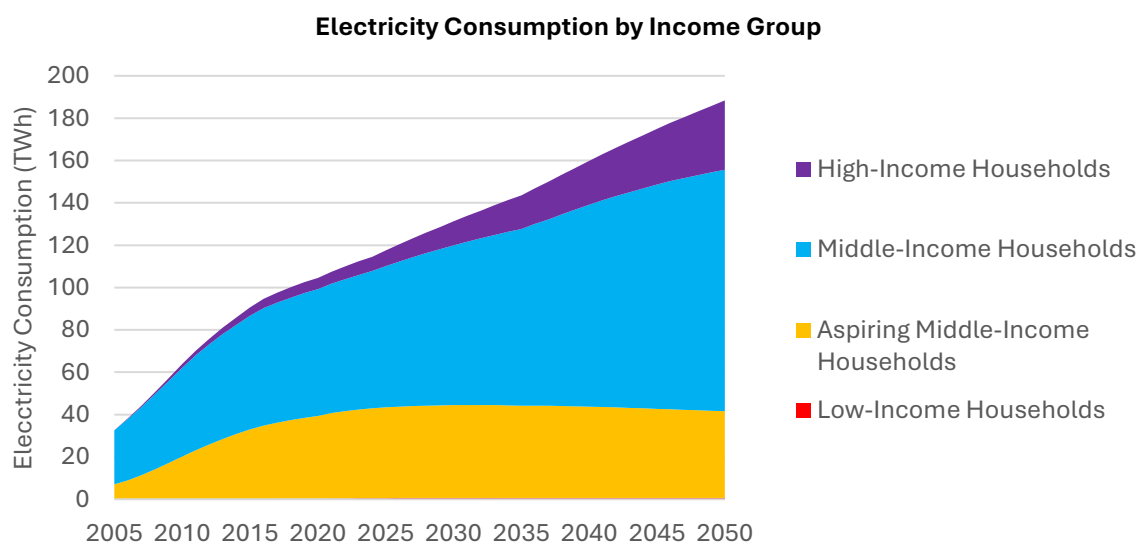


Figure 4.11. Home appliances electricity consumption by household income group.

Breaking down per device, most of the electricity consumption is for air conditioning which not only has a high power-rate but also a high usage rate since Indonesia has a relatively high

temperature all year around. The total electricity consumption in 2050 could reach 191 TWh, growing 2% per year from the current level. Electricity for electric stoves would be the third largest although its proportion would only be around 12% if the adoption path follows the results in Figure 4.10.

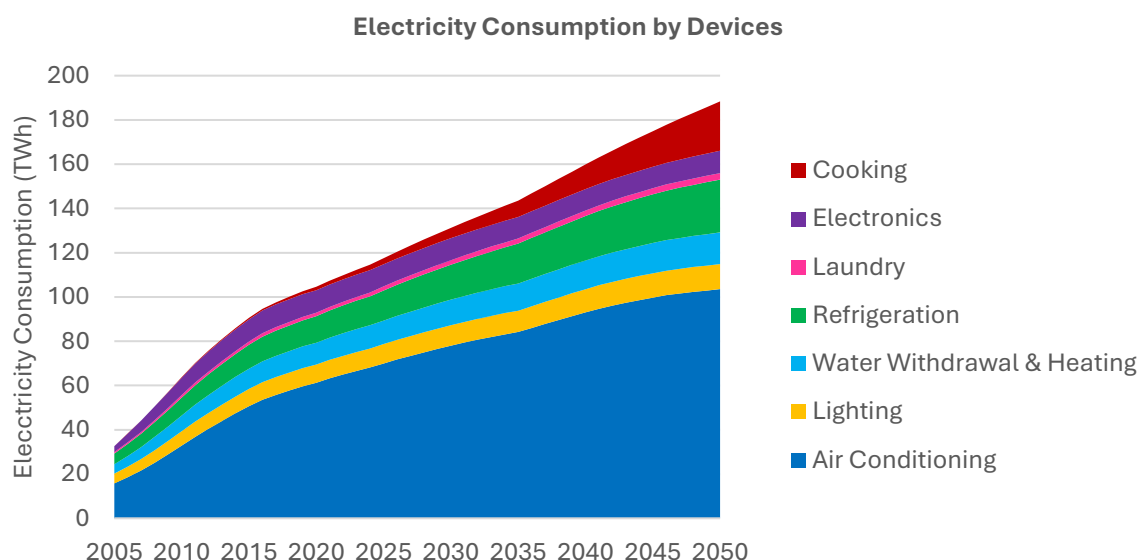


Figure 4.12. Home appliance total residential electricity consumption by devices.

4.3.6. Rooftop solar adoption

Like the adoption of electric stoves, the adoption of rooftop solar would also follow an s-curve. The total adopters are around 14 million households by 2050 (Figure 4.13), or about 19% of the total households (Figure 4.14). While most of the adopters are aspiring middle-income and middle-income households as shown in Figure 4.15(a), looking at the adoption share in each household in Figure 4.14, high-income households have the highest tendency to adopt rooftop solar. Because of the different house size in each income group, the power generation capacity would also be different as depicted in Figure 4.15(b). Although 70% of the rooftop solar adopters are from the aspiring middle-income group, the electricity they generate is 35% of the total rooftop solar power generation capacity. On the other hand, while high-income household adopters are only 0.6%, they would generate 2.7% of the total generation capacity.

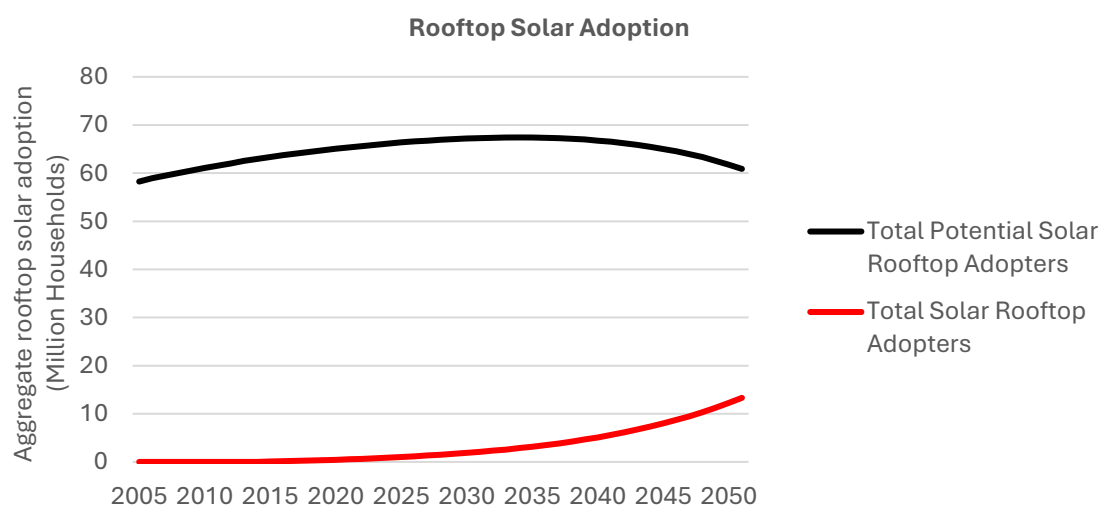


Figure 4.13. Aggregate rooftop solar adoption.

The amount of electricity produced from all rooftop solar in households could reach 1.8 TWh by 2050, accounting for solar panel efficiency and performance ratio³³. While the production is far less than the total electricity consumption in the residential sector around 234 TWh as shown in Figure 4.12, this does not mean there would be no electricity exported to the grid. Looking at individual households, high-income households turn out to have less sufficient solar power generation compared to the demand. On the other hand, aspiring middle-income households could have excess in rooftop solar power generation since they have significantly less electricity demand compared to high-income households.

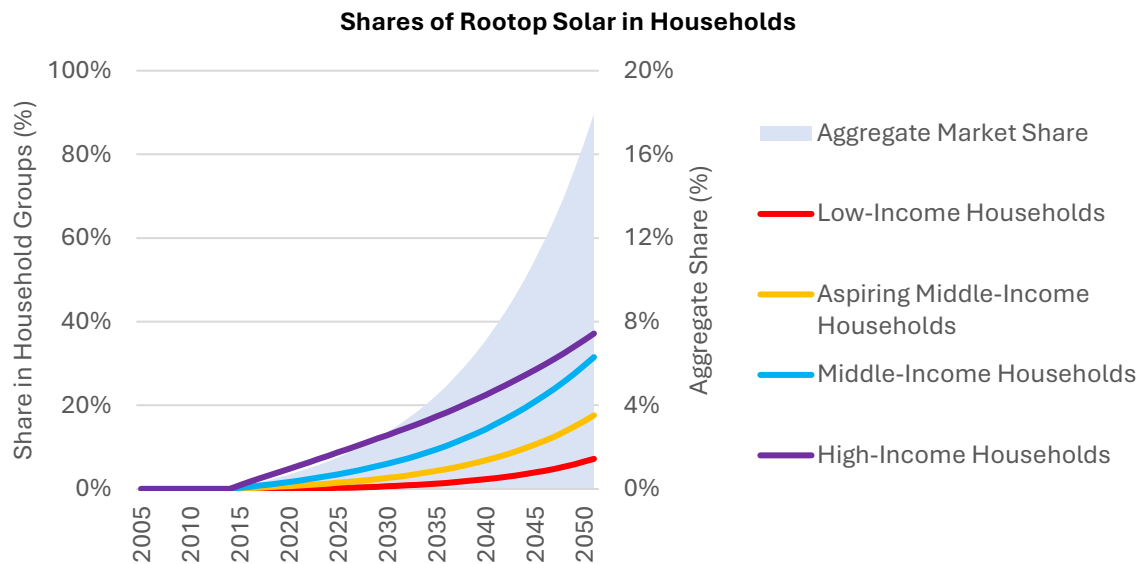


Figure 4.14. Aggregate rooftop solar market share and in each household income group.

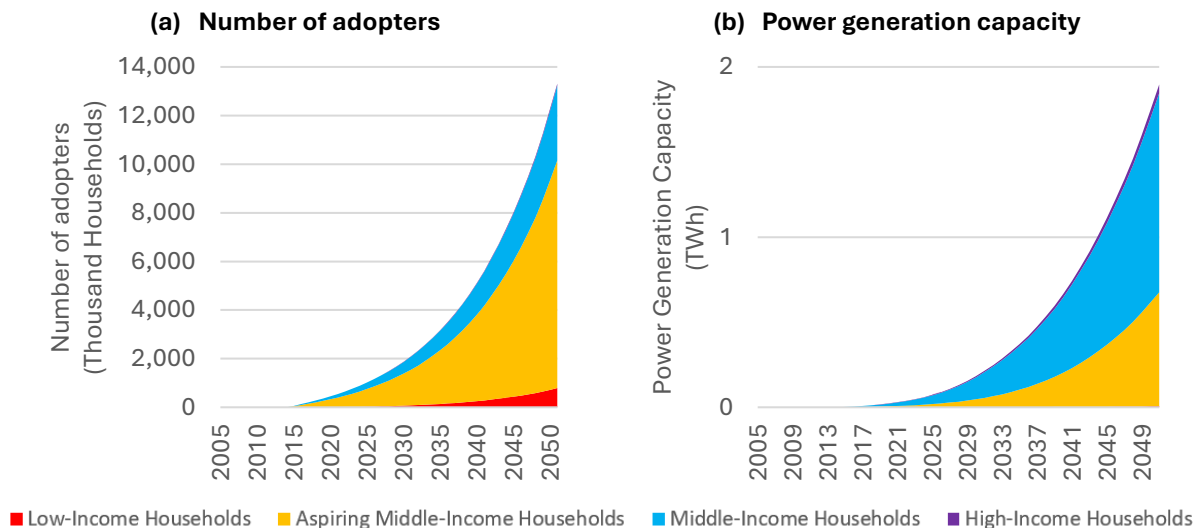


Figure 4.15. Adoption of rooftop solar and generation capacity in each household income group.

At the individual household level shown in Figure 4.16, all households started with an insufficient electricity generation from rooftop solar. However, as the cost of rooftop solar decreases, households can install larger capacity systems, which explains the increasing rooftop solar generation. On the other hand, electricity demand tends to decrease following the decrease in house sizes as illustrated in Figure 4.7. While the decrease in house size also affects the potential area to be used for rooftop solar, the decreasing rate of rooftop solar cost is faster,

leading to an overall increase in generation capacity. Among all household income groups, middle-income households have the highest level of rooftop solar generation aggregate sufficiency (1.7%) due to their much lower electricity demand but ample house size. Nonetheless, this sufficiency is only slightly different with the aspiring middle-income (1.2%) or high-income households (1%). On the other hand, low-income households have the lowest sufficiency at 0.6%.

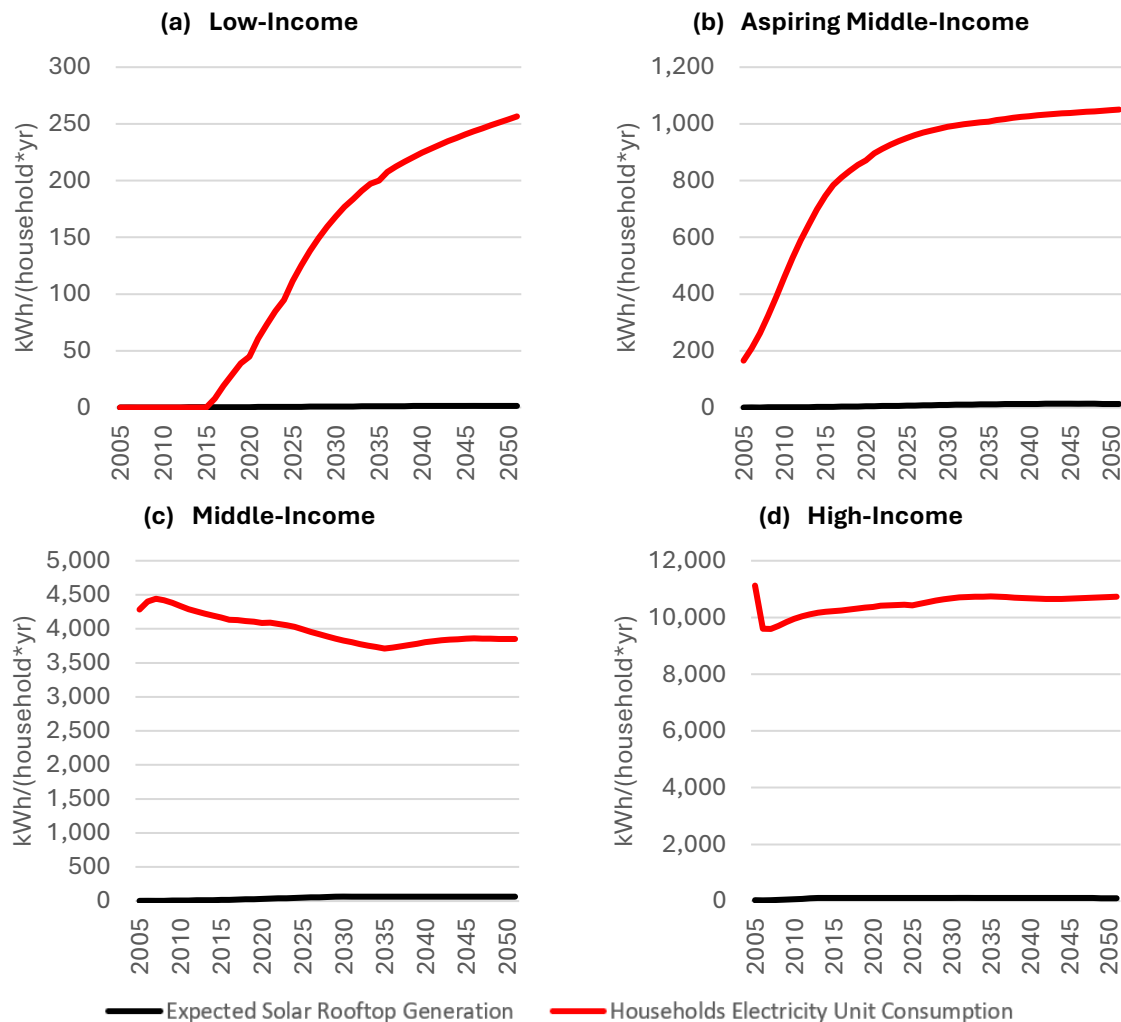


Figure 4.16. Sufficiency of rooftop solar generation in each household income group.

4.3.7. Residential sector energy security assessment

The effect of technology adoption and climbing the energy service ladder in the residential sector on household energy security can be seen in Figure 4.17 through Figure 4.20. From the perspective of energy availability, households' dependence on traditional fuel declined significantly over the years with low-income households be the last to shift away from it (Figure 4.17 (a)). However, when the shift from LPG as well, only high-income households can enjoy the transition (Figure 4.17(b)) and the consequences of electric stove adoption discussed in Section 4.3.4. Since they form only a small fraction in the population, 84% of the households are still reliant on fossil fuels. Hence, the overall dependence on non-fossil fuel availability only improved 5%.

Similarly, the low-income households are the slowest to have accessibility to clean fuels as shown in Figure 4.18(a), while high-income household are the fastest to have access to zero

local emission energy as in Figure 4.18(b). In aggregate, energy accessibility improved very little, indicating an inequitable transition in the residential sector where only around 6% of the population have access to zero local emission energy. The inequity is also visible in terms of energy affordability and acceptability at the household level. In general, the proportion of energy expenditure in household income increases, mainly due to the rising price of LPG following the price of oil and gas as projected by the EIA²¹⁷. The shift to electric stoves helped with affordability since operation costs are slightly lower than gas stoves. However, the aspiring middle-income group suffers from the highest increase in energy expenditure as depicted in Figure 4.19. The reason for this is, firstly the transition away from traditional fuel. Secondly, unlike the middle and high-income households who have a higher rooftop solar penetration as discussed in Section 4.3.6, aspiring middle-income households have minimum aggregate electricity cost savings. As the result of the inequity, the aggregate energy expenditure could increase around 30% from 11% in the present day to 15% of household income by 2050 which is particularly burdensome for lower income households.

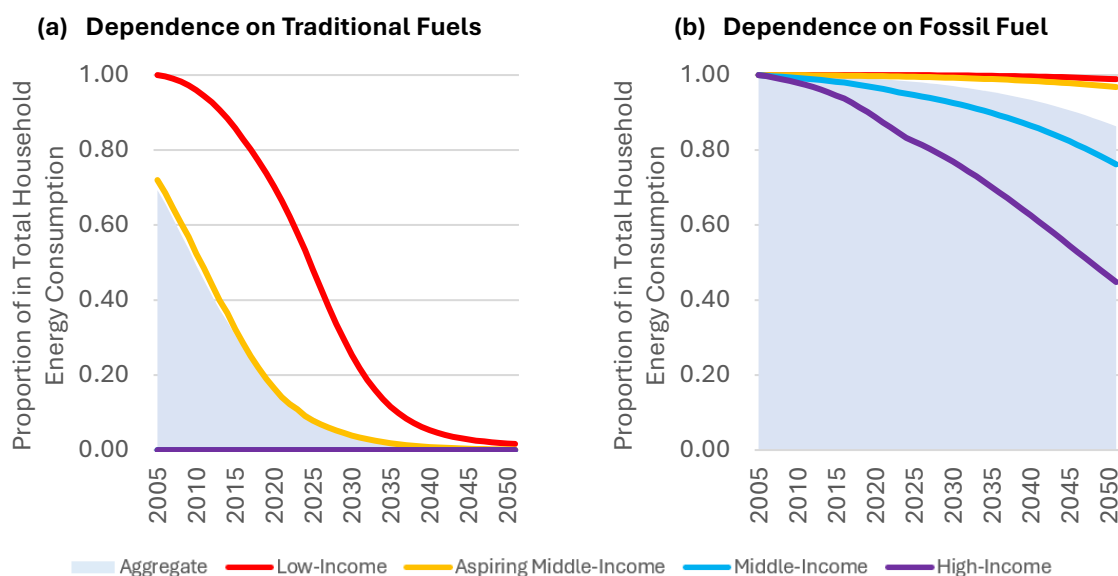


Figure 4.17. Household Energy Availability.

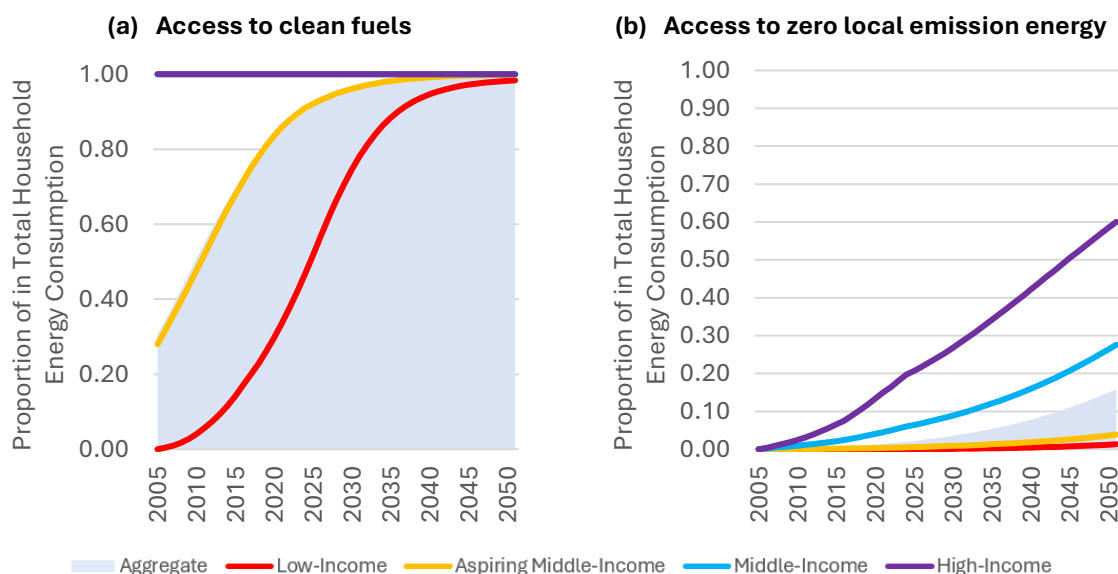


Figure 4.18. Household Energy Accessibility.

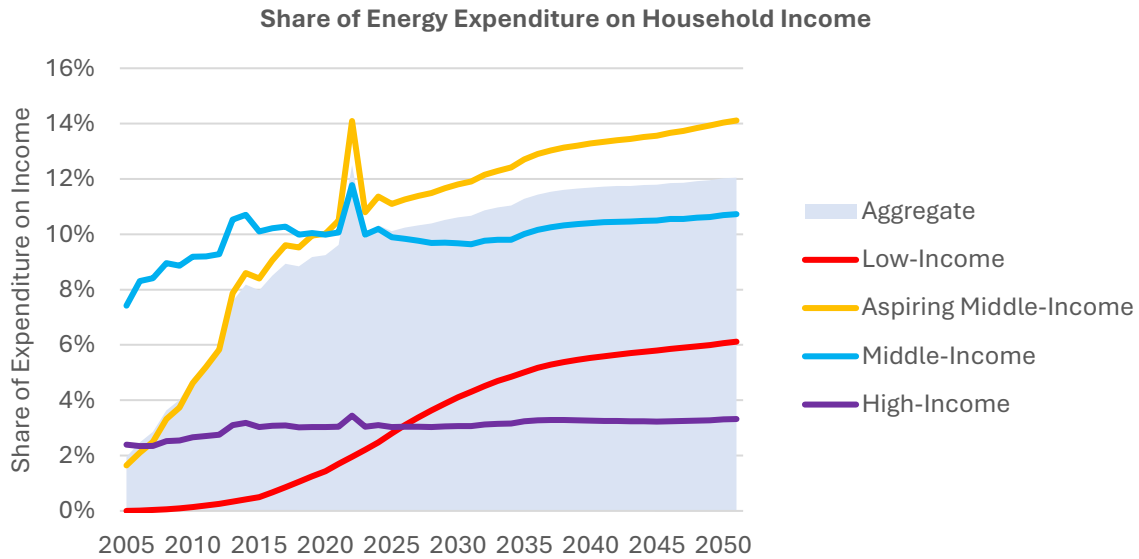


Figure 4.19. Household Energy Affordability.

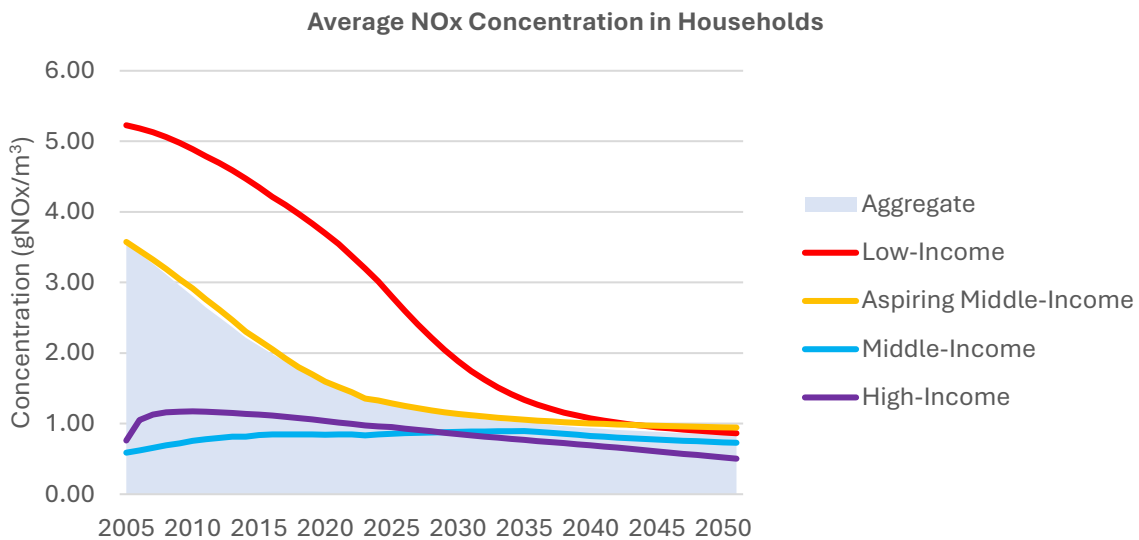


Figure 4.20. Household Energy Acceptability.

In terms of acceptability, despite middle-income households having high accessibility to clean fuel, they could suffer from the decreasing size of the houses based on the output in Figure 4.7 which negatively affects the NOx emissions. In addition, middle-income households tend to have higher demand to cook¹⁹ which could further increase the NOx concentration in the house. As shown in Figure 4.20, NOx concentration in the middle-income households increased steadily from to around 0.6 grams of NOx per m³ and reached its peak at 0.9 grams of NOx per m³. The adoption of electric stove slightly reduced the to around 0.7 grams of NOx per m³ by the end of the simulation. The benefit of shifting to electric stoves is seen greatly in high-income households despite them experiencing a decrease in house size (and therefore volume into which NOx would be emitted).

From the perspective of national energy security, the transition in the residential sector provided relatively positive results. In terms of energy availability, Figure 4.21(b) and Figure 4.21(d) shows that indeed all resources are depleting. However, this cannot be completely attributed to the residential sector alone since the same resources are also used in the transportation,

industrial, and commercial sectors. Nonetheless, the effect of the residential sector on energy availability can be best observed by the coal and renewable resources since they are dominantly used to generate electricity. Due to the high share of coal power generation, the coal reserves continue to be extracted, and the R/P eventually reaches around 2 years by the end of the simulation. As for renewables, while their share in power generation is small – only 12%, the remaining potential will have already halved in 2050, indicating the limitation of renewables potential. A particularly low availability is seen for bioenergy where more than 90% of its potential will have been used although its share in the power mix is only 7%.

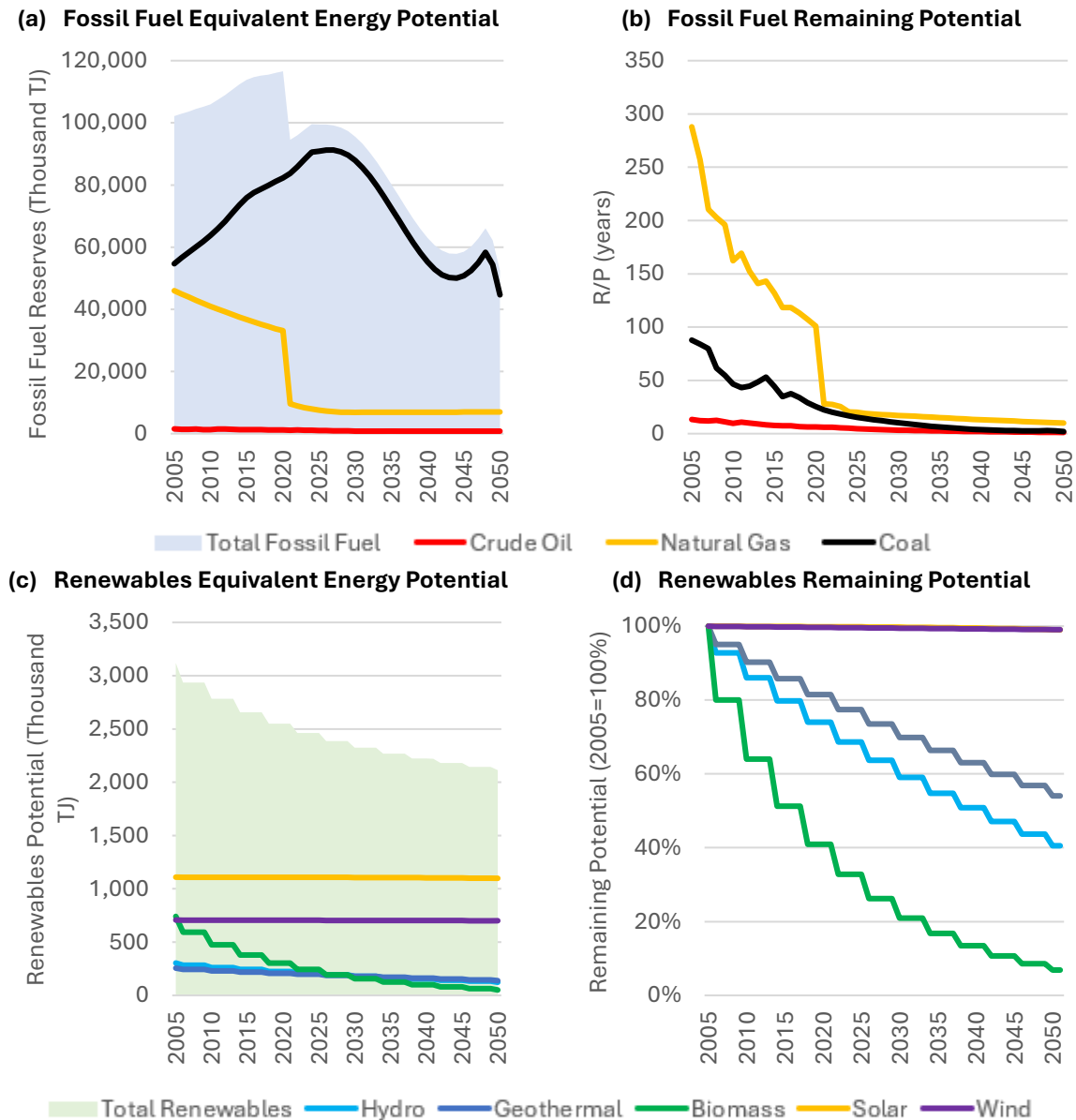


Figure 4.21. National Energy Availability.

Alternatively, energy availability can be observed by the resource energy potential, in which efficiency should be included in the calculation. Among power generation technologies, coal-fired power plants have the highest potential for efficiency improvements from 34% for sub-critical²⁵⁹ to 50% for advanced ultra-super critical technologies²⁶⁰. The resulting energy potential for coal can be seen in Figure 4.21(a) where it increased until 2025 but then decreased since the rate of consumption growth is faster than the efficiency improvement rate.

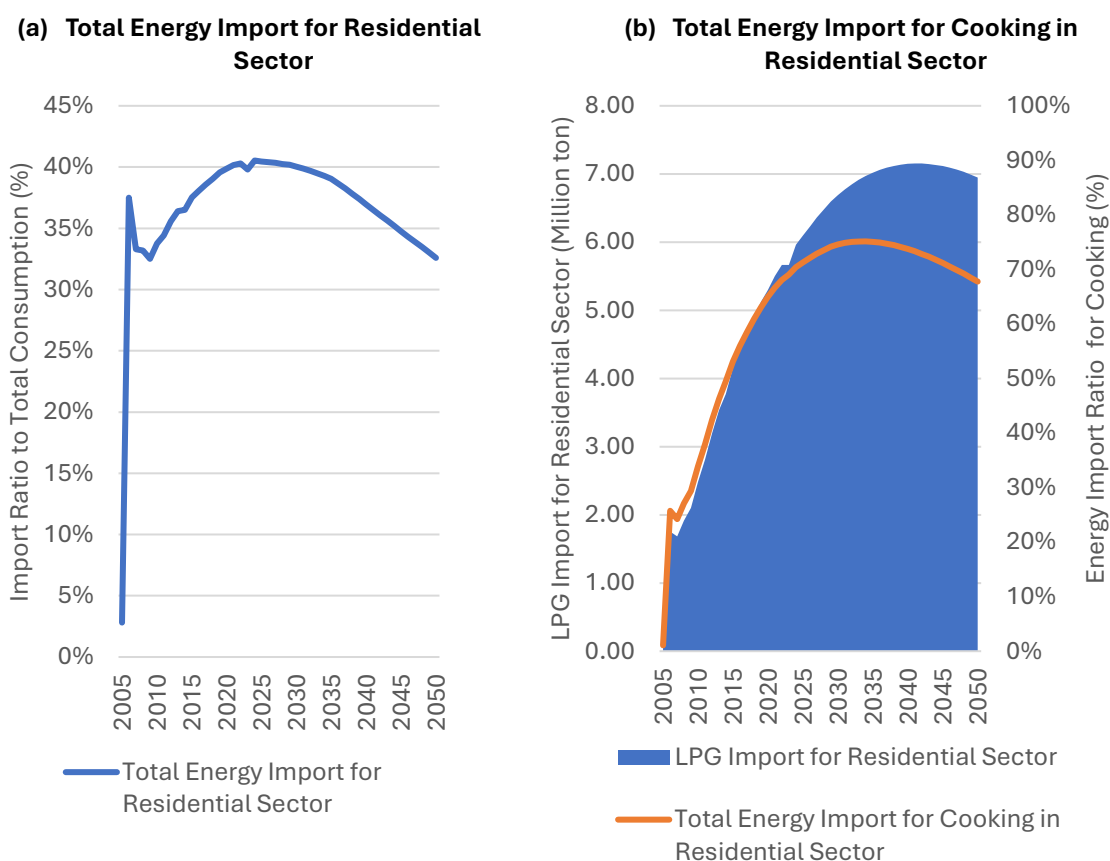


Figure 4.22. National Energy Accessibility.

The nation's energy accessibility would continue to improve as the proportion of electricity in the total household energy consumption increase as in Figure 4.22(a). However, this does not mean that the LPG import value decreases. Instead, it continues to increase since the overall household dependence on LPG continues as shown in Figure 4.22(b). Nonetheless, the LPG import ratio to the overall energy consumption for cooking eventually decreases starting in 2040 due to the increase in electric stove adoption which also helps with the saturating import quantity. In addition, the increasing import value may not be an issue nationally since its proportion to GDP is decreasing over time as depicted in Figure 4.23.

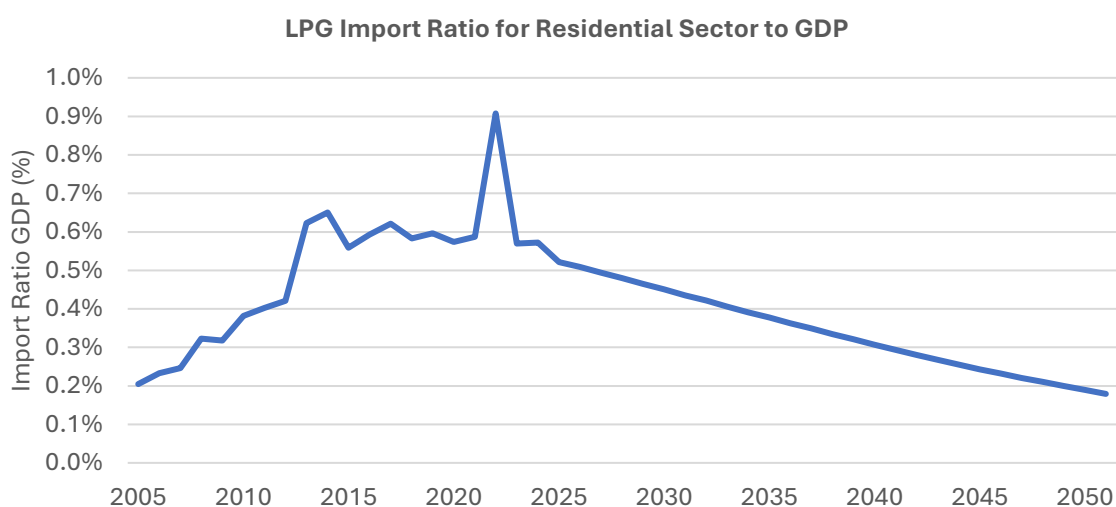


Figure 4.23. National Energy Affordability.

The total electricity CO₂ emissions from the residential sector continues to increase over the years following the increase in its consumption as seen in Figure 4.11 and Figure 4.12. However, in Figure 4.24, the increase in CO₂ emissions is not as steep as the increase in total electricity consumption due to the improvement in power plant efficiency, dampening the CO₂ emissions increase rate. Thus, it is equally important for the power sector to increase its efficiency. Shifting away from fossil fuel would have an even greater impact on the total emissions.

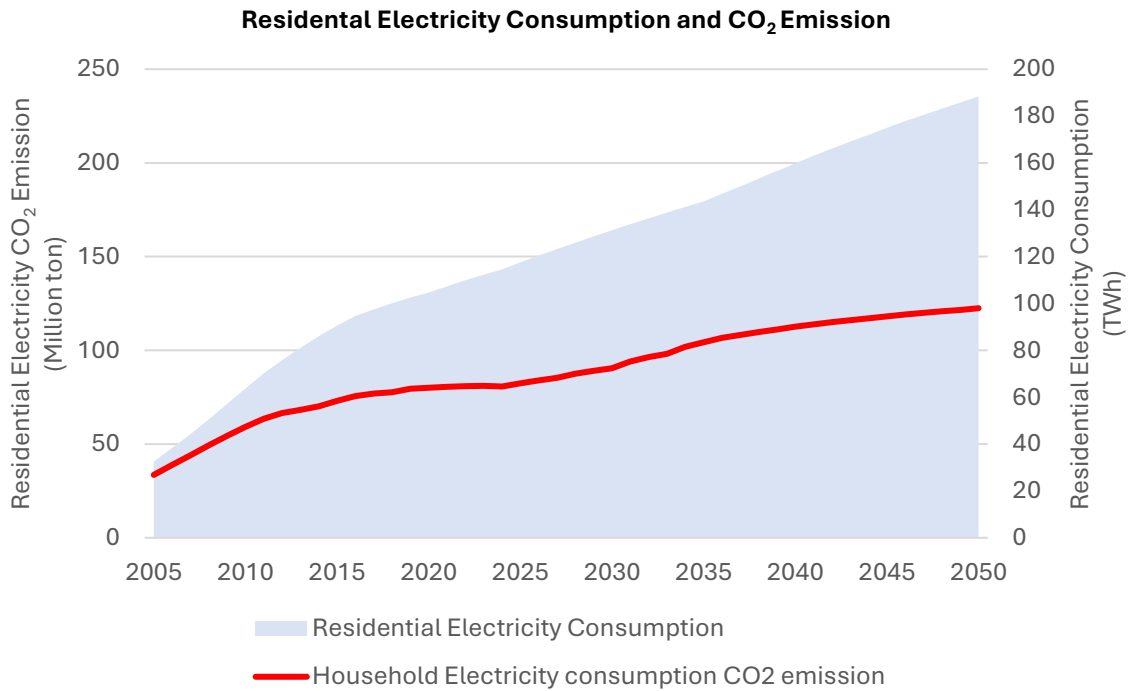


Figure 4.24. National Energy Acceptability.

4.4. Discussion

4.4.1. Home appliances power rate

As the households climbs the energy service ladder, electricity becomes the predominant energy in the residential sector regardless of the transition to electric stoves as can be seen in Figure 4.12. In Section 4.2.1, it has been explained that electricity consumption is determined by the power rate of each home appliances, hence its improvement in would be a major factor in determining the electricity consumption in the power sector.

We tested the model to simulate the energy consumption under different home appliances power rate improvements. Specifically for mobile devices, the value of the battery capacity is changed to emulate the rising demand for larger capacity as elaborated in Section 4.2.1. Under the baseline simulation, it is assumed that the power rate of the best-available technology for a device remains the same as it has been. From the baseline, the residential sector's consumption is simulated with power rate (battery capacity in the case of mobile devices) 20% higher and lower than the current best-available technology, and electricity consumption if the power rate is frozen at 2024 level.

The results are shown in Figure 4.25. It can be observed that if there is an improvement in home appliances power rate, the increase in electricity consumption could be dampened. If there are no improvements, the electricity consumption from the residential sector in 2050 could reach 204 TWh, which is 7% higher than the baseline. A $\pm 20\%$ change in best-available

power rate inversely leads to a $\pm 2\%$ in electricity consumption by 2050. The inelasticity is the result of the shifts in household income where higher income households have higher energy demand as explained in Section 4.2.1.

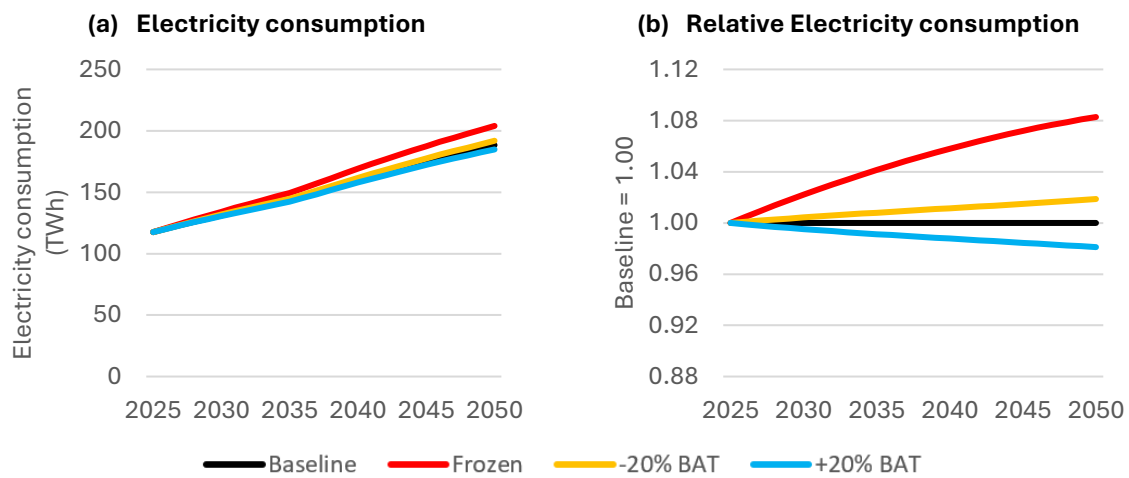


Figure 4.25. Residential sector electricity consumption under different home appliances power rate improvements.

The result of power rate changes on the household and national energy security are presented in Figure 4.26 through Figure 4.28. Since changes in power rate affects electricity consumption, they would have a direct impact on household energy affordability while not significantly affecting the remaining household energy security indicators. The effect of power rate changes on household energy affordability mimics their effect on electricity consumption shown in Figure 4.25(b). However, the impact on affordability is lower where a $\pm 20\%$ change in best-available power rate inversely leads to a $\pm 0.9\%$ in electricity consumption by 2050 since the price of electricity is also increasing overtime.

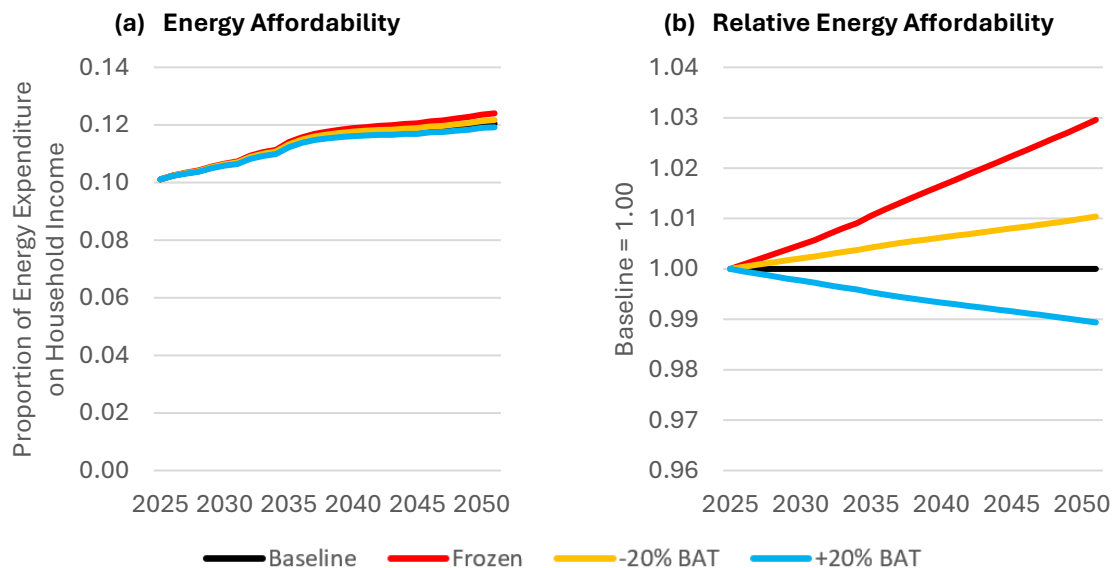


Figure 4.26. Home appliances power rate changes effect on household energy affordability.

Changes in power rate also influence national energy security indicators. Figure 4.27 shows there is a negative effect on the national energy accessibility although it is not necessarily be so practically, because the observed accessibility indicator compares the total energy imports to the overall energy consumption. Since improvement in power rate reduces the overall energy

consumption but not does not affect the energy imports for LPG, hence the import ratio increased. On the other hand, improvement in power rate would improve energy acceptability since it directly reduces electricity consumption and, in turn, the resulting grid emission.

In addition to energy acceptability, the changes in electricity consumption due to changes in home appliances power rate also affects energy availability. However, the implication is not as straightforward. An increase in electricity consumption would drive resources production capacity and resources exploitation. Consequently, reserves could momentarily increase until the recoverable resource potential is reached. To demonstrate, fossil fuel is chosen as an example since it is the dominant primary energy for electricity generation. Presented in Figure 4.29, fossil fuel reserves continue to increase from the baseline under the frozen technology scenario in which the electricity consumption is higher. However, the effect of higher energy consumption is quickly reversed when the physical resource of fossil fuels has been reached.

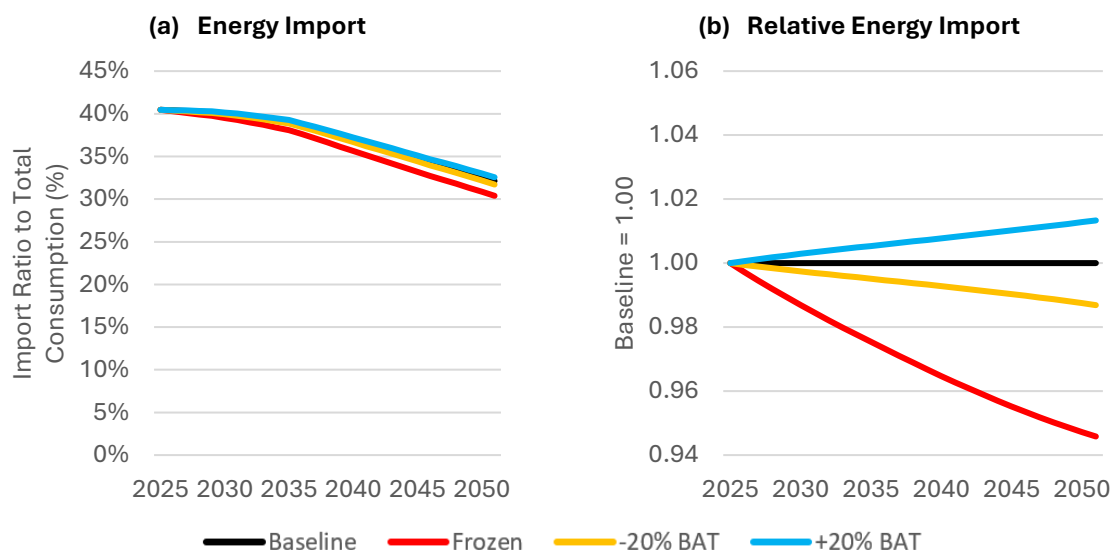


Figure 4.27. Home appliances power rate changes effect on national energy accessibility.

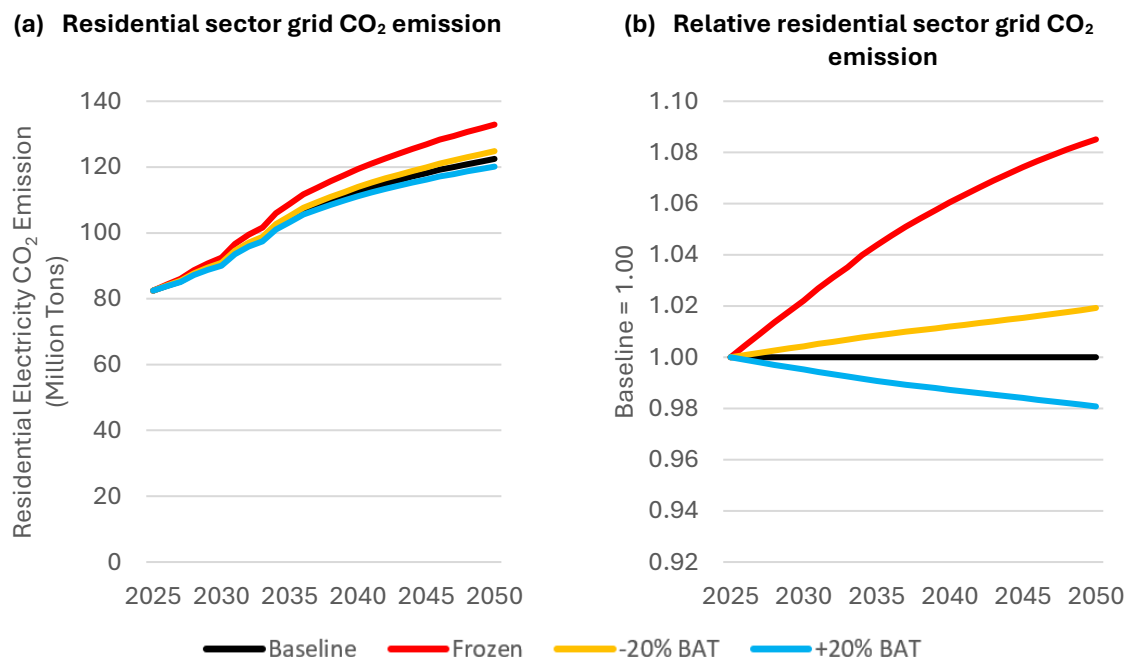


Figure 4.28. Home appliances power rate changes effect on national energy acceptability.

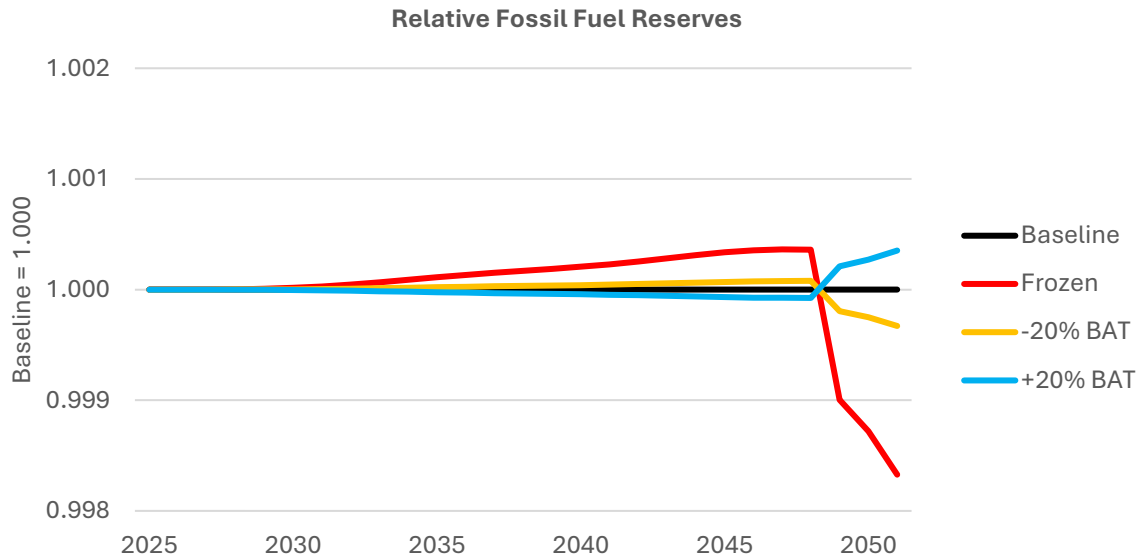


Figure 4.29. Home appliances power rate changes effect on national energy availability.

4.4.2. Electric Stove Adoption

The adoption of electric stove under the baseline simulation, shown in Figure 4.12, does not have a significant effect on electricity consumption. However, this is the result of a relatively low adoption – only 16% of all households. Should all households use electric stove, it could put a heavy burden on the grid. This energy consumption is equal to 107 TWh, around the same amount of electricity used for all other home appliances¹. On the other hand, transitioning to electric stove was shown to be mostly beneficial in for both household and national energy security. Thus, it is important to investigate how far can the adoption of electric stove could grow, and its impact on energy security.

One of the main barriers to electric stove adoption is the installed power capacity in houses, where electric stove ideally requires 3500 VA although 2200 VA would suffice for low wattage stoves¹⁹. In this regard, the government had pushed for upgrades in houses with installed power less than 2200VA²⁶¹, although the program was soon abolished due to the economy still recovering from the Covid-19 pandemic²⁶². Nonetheless, the plan to push for the transition to electric stove has resumed²⁶³, and the plan to upgrade installed power capacity may be reinstated. Another barrier is the high initial costs of electric stoves¹⁹, which the government had also planned to address via incentives²⁶¹. Both policies were simulated, and the impact on electric stove adoption can be observed in Figure 4.30 and Figure 4.31. For the installed power capacity, the model was simulated using 25%, 50%, and 100% of all the households with installed power below 2200VA are supported by the government with the upgrade. As for the purchase incentive, the effect of providing 25%, 50%, and 100% incentives was used.

Pushing for installed power capacity upgrades to at least 2200 VA has a significant impact on the adoption of electric stoves. By supporting 25% of households who still have installed power capacity under 2200 VA resulted in an increase of electric stove share from 16% to 20%. The share can be further increased to 27% if half of those households receive an upgrade, and to 47% if all of them receive an upgrade. As a result, the residential electricity consumption in 2050 could increase by up to 15% from the baseline, or from 238 TWh to 273 TWh as shown in Figure 4.30(b). On the other hand, providing purchase incentives is not as effective unless it is a full and non-discriminating incentive, i.e. given free by the government to all households.

Under this policy, the electricity consumption 2050 could increase by 10%, from 238 TWh to 261 TWh. The reason why purchase incentives performed less than power capacity upgrades is because purchase incentives only affect one dimension of the four adoption factors elaborated in Section 4.2.3.1. In addition, the weight of economic benefits is dominant in lower income households who are more likely to have installed power capacity less than 2200 VA.

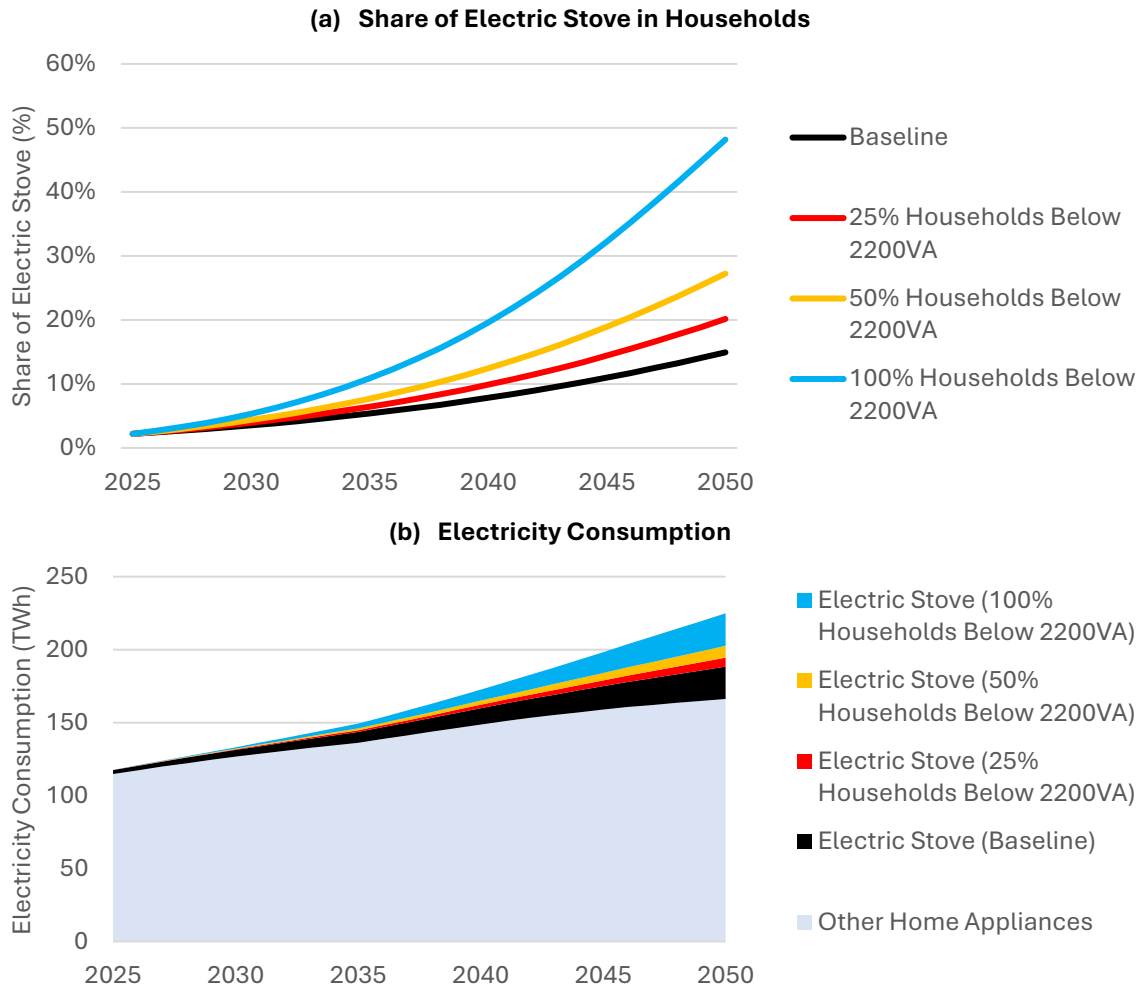


Figure 4.30. The effect of supporting installed power capacity upgrades on electric stove adoption and the resulting residential sector electricity consumption.

As mentioned in the opening of this section, the use of electric stoves can improve energy security. The benefit is mainly from the reduction of LPG consumption. At the household level, Figure 4.32 shows the dependence in fossil fuel reduced significantly from 0.95 to 0.64 when all households have 2200 VA installed power capacity. In turn, upgrading installed power capacity in all households also significantly improved access to zero local emission energy as in Figure 4.43. Figure 4.34 shows that the direct effect of increasing the adoption electric stove on household energy affordability is positive. This result is consistent with the finding in Section 4.3.7 since the operating cost of electric stoves is slightly lower than gas. The changes in household expenditure compared to the baseline fluctuates due to the dynamics in household income changes and the adoption rate but generally decreases. The decrease enlarges as the number of electric stove adopters increase. On aggregate, the difference in household expenditure with the baseline is 2% between 2025-2050. The increase in electricity consumption also reduces the sufficiency of rooftop solar generation which resulted in a

decrease in rooftop solar adoption. Nonetheless, the resulting net household expenditure would still be reduced.

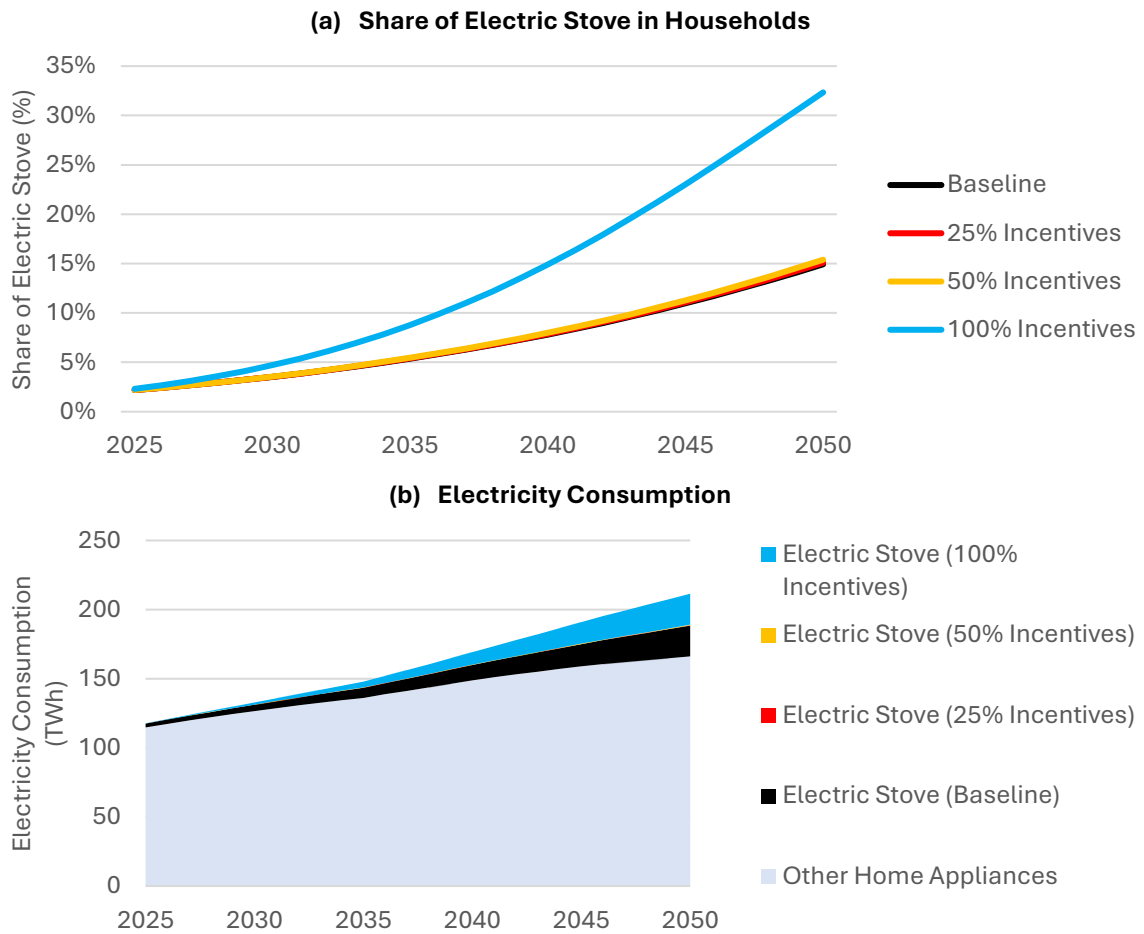


Figure 4.31. Electric stove purchase cost incentives effect on its adoption and the resulting residential sector electricity consumption.

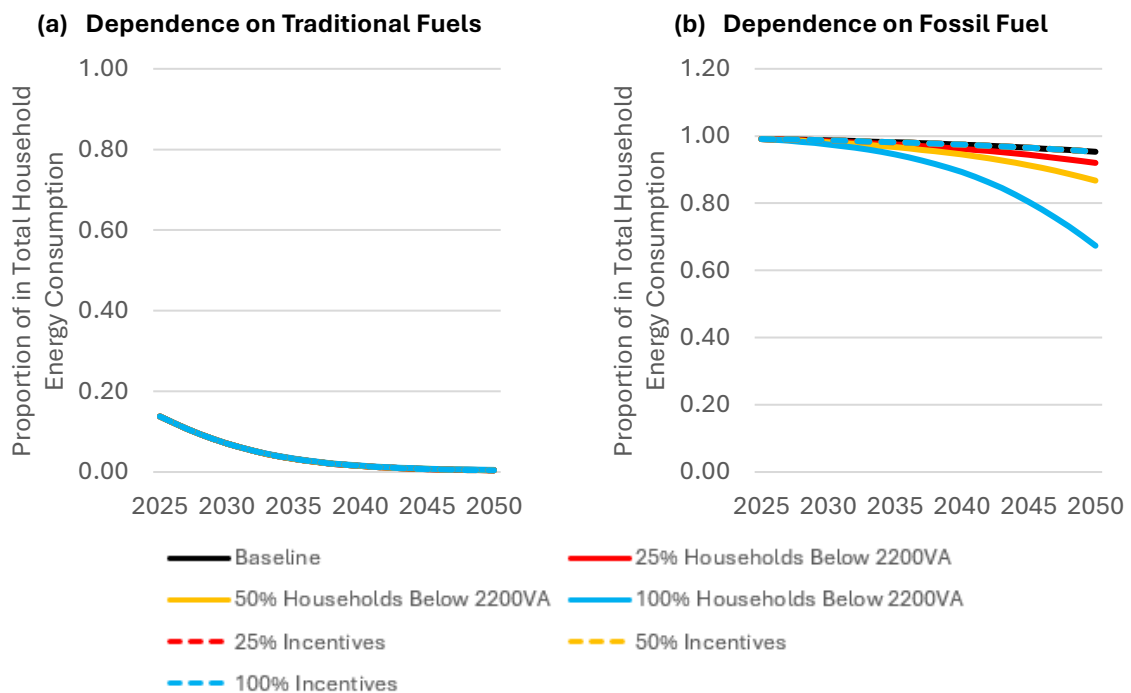


Figure 4.32. The effect of increasing electric stove adoption on the household energy availability.

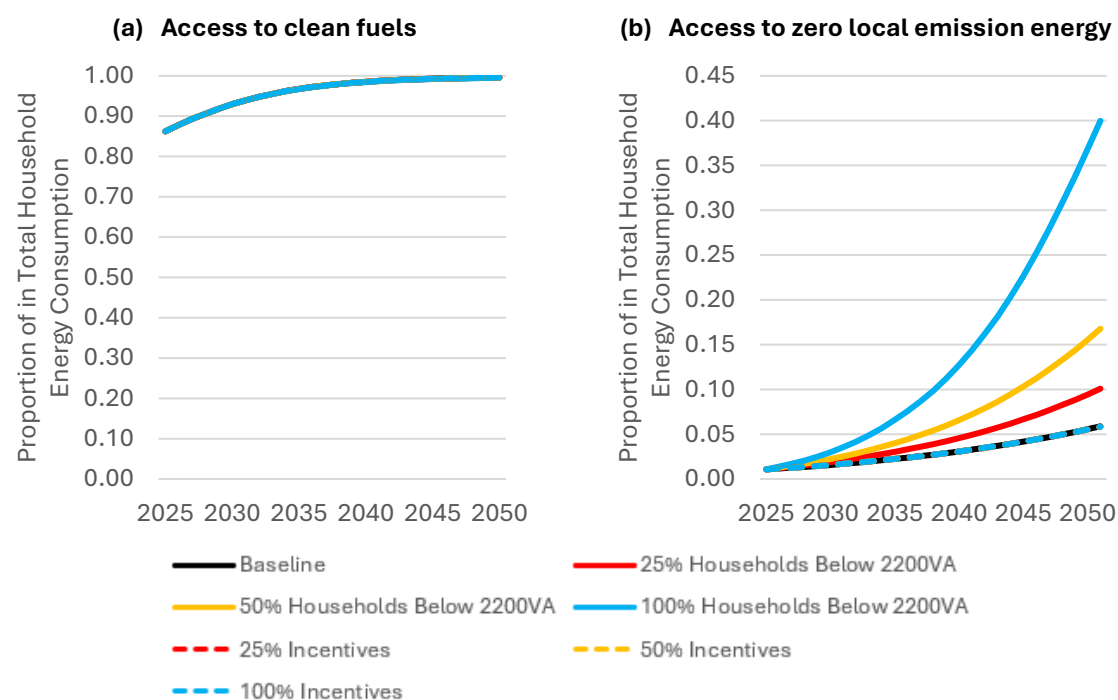


Figure 4.33. The effect of increasing electric stove adoption on the household energy accessibility.

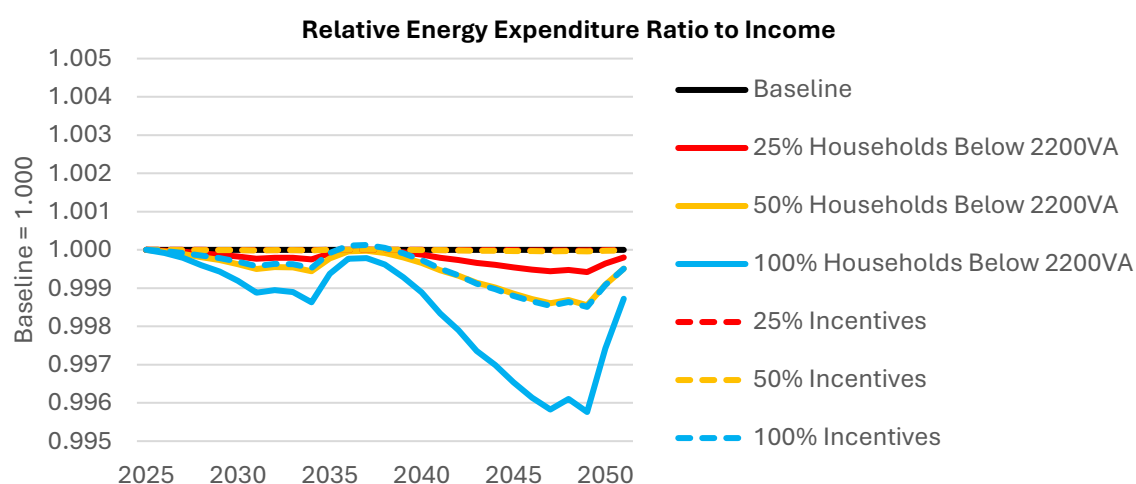


Figure 4.34. The effect of increasing electric stove adoption on the household energy affordability.

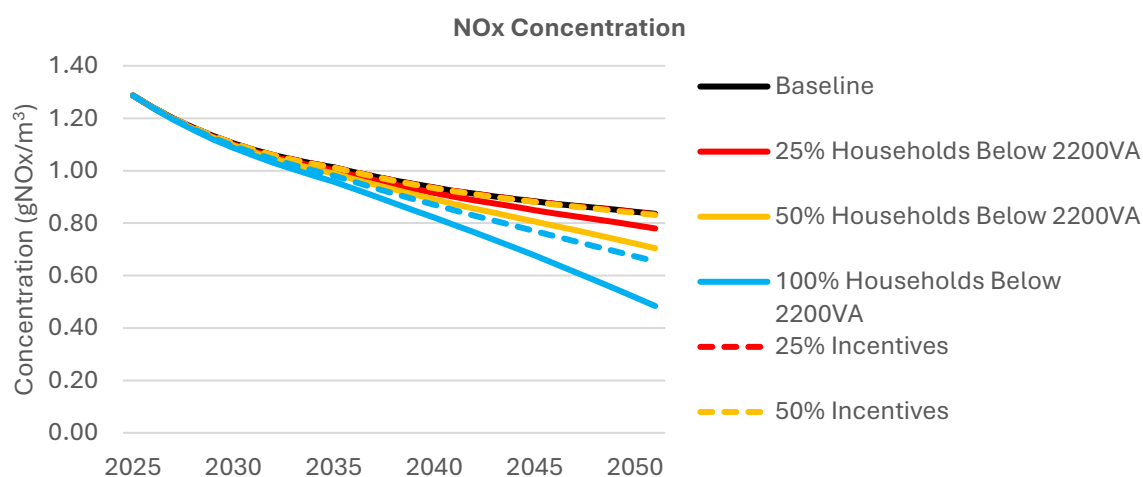


Figure 4.35. The effect of increasing electric stove adoption on the household energy acceptability.

Increasing the adoption of electric stove would have a positive impact on the household energy acceptability. In Figure 4.35, it is shown that under the most extreme case of providing installed power capacity upgrade, the NO_x concentration may be reduced 42% from the baseline which will reduce the risk for respiratory diseases¹⁰⁴.

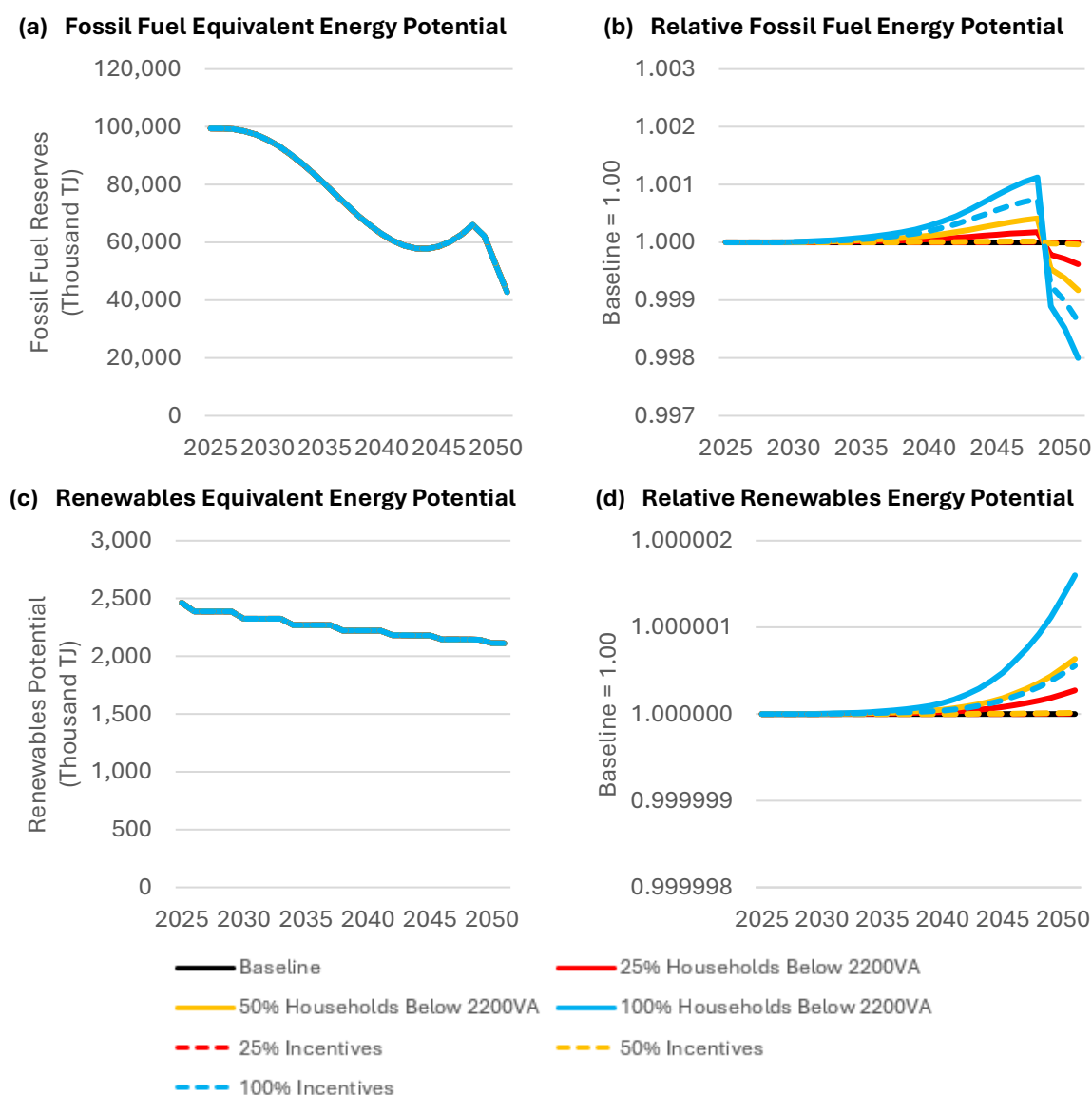


Figure 4.36. The effect of increasing electric stove adoption on the national energy availability.

Reducing LPG consumption through shifting to electric stoves extends the benefit at household level to the national level by reducing LPG imports. The implications of the reduced imports are reflected in energy accessibility and energy affordability as seen in Figure 4.37 and Figure 4.38. On the other hand, it has a negative implication on the grid emissions since the use of electric stoves increases grid electricity consumption as in Figure 4.39. As explained in 4.3.7, the increase in electricity consumption leads to a temporary increase in energy availability if there is sufficient physical availability. Figure 4.36(b) shows the sudden diminishing of fossil energy availability due to the increased electricity consumption from electric stoves while Figure 4.36(d) renewables energy availability continues to increase – although very slightly – since it has yet to reach its full potential.

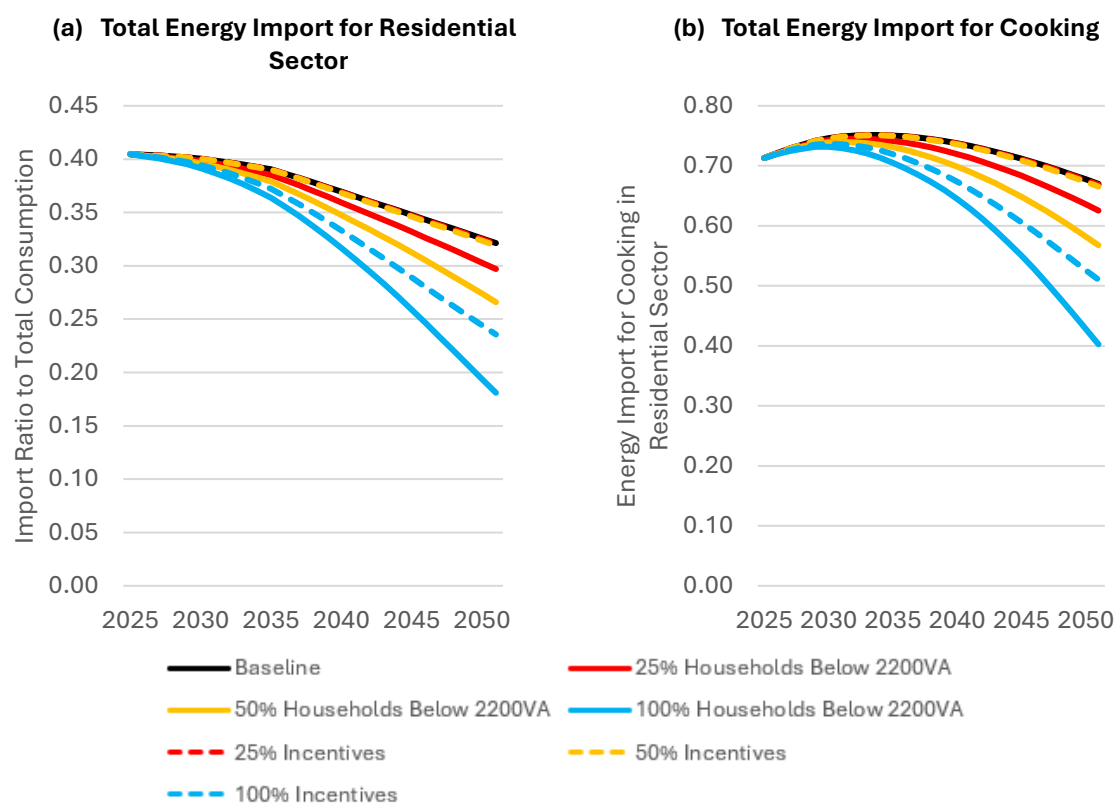


Figure 4.37. The effect of increasing electric stove adoption on the national energy accessibility.

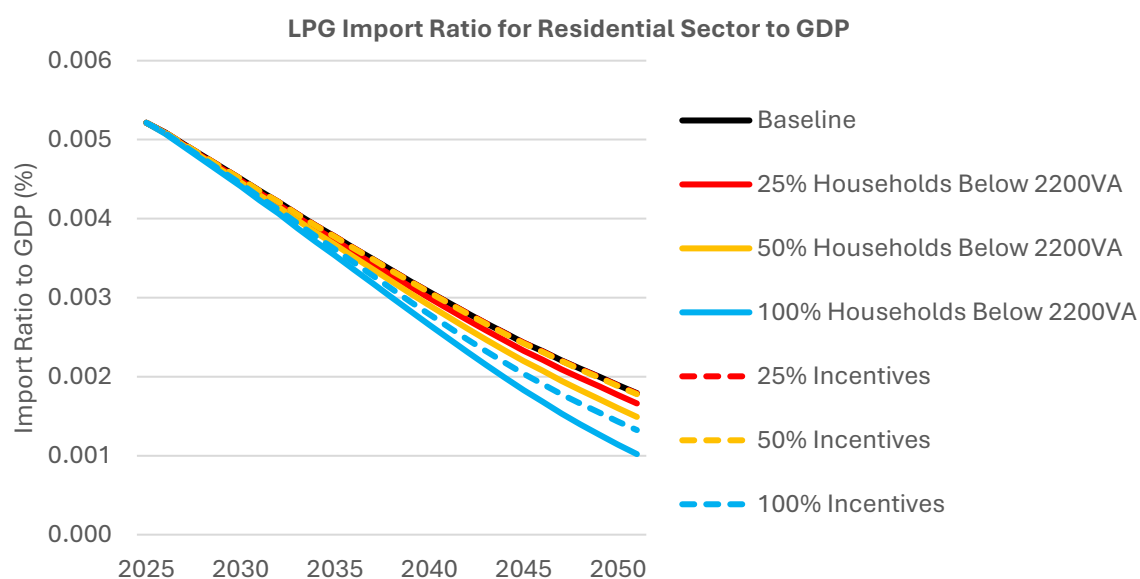


Figure 4.38. The effect of increasing electric stove adoption on the national energy affordability.

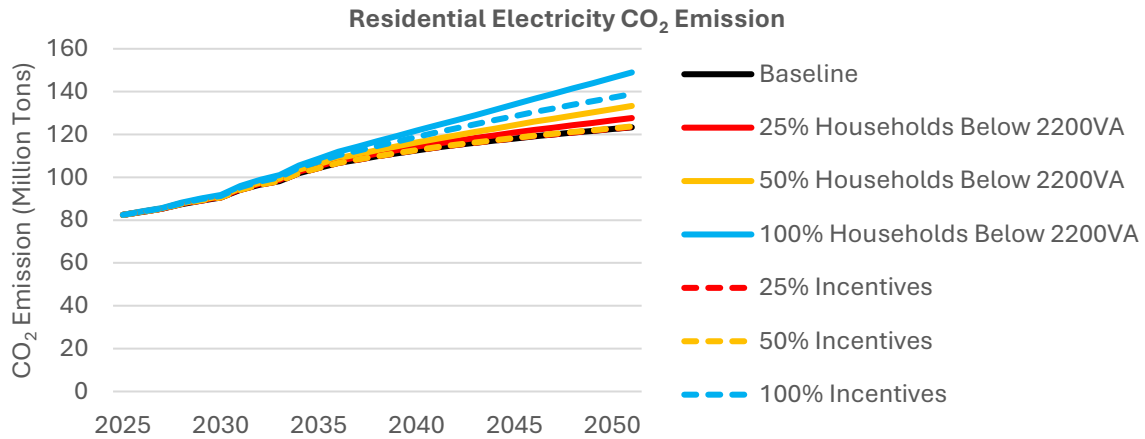


Figure 4.39. The effect of increasing electric stove adoption on the national energy acceptability.

4.4.3. Rooftop solar Adoption

The use of rooftop solar has the potential to reduce the increasing demand for electricity from the grid that is exacerbated by electric stoves. With the potential for 32.5 GW installed capacity²⁶⁴ and around half projected to come from residentials, the total electricity generation from rooftop solar in the residential sectors could reach 21 TWh which is 11% of the residential sector total electricity demand in the highest electric stove adoption scenario in Section 4.4.2. However, only 19% of the households adopts rooftop solar and combined generated only 2 TWh in the baseline run as in Figure 4.15.

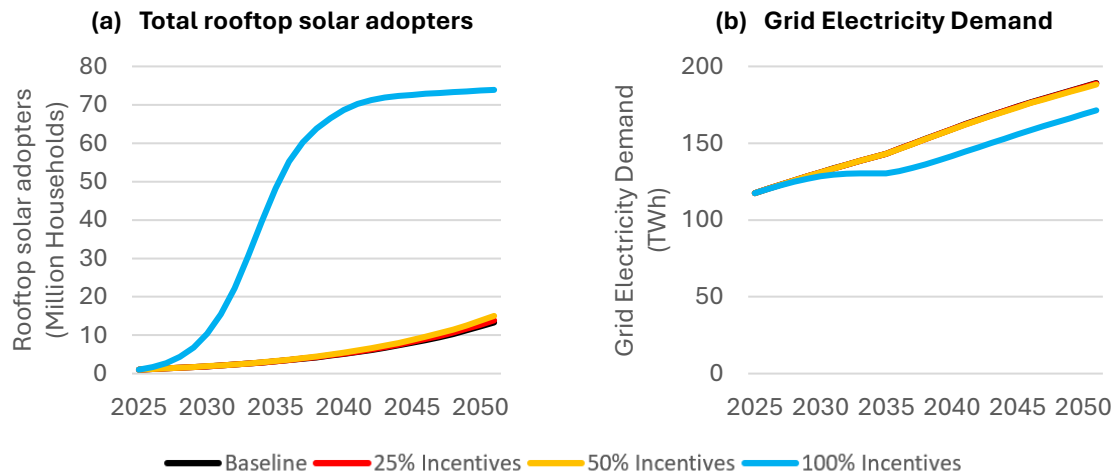


Figure 4.40. The effect of purchase incentive on rooftop solar adoption and the resulting residential sector electricity consumption.

Like electric stoves, economic benefit is the main barrier for rooftop solar adoptions. To increase the adoption of rooftop solar, purchase incentives may be applied. The provision of 25%, 50%, and 100% incentives to all households was used. The result in Figure 4.40(a) shows that incentives can improve rooftop solar adoption. However, the increase is not linear. When the incentive is 25%, the number of rooftop solar adopters could only increase by 5% at most. The increase is tripled when the incentives are doubled to 50%. The non-linearity in adoption rate is explained by the bass-diffusion model where the effect of word-of-mouth creates an exponential growth to the adoption of a technology²⁴². The adoption s-curve of the diffusion model is demonstrated in Figure 4.40(a) when the households are given 100% rooftop solar purchase incentives. The net residential sector electricity demand as the result of the rooftop

solar adoption is shown in Figure 4.40(b). As noted above, the grid electricity demand would be 11% lower than then baseline when all households have adopted rooftop solar.

The direct implication of reduced electricity demand on households is the electricity bill. Figure 4.41 shows that low-income households receive the highest benefit since they have a relatively low electricity demand to begin with. In addition, purchase incentive would help them greatly since they have the least purchasing power. In contrast, incentives do not affect the middle-income and high-income households significantly. The remaining household energy security indicators were not significantly affected by the increased adoption of rooftop solar.

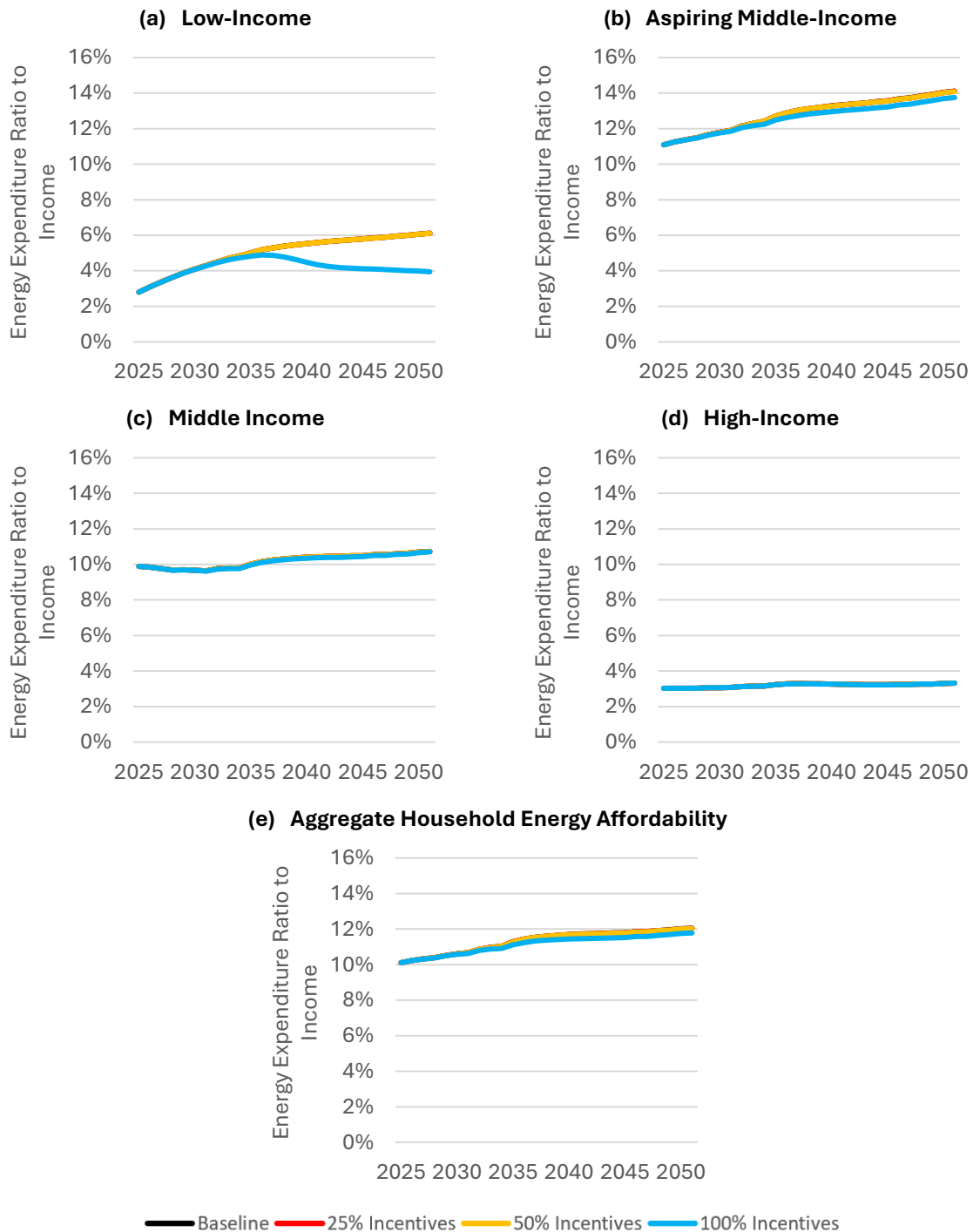


Figure 4.41. The effect of rooftop solar purchase incentive on household energy affordability.

At the national level, rooftop solar adoption affects energy availability and energy acceptability since it reduces electricity consumption. Naturally, renewables potential – specifically solar potential – is the factor impacted the most as shown in Figure 4.42 (b) and (d). Even if all households have adopted rooftop solar, the remaining solar potential would still be 94% since the total rooftop solar potential is reported to be 32.5 GW²⁶⁴ while the total solar potential reached 207 GW¹⁰, and around 40% that rooftop solar potential is in the residential sector²⁶⁵.

In terms of national energy acceptability, the increase in rooftop solar adoption can reduce grid electricity emissions. However, since the effect of purchase incentives on rooftop solar adoption is non-linear, so too is the effect on the reduction of grid CO₂ emissions. With 25% purchase incentives, the cumulative grid emission from 2025 to 2050 could only be reduced by 0.1% or around 2 million tons CO₂. However, as the incentive increases, the effect increases exponentially, and the reductions can reach 8% or 228 million tons CO₂ when all households use rooftop solar. In addition to the direct emission reduction, the reduced electricity demand also leads to a lower grid emission factor. This unprecedented effect is due to the power sector using the least-cost approach²⁶⁶ and reliability-focus²⁶⁷ in this chapter. Under these priorities, any required additional installed capacity on the grid would favour thermal power plant over renewables. The changes in generation technology adoption consideration in the power sector will be explored more in detail on Chapter 6 of this thesis. Since the electricity generated from rooftop solar are insufficient to fulfil household energy demand, no excess can be sold to the grid and hence the net-metering policy will not have any effect on the rooftop solar adoption.

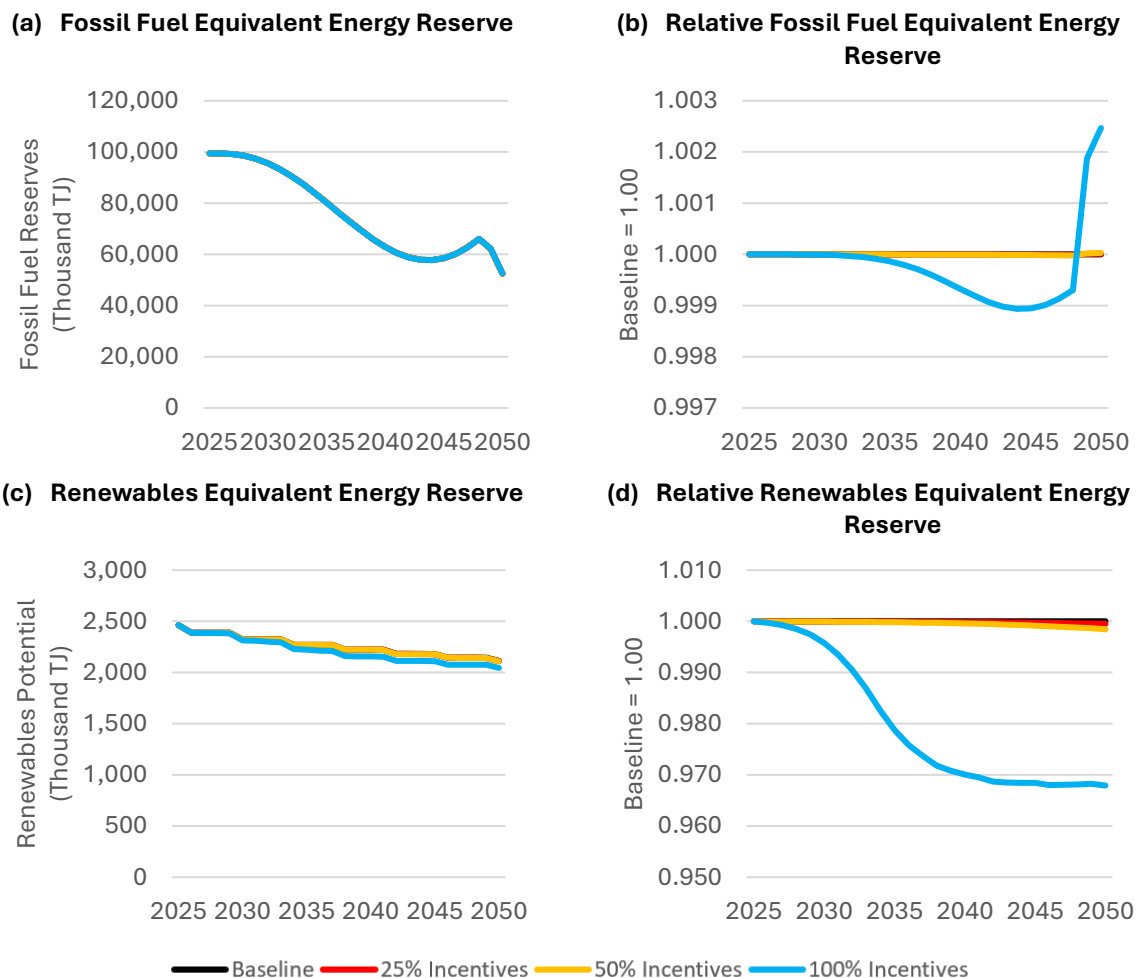


Figure 4.42. The effect of rooftop solar purchase incentive on national energy availability.

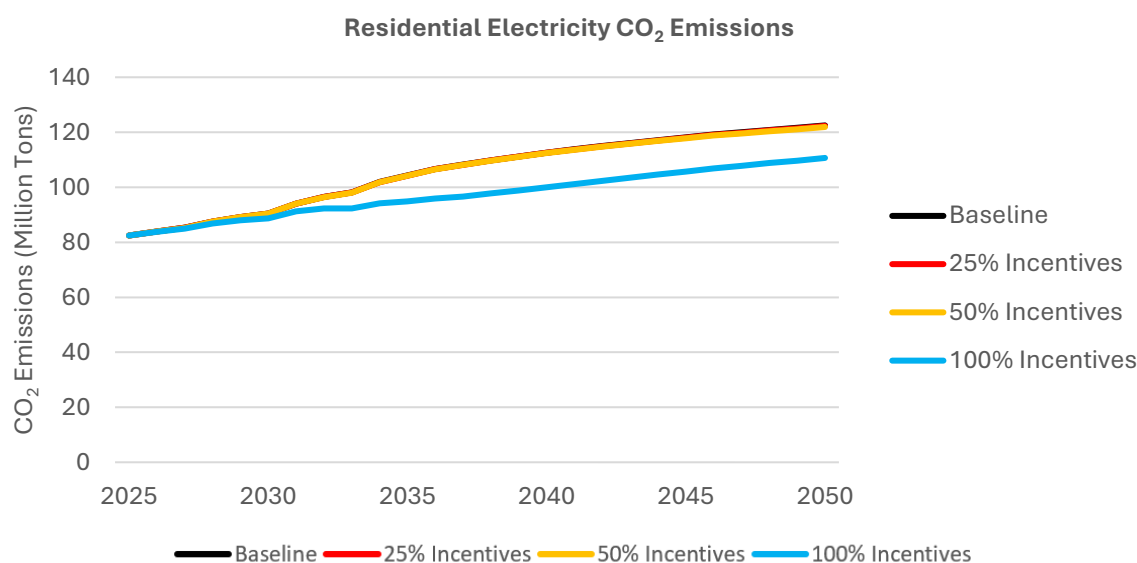


Figure 4.43. The effect of rooftop solar purchase incentive on national energy acceptability.

4.4.4. Energy Subsidy Budget

Energy subsidies are applied to LPG, electricity, and fuels for the transportation sector by the Government of Indonesia²⁶⁸. Between 2004 and 2014 the total subsidies, including for non-energy allocation, were equal to 16.3-25.9% of state revenues²⁶⁹. However, since the abolishment of fuel subsidies for the transportation sector in 2015, the total subsidies range between 9.6% to 12.3% of the state revenues²⁷⁰. Of all the subsidies, energy subsidy is the largest – more than 90% before the fuel subsidy abolition but then reduced to around 60% afterwards^{268,270,271}. The proportion subsidies for LPG and electricity within the energy subsidy may vary yearly, but in 2024 the subsidy for electricity is around 40% the total energy subsidy budget²⁶⁸.

Subsidised LPG was first implemented in 2007, and only low-income households are eligible to receive them. The price was equal to the market price at that time of 0.44 USD per kg and has been kept the same to this day although LPG market price fluctuate¹. As a result, the gap between market and subsidised price has widened from 25% in 2008 to 80% in 2022 below the market price. To simulate the changes in energy subsidy, the value of the state budget allocation for energy subsidy and the subsidy rate for LPG were changed by reducing them 25% and 50% from the baseline.

Figure 4.44 shows that as the allocation halved, subsidised LPG prices would eventually need to be increased. In addition, the subsidised LPG price would be immediately impacted if the subsidy rate is changed. Electricity price also increased with the reduction of the energy subsidy budget although not as significantly. However, subsidised LPG is only used for low-income households whose proportion is decreasing significantly over the years. On the other hand, electricity subsidies are enjoyed more widely. As a result, the economic benefit of using electric stoves decreases, and less households would be inclined to use them.

As a result of the change in electricity price, changing of the energy subsidy allocation changes to have the most impact on the use of electric stoves. Figure 4.45 shows that by halving the energy subsidy allocation, the number of electric stove adopters decreased by almost 4% in 2050, or 417 thousand less adopters than the baseline which also shows the decrease in the electricity consumption. However, the decrease is slightly lower than decrease in number of

adopters, since aspiring middle-income and middle-income – who have less energy demand for cooking compared to high-income households¹⁹ – are the most likely to avoid electric stove adoption due to the increased electricity price. In addition, since electricity consumption for cooking is only a small fraction of the total electricity consumption, the effect of an increased electricity price on electricity consumption in this case is very small. Hence, while the electricity consumption for cooking reduced by 3%, the total electricity consumption only reduced by 0.4% in 2050 as a result of the decreased electric stove adopters.

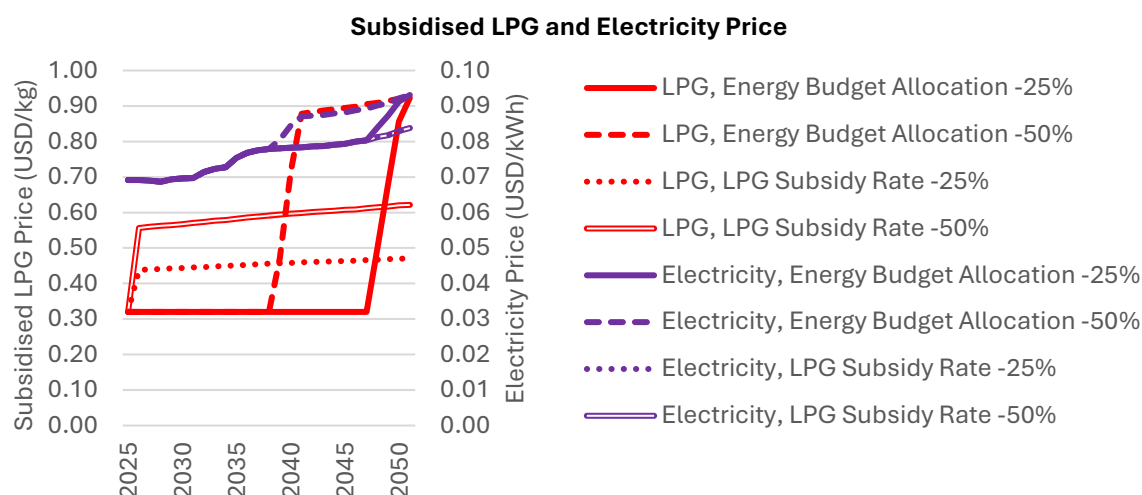


Figure 4.44. Energy subsidy adjustment effect on subsidised LPG price and electricity price.

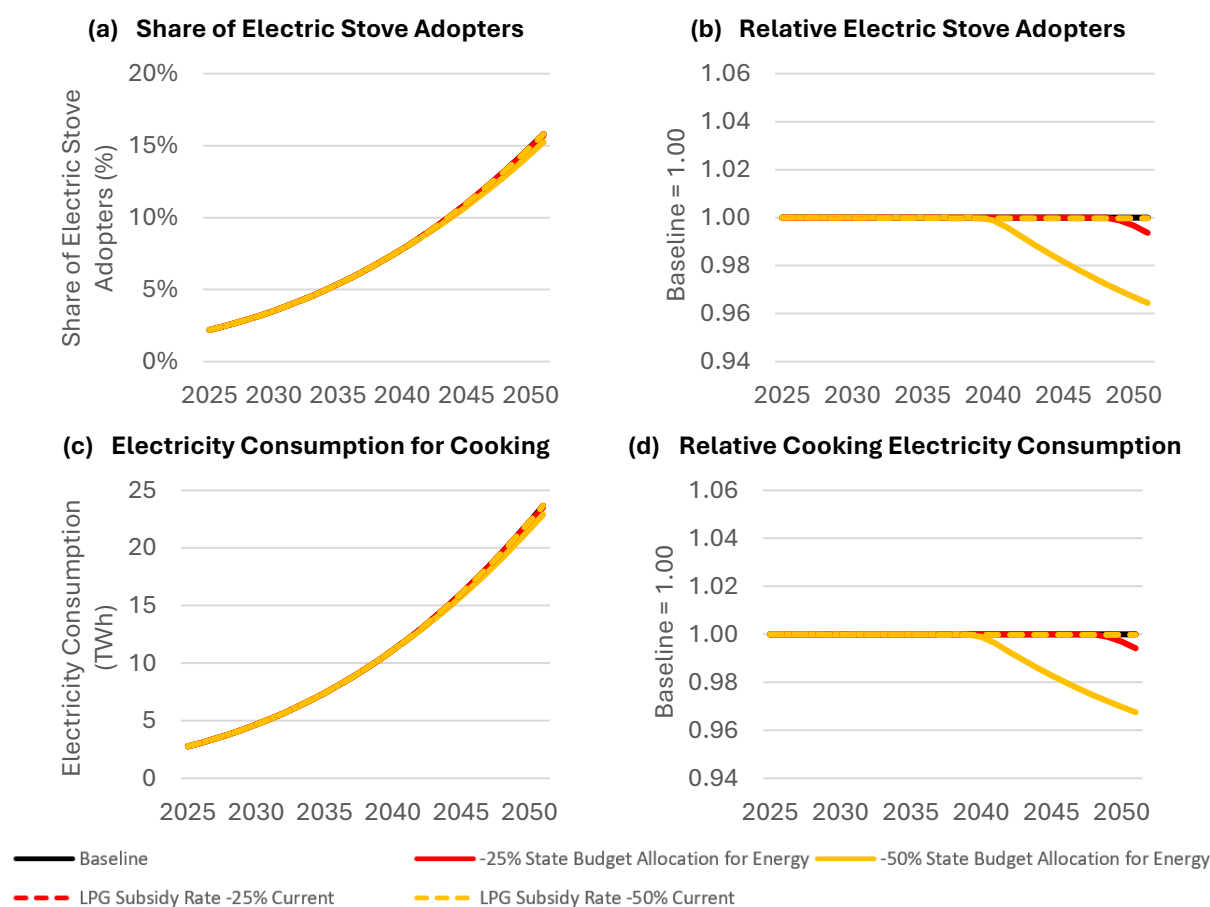


Figure 4.45. Energy subsidy adjustment effect on electric stove adoption and electricity consumption.

The effect of changing energy subsidy allocation also affects the adoption of rooftop solar although not as significant as in electric stove. Reducing energy subsidy would lead to an increase in electricity price which in turn increases the potential electricity bill savings. The increased economic benefit pushed more potential adopters to install rooftop solar in their homes. By reducing the energy subsidy by half which led to an annual 1% electricity price as in Figure 4.44, the number of adopters could grow 0.03% faster and ultimately be 0.8% higher than the baseline in 2050 as shown in Figure 4.46.

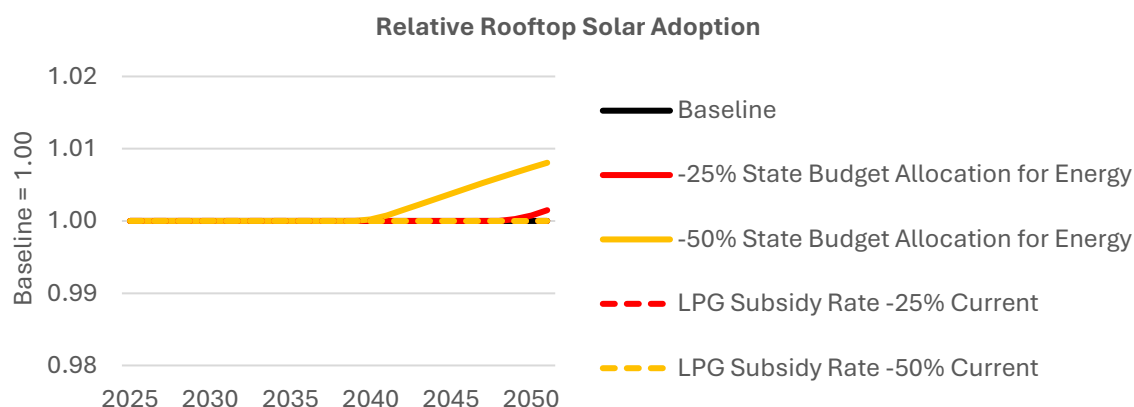


Figure 4.46. Energy subsidy adjustment effect on rooftop solar adoption.

As mentioned earlier at the beginning of this sub-section, reducing the LPG subsidy rate would immediately impact its price and in turn the adoption of gas stoves in the low-income and aspiring middle-income households. The result is a higher dependence on traditional fuel, which could be 41% higher in 2050 as shown in Figure 4.47(a). Reducing the overall energy subsidy budget would have an even higher impact on LPG price as in Figure 4.44, which leads to a lower gas stove adoption rate and the dependence on traditional fuel rises to 49% higher than the baseline in 2050. Reducing the energy subsidy budget also increased the dependence on conventional fuels by 0.2% in 2050 since less households would adopt electric stove as shown in Figure 4.47(b). The impacts of these energy subsidy adjustments affect household energy accessibility similarly to the energy availability.

Since subsidised LPG is dedicated to low-income households, changes in its price would greatly impact them. Figure 4.48 shows that low-income households suffer from more than doubled increase in energy expenditure when the energy subsidy allocation is halved. Their energy expenditure would also increase if the subsidy rate were reduced, although to a much lesser extent. As expected, high-income households are relatively unaffected by changes in energy price as the result of energy subsidy allocation reduction. In aggregate, the energy expenditure could increase by 14% by 2050 if the energy subsidy is reduced. Interestingly, that increase would be reached despite the subsidy allocation only being reduced by 25%. The difference is when the increase would happen, where a lower reduction would delay the increase in energy price.

Another consequence of the reduced adoption of cleaner fuel is the increased emissions from cooking. Again, the impact would be most felt by low-income households since they would have the highest tendency not to shift away from traditional fuels with the increased cost of LPG. Household energy acceptability would also suffer due to increased emissions from traditional stoves as shown in Figure 4.49. In the reduced LPG subsidy rate scenario, the NOx concentration is depicted to increase rapidly but then approach the baseline. The behaviour is

Figure 10 consists of four subplots (a, b, c, d) showing the impact of different budget and subsidy scenarios on household energy dependence from 2025 to 2050. The y-axis for all plots represents the 'Proportion of in Total Household Energy Consumption'.

- (a) Household Dependence on Traditional Fuel:** The y-axis ranges from 0.00 to 0.16. It shows a sharp decline in dependence on traditional fuel for all scenarios, starting at approximately 0.14 in 2025 and reaching near zero by 2050. The scenarios are: Baseline (solid black), -25% State Budget Allocation for Energy (solid red), -50% State Budget Allocation for Energy (solid yellow), LPG Subsidy Rate -25% Current (dashed red), and LPG Subsidy Rate -50% Current (dashed yellow).
- (b) Relative Dependence on Conventional Fuel:** The y-axis ranges from 0.40 to 1.60, with a baseline at 1.00. It shows that relative dependence on conventional fuel increases over time for all scenarios except the baseline, which remains at 1.00. The -50% State Budget Allocation scenario (solid yellow) shows the highest relative dependence, reaching approximately 1.50 by 2050. The -25% State Budget Allocation scenario (solid red) reaches approximately 1.10. The LPG subsidy scenarios (dashed lines) reach approximately 1.40.
- (c) Household Dependence on Conventional Fuel:** The y-axis ranges from 0.93 to 1.00. It shows a gradual decline in dependence on conventional fuel for all scenarios, starting at approximately 0.99 in 2025 and reaching approximately 0.95 by 2050. The scenarios are: Baseline (solid black), -25% State Budget Allocation for Energy (solid red), -50% State Budget Allocation for Energy (solid yellow), LPG Subsidy Rate -25% Current (dashed red), and LPG Subsidy Rate -50% Current (dashed yellow).
- (d) Relative Dependence on Conventional Fuel:** The y-axis ranges from 0.98 to 1.02, with a baseline at 1.00. It shows that relative dependence on conventional fuel remains very close to 1.00 for all scenarios, with a slight increase for the -50% State Budget Allocation scenario (solid yellow) reaching approximately 1.01 by 2050.

Legend:

- Baseline (solid black line)
- 25% State Budget Allocation for Energy (solid red line)
- 50% State Budget Allocation for Energy (solid yellow line)
- LPG Subsidy Rate -25% Current (dashed red line)
- LPG Subsidy Rate -50% Current (dashed yellow line)

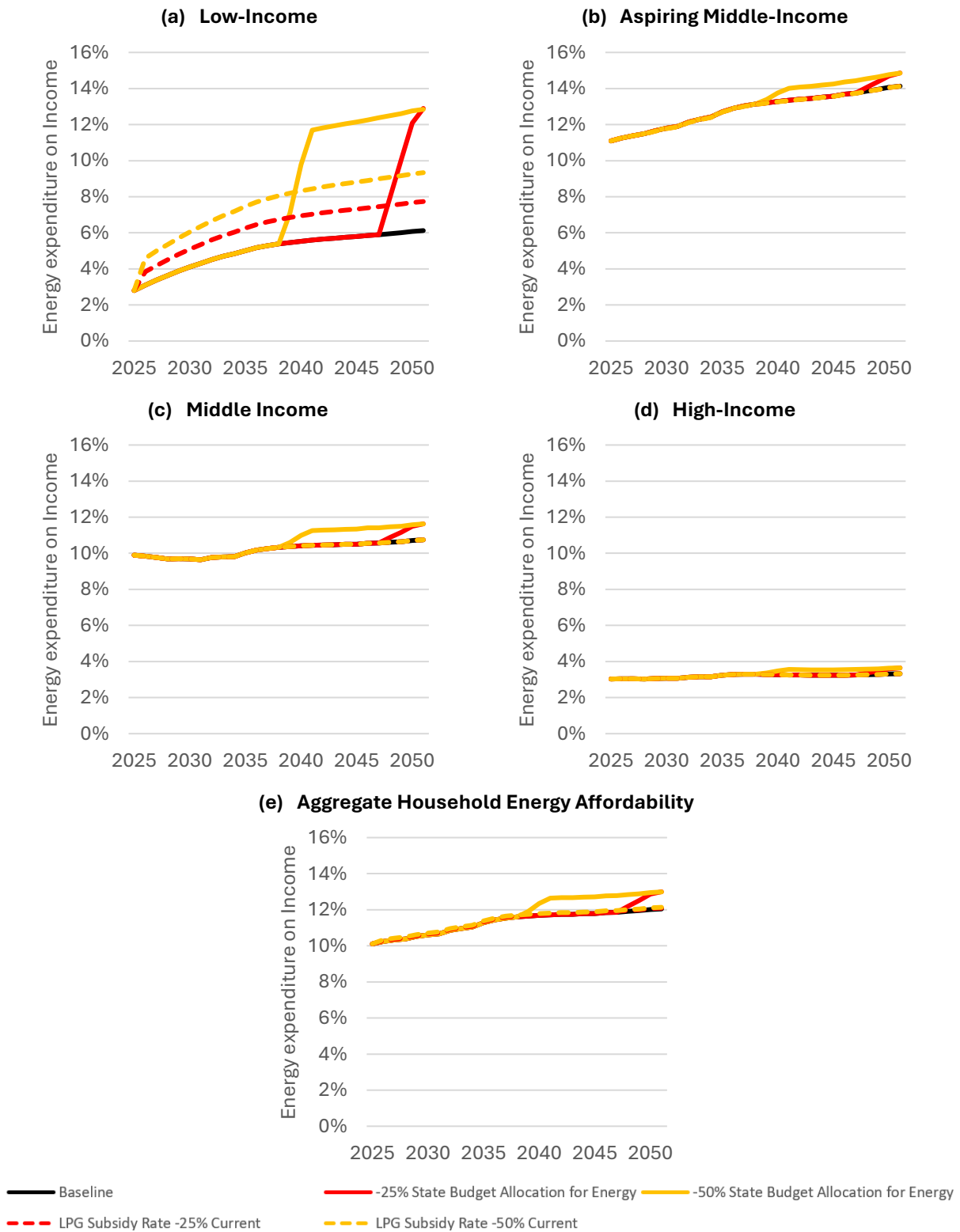


Figure 4.48. Energy subsidy adjustment effect on household energy affordability.

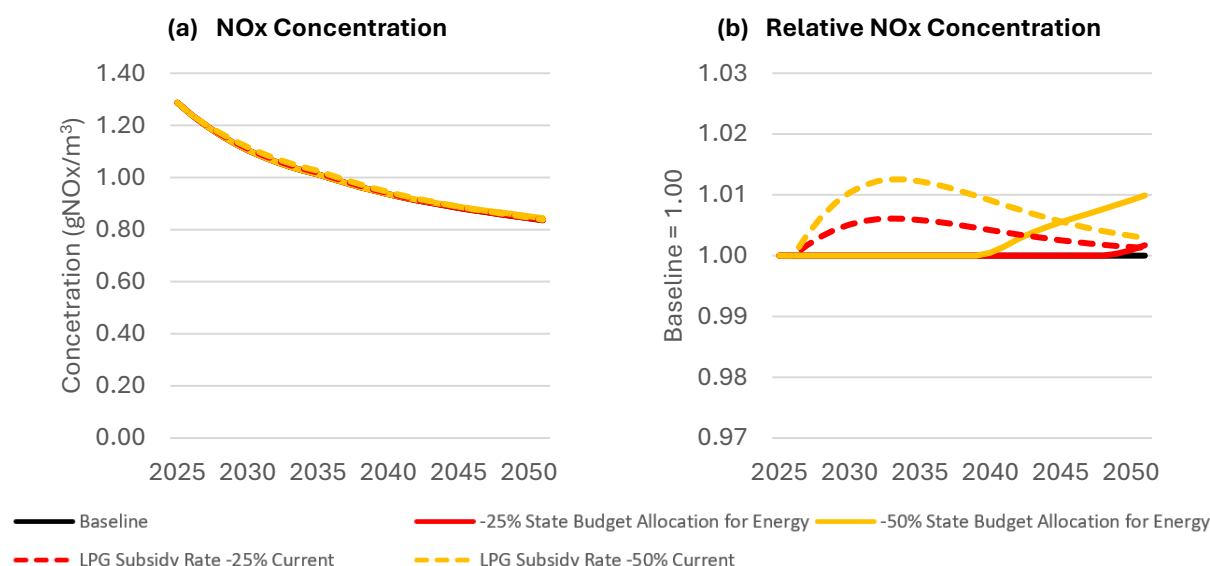


Figure 4.49. Energy subsidy adjustment effect on household energy acceptability.

At the national level, reducing the energy subsidy allocation and LPG subsidy rate affects LPG imports which impacted the energy accessibility as shown in Figure 4.50. As explained by the transition from stove technology adoption illustrated in Figure 4.47, the reduced LPG subsidy rate caused an increase in traditional stove use, hence reducing the energy imports although the effect then subsided with the continued transition to gas stoves. While reducing the energy subsidy allocation increased both subsidised LPG price and electricity price, electric stove potential adopters use market-priced LPG. Thus, the reduction in budget allocation would reduce the adoption of electric stove instead, increasing LPG energy imports for cooking in the residential sector. Figure 4.51 shows that reducing energy subsidies causes the increased imports while also negatively impacted the energy affordability, increasing the ratio between energy import value to GDP by 0.8% in 2050.

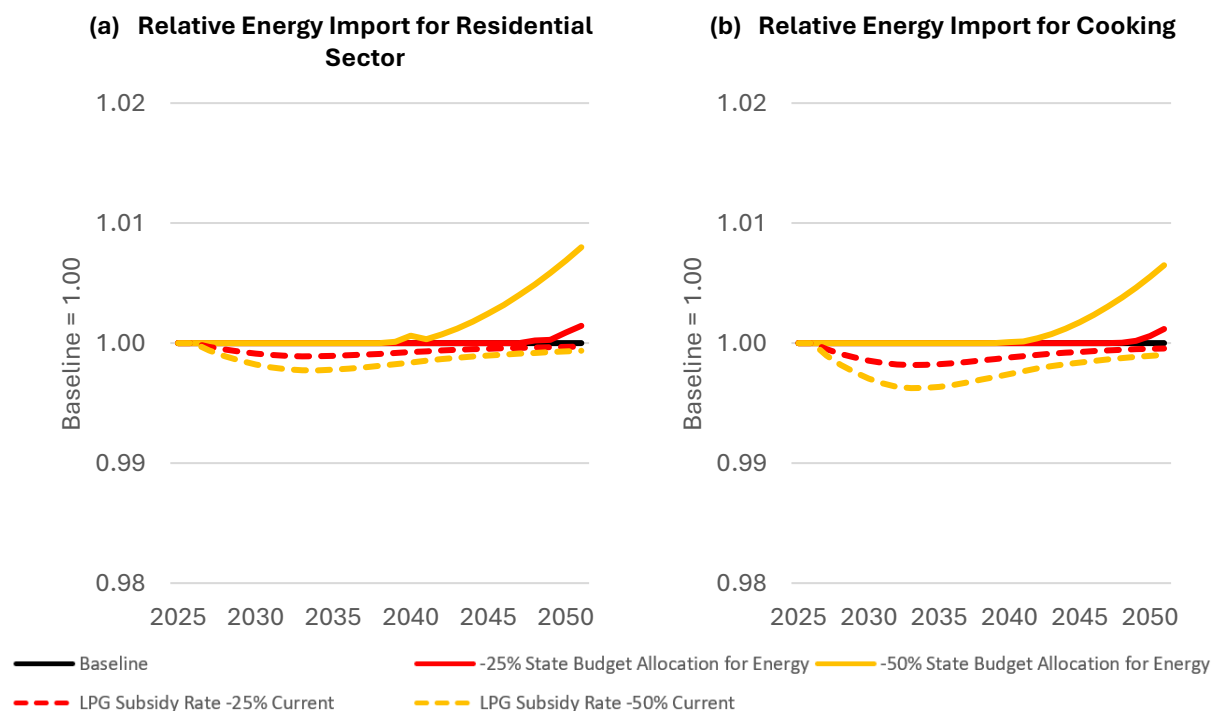


Figure 4.50. Energy subsidy adjustment effect on national energy accessibility.

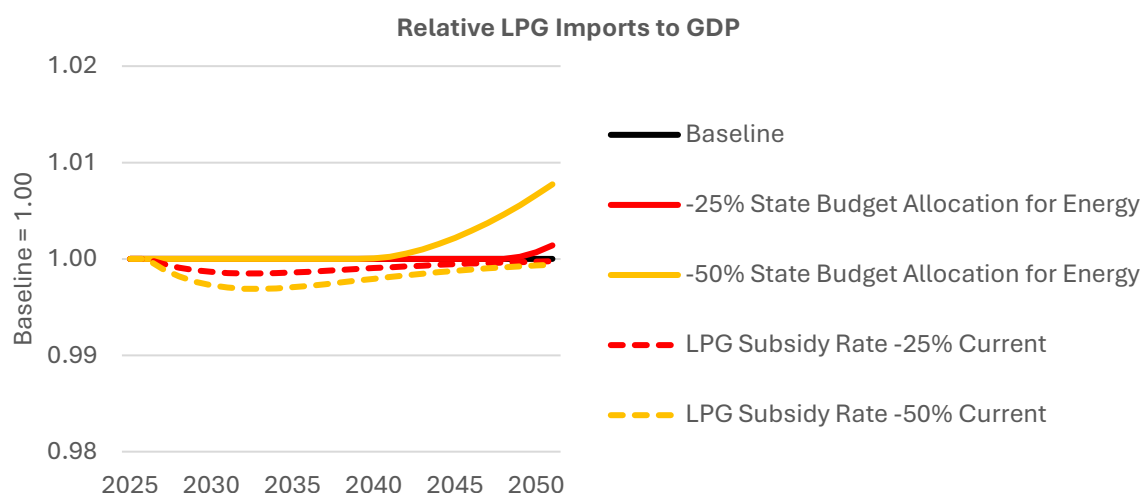


Figure 4.51. Energy subsidy adjustment effect on national energy affordability.

Finally, reducing energy subsidies slightly decreased the grid electricity emissions due to the reduction of electric stove adopters, in line with the result in Figure 4.52. However, while the electricity consumption for cooking is decreased by around 5% in 2050 due to the energy subsidy allocation is being halved, the total grid emission is only reduced by 0.4%, which represents the emission reduction from having less electric stove adopters and not from the other home appliances. The small downward nudge around 2040 in Figure 4.52 shows the effect of the sudden rise in electricity price on the overall electricity consumption similar to that reported by Csereklyei who found there is a short-term and long-term price elasticity on residential electricity demand, although in the short-term it was reported to be inelastic²⁷².

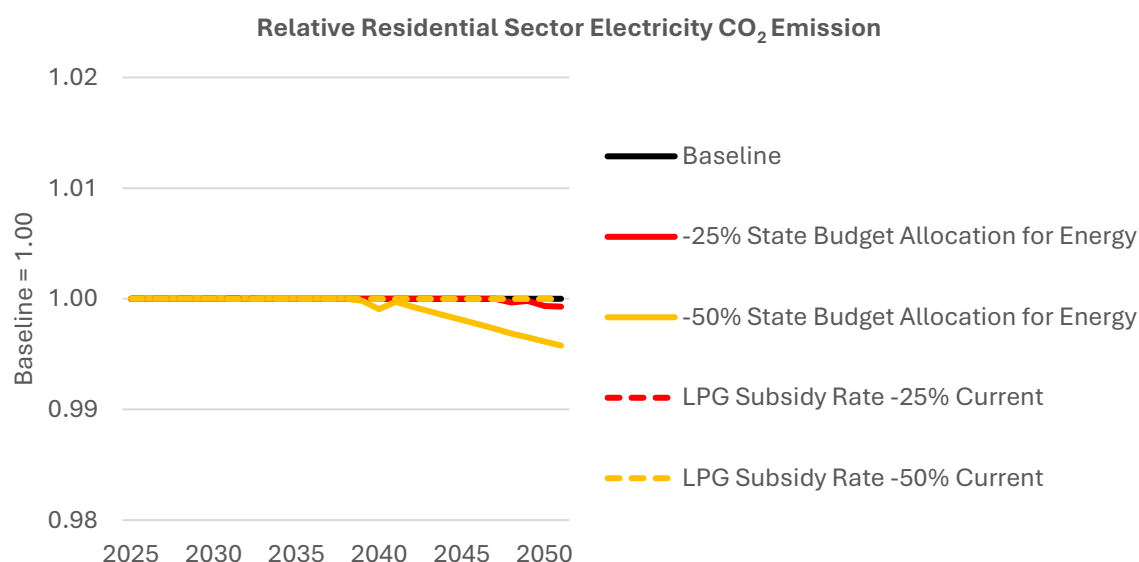


Figure 4.52. Energy subsidy adjustment effect on national energy acceptability.

4.5. Conclusion

The Indonesian residential sector is a recent example of a successful transition to a cleaner energy transition, shifting from traditional fuels to LPG. Nonetheless, the sector has become central subject to further transition, now to a decarbonised fuel. The adoption of two technologies, namely electric stove and rooftop solar has been proposed to achieve the sector's decarbonisation goals. This research investigated the adoption of both technologies and

assessed its impacts on households' energy security based on availability, accessibility, affordability, and acceptability using system dynamics. The Bass Diffusion model was used for the technology adoption, with adoption factors are based on the findings of previous research. The effect of the adoptions of both technologies on energy security is summarized in Table 4.4.

Table 4.4. Summary of the technology adoption impact on household and national energy security

Energy Security Level	Energy Security Indicators	Electric Stove	Rooftop solar
Household	Availability	○ Reduce dependence on traditional and fossil fuel, hence improving household energy availability.	NA Does not have any impact on the dependence in traditional or conventional fuel for cooking.
	Accessibility	○ Increase the accessibility to clean energy.	NA Does not have any impact on the access to clean or zero local emission fuel for cooking.
	Affordability	△ The impact is inequitable, since energy expenditure in low-income households would increase but decreased in other income groups, since the gap between subsidised LPG price to electricity is large.	○ Increase energy affordability by electricity bill savings.
	Acceptability	○ Improves household energy acceptability by reducing NOx emission from cooking.	NA Does not have any impact on the NOx emission from cooking.
National	Availability	△ The increase in electricity consumption would drive exploitation of resources, temporarily increasing availability but will eventually reduce it when the physical limitation of the resources has been reached.	△ Resources availability is temporarily reduced with less grid electricity demand. Once the physical limitation has been reached, its consumption would be less due to the decreased grid electricity demand. Thus, increasing availability.
	Accessibility	○ Improves energy accessibility by reducing the dependence on imported energy	NA Does not have any impact on energy imports.
	Affordability	○ Improves energy affordability by reducing the cost of LPG imports	NA Does not have any impact on energy imports.
	Acceptability	× Increases the grid electricity emissions due to the increase electricity consumption.	○ Reduces grid electricity emissions due to the decreased grid electricity demand.

Note: ○ = Favourable, × = Unfavourable, △ = Temporarily Favourable/Unfavourable, NA = No Significant Effect

Our model showed the general direction of electricity consumption in the power sector, which saturates at a certain level. The consumption growth is due to inclusion of the two most well-documented drivers to energy consumption – household income and house size. The number of low-income households decreased, while middle-income and high-income households

would increase following economic growth. In addition, the number of aspiring middle-income households would increase up to a certain point but then they would climb the socioeconomic ladder, becoming middle-income households. On the other hand, house sizes generally decreased. Thus, while the number of higher income households increased – which should have resulted in a proportionally high electricity consumption – the decrease in house size balances the increase.

With the addition of electric stove adoption however, the electricity consumption in the sector will continue to increase. Electricity for electric stove would be the third largest single component of electricity consumption although its proportion would only be around 24 TWh, or 12%% of the total electricity consumed in 2050 under the baseline. However, the electric stove electricity consumption could jump to 63 TWh should all households are given access to a minimum installed power capacity of 2200 VA. This study also showed that providing purchase incentives for electric stove was not as effective for their adoption as providing support for increasing the installed power capacity. Electric stoves improve all the household energy security indicators. At the national level, the overall impact is positive as adoption of electric stoves naturally exploits renewable energy availability but saves fossil resources availability. In addition, it could reduce dependence on LPG imports which positively affects energy accessibility and affordability. However, the increased electricity consumption led to higher grid electricity emissions. Thus, it is equally important to transition in the power sector.

Rooftop solar were planned to act as a counterbalance to the increase in electricity consumption in the residential sector. However, the results showed the adoption was underwhelming with only 19% of households adopted the technology, generating only 1.8 TWh in the baseline scenario. The government could boost rooftop solar adoption, but they would need to provide 100% purchase incentives until 2050 so that all households adopt them. Should this be implemented, the total generated electricity could reach 19.6 TWh. Even so, the amount of electricity generated will not be able to fulfil the increase in electricity consumption from electric stoves under the same extreme case. Nonetheless, rooftop solar in the residential sector is only one of many ways to exploit solar potential. The large remaining solar potential indicates the immensely untapped solar potential in Indonesia which the other sectors need to exploit also. The adoption of rooftop solar may improve energy affordability at the household level, providing them with electric bill savings which is particularly felt by the lower income households. At the national level, rooftop solar adoption could reduce grid emissions, but it would require massive adoption.

In addition, this study found the adoption of both technologies would be inequitable without any interventions from the government, where higher income households would be the most likely to adopt them and attain their benefits such as reduced NO_x emissions when using electric stoves or reduced electricity bill when using rooftop solar. Furthermore, reducing energy subsidy may shift the energy burden from the national to the household level not only in aggregate but also unequally. While reducing the subsidy would alleviate its strain on the state budget, it would affect low-income households' energy affordability. Thus, the government should also formulate the necessary policy which could balance energy security at both levels.

The policy that seems to be most cost-effective and which can equally benefit household and national level equally is providing all households with access to 2200 VA installed capacity since it was shown to significantly boost the adoption of electric stove. By pushing for electric

stove adoption, the remaining task is to reduce the grid emission factor through the adoption of renewables or improved efficiency in thermal power plants. Since other electricity demand sectors would also benefit the improvements in the power sector, it may not be necessary to aggressively push for rooftop solar adoption in the residential sector since it may be not cost effective should the government provide incentives.

Finally, the model has not been simulated under a scenario, a work to be done in Chapter 6 in this thesis.

Chapter 5

Interplay Between Energy Demand, Energy Supply, and The Environment: Case Study in The Steel Industry Decarbonisation

5.1. Introduction

The industrial sector is the largest energy consumer, consuming on average 37% of the national energy consumption¹. As presented in Figure 5.1, the industrial sectors' energy consumption continues to increase and reaching more than 3 million TJ in 2022. By energy carrier, Figure 5.12 shows that electricity consumption has increased substantially by 6.9% per year between 2011 to 2022 owing to the rapid growth of the consumer goods industry which primarily consume electricity for their production^{116,273}. By 2022, the industrial sector electricity consumption has surpassed 113 TWh¹.

Although the sector is moving towards consumer goods manufacturing, Figure 5.3 shows four industries, namely the iron and steel industry, non-ferrous metal industries, non-metallic minerals (cement industry), chemical and petrochemical industries is responsible for 80% the industrial sector energy demand. Furthermore, the iron and steel industry and non-ferrous metal industries (together the base metal industry) energy consumption have grown even more substantially²⁷⁴. The iron and steel industry energy consumption grew from 11% of total industry sector energy consumption to 36% in 2020, while non-ferrous metals grew much more substantially from 1% to 35%¹. The increase in the base metal industries production in part is the result of increased export²⁷⁵ and the Government of Indonesia (GOI) plan to push for metals downstream production²⁷⁶ to accommodate critical mineral demand for transition technologies, particularly electric vehicles (EV)²⁷⁷. Unfortunately, the base metal industry is energy intensive, relying mostly on coal for their production^{278,279}. As a result, coal consumption has increased at a rate of 6.7% per year since 2011. In addition, the Indonesian steel industry has been more reliant in a more energy-intensive production pathway as shown in Figure 5.7.

The increase in coal demand from the Indonesian industrial sector poses threat to the decarbonisation effort as the nation's economy is expected to continue to grow and subsequently push the demand for industrial products. Electrification of production pathways are available in various industries, however most of them requires high capital investments^{280–283}. In addition, 82% of grid electricity is generated from coal and natural gas¹ which is counterproductive to the decarbonisation effort even production pathways are fully electrified. Taking the power mix into account, the industrial sector obtains 72% of its energy from coal and gas on average when considering primary energy consumption. Hence, it is imperative that the industrial sector itself must be transition into a cleaner production pathway without over relying on the power sector.

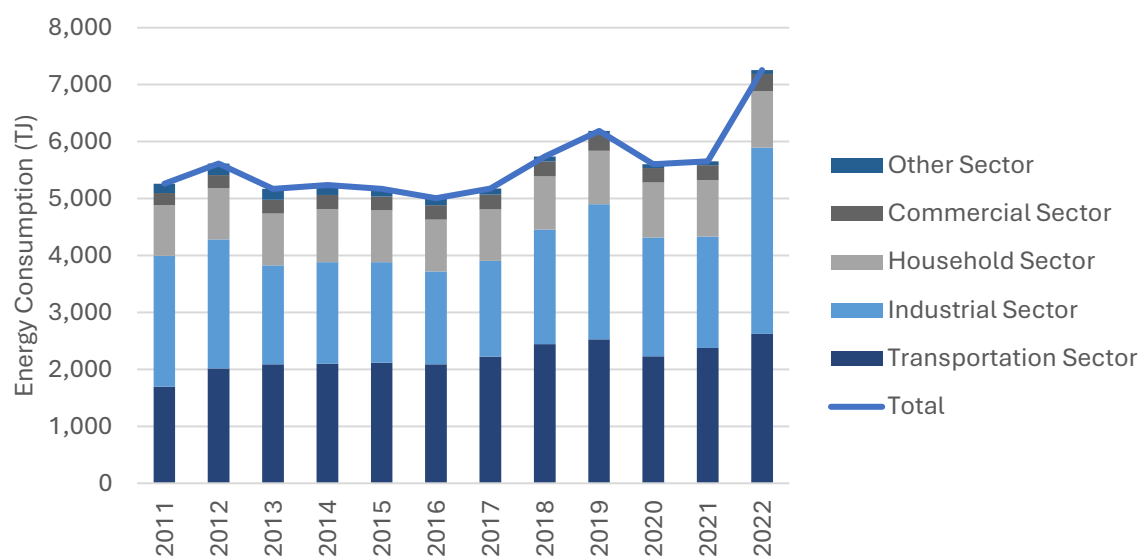


Figure 5.1. 2011-2022 energy consumption by demand sectors¹.

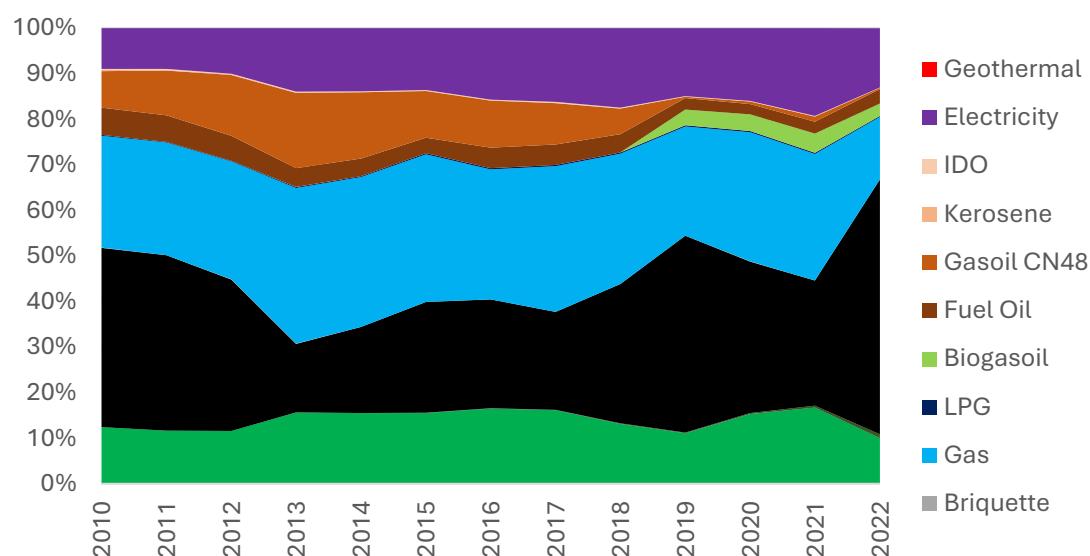


Figure 5.2. Industrial sector energy consumption by industry classification¹.

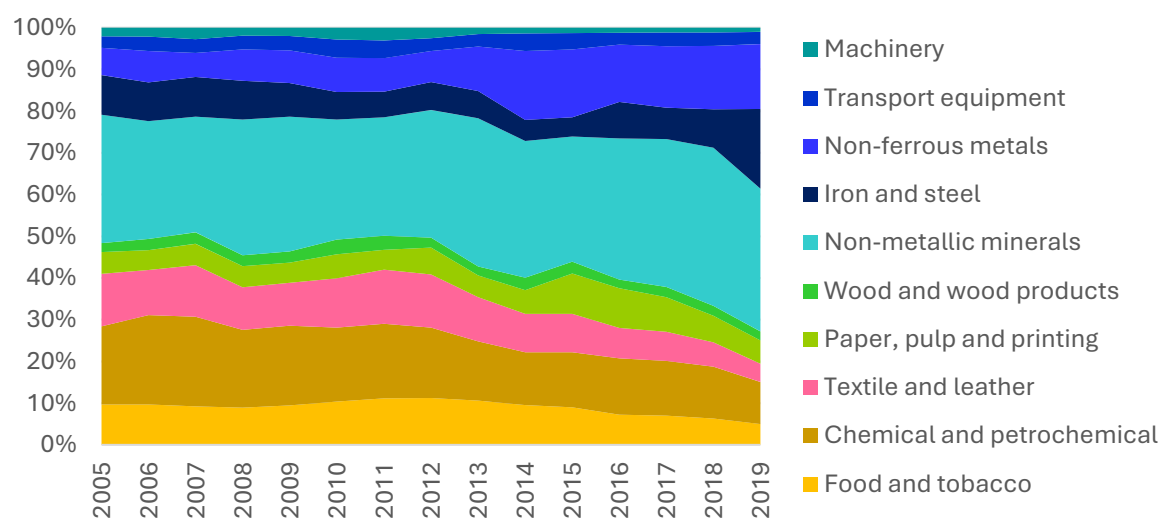


Figure 5.3. Industrial sector energy consumption by industry classification²⁷⁴.

In general, decarbonisation strategies in the industrial sector can be grouped into energy efficiency improvement, raw materials improvement, production pathway electrification, and fuel switches. In many cases, efficiency was shown to have the largest impact to both resource consumption and carbon emission reduction^{284–286}, except for the cement industry where CCUS provided 65% of emission reduction²⁸⁷. In case of steel production, material efficiency is projected to provide 40% of emission reduction, followed by technology performance, and CCUS²⁸⁵. The high capital cost, technology readiness, production process adaptation of electrified production pathway has led to the prescription of fuel switching and energy efficiency for the industrial sector as shown in Table 5.1. Nonetheless, it remains an important strategy in the industrial sector as it is consistently included as one of the key strategies in different industries.

Table 5.1. Decarbonisation and sustainability strategies in different industrial sub-sectors

Cement	Iron & Steel and Non-Ferrous Metals	Chemical & Petrochemicals
• Adopt waste-heat recovery.^{287–289} • Use of low-carbon binding materials and natural supplementary cementitious materials (SCMs).²⁸⁷ • Replacing coal with natural gas, biomass, hydrogen, or wastes.^{287–289} • Process electrification, particularly in pre-calciner kilns.²⁸⁷ • CCUS application.²⁸⁷	• Processing higher grade ores.^{284,285} • Efficiency improvements, for example increasing the use of secondary production or adopting waste heat recovery systems.^{284,285,290} • Electrification or replacement of coal with natural gas, biomass, or hydrogen.^{285,290–292} • Renewable electricity if process is electricity intensive, e.g. aluminium production.²⁹³ • Using CCUS especially if coal is used as fuel.²⁸⁵	• Advanced distillation process, for example, reactive distillation, heat pump distillation, or dividing-wall columns²⁸⁶. • Hybrid chemical separation process²⁸⁶. • Electrification or replacing fossil fuel with renewables as fuel^{286,294,295}. • Feedstock replacement to lower carbon sources, renewables, or hydrogen^{283,294}. • CCUS application^{283,294}.

The Indonesian government have put forth energy policies to accelerate decarbonisation and sustainability strategies in the industrial sector, which can be categorized as fiscal incentives, alternative energy provision, and resource allocation¹⁰. The policies are listed in Table 5.2. Some of them are in line with the decarbonisation strategy in Table 5.1, particularly concerning alternative energy provision. It can also be observed that the Indonesian government has not developed innovation plan on energy substitution, except biodiesel program that has been implemented in all sectors. Instead, the focus is on fiscal incentives and resource allocation strategies. In addition, while the strategies prescribe the moving away from coal, the Indonesian government promotes it instead due to its abundance compared to other fossil fuel¹. While biodiesel is mentioned as an alternative to fossil fuel in the industrial sector, the key energy-intensive industries was found to use only a small portion of oil products in their energy mix as shown in Figure 5.8, hence the effect of the policy is unlikely to be substantial.

Table 5.2. Energy policies in Indonesia aimed at the industrial sector.¹⁰

Fiscal Incentives	Alternative Energy Provision	Resource Allocation
• Energy price regulation for domestic industries to increase value-addition. • Electricity price regulation based on energy intensity. • Fiscal and non-fiscal incentive for energy intensity reduction. • Disincentives for inefficient industries using fossil-fuels.	• Increasing biodiesel production for industrial sector. • Solar power utilization in the industrial sector with mandatory minimum 25% of industrial rooftop are for solar power generation. • Waste heat utilization for industrial thermal process.	• Fossil resources prioritization for domestic industry. • Gradual natural gas domestic market obligation, maximum 20% for exports in 2025, and 100% domestic market in 2036. • Increasing coal utilization for the industrial sector – 55.2 million ton in 2025, and 115 million ton in 2050. • Increasing fossil fuel refinery capacity to reduce imports and improve value-addition.

In line with the alternative energy provision strategy and policy for the industrial sector decarbonisation and pertaining to the scope of this thesis, the effect of production pathway electrification on the industrial sector electricity demand is explored. However, with the breadth of the industrial sector and the unique production pathways, the focus of this study is turned to the iron and steel industry for several reasons. First, the steel industry is energy-intensive which means transition to an electrified production pathway could lead to a high electricity demand²⁷⁸. In addition, the recent production increase in the steel industry could further increase the electricity demand in the future²⁷⁴. Third, the electrified production pathway in the steel industry is a relatively mature technology hence its adoption is more likely²⁸⁵. In fact, steel production facility in Indonesia started by using this technology although recent facilities use the thermal production facilities instead^{296,297}. Finally, the transition to the cleaner production pathway necessitates fuel switch strategy which invokes entanglement with another industry and sector, namely the fertilizer industry and the power sector which will be discussed in detail in Section 5.3.

Before focusing on the steel industry, however, the general dynamics of the energy transition in the industrial sector is presented in Section 5.2. Section 5.4 focuses on the decision of the key energy-intensive industries – steel, cement, non-ferrous metals, chemical and petrochemical industries as explained at the beginning of this section – to outsource their electricity to the grid or to use captive generation. The steel industry energy transition model is integrated in this section, particularly to include the overall energy and resources demand which will be used later in Chapter 6. The implications of the industrial sector energy transition from 5.3 and Section 5.4 on the indicators defined in Chapter 2 are discussed in Section 5.5. Finally, 5.6 concludes the findings and discuss future work regarding the energy transition in the industrial sector.

5.2. General Energy Demand Model and Technology Adoption the Industrial Sector

5.2.1. Industrial Sector Demand

In general, drivers of demand are population, inflation, purchasing power parity (PPP), gross domestic product (GDP), and household final expenditures (HFE) based on the work done by Maaouane et al²⁹⁸. Each industrial sector is affected differently by the changes in these drivers. However, the regression was modified from linear log-regression to a nonlinear regression. The

approach is more fitting since it is desirable to observe the long-run demand, as can also be found in the Solow-Swan model for modelling of long-run economic growth²⁹. The regression model is shown in the following equation

$$y_t = y_0 \left(\frac{POP_t}{POP_0} \right)^\alpha \left(\frac{PL_t}{PL_0} \right)^\beta \left(\frac{PPP_t}{PPP_0} \right)^\gamma \left(\frac{GDP_t}{GDP_0} \right)^\delta \left(\frac{HFC_t}{HFC_0} \right)^\sigma$$

Where y , POP , PL , PPP , GDP , and HFE are the demand, population, price level, purchasing power parity, gross domestic product, and household final consumption expenditure. The subscript 0 denotes the initial value of the respective variable while t denotes the value of that variable at time t .

The result of the demand regression result for the steel industry and fertilizer industry is shown in Table 5.3.

Table 5.3. Nonlinear Regression Result for Industrial Sector Demand

	Steel	Cement	Non-Ferrous Metals	Fertilizer	Plastics
R2	0.948	0.992	0.944	0.998	0.999
Significance F	0.000	0.000	0.000	0.000	0.000
α (Population)	9.480	-1.350	0.000	0.191	0.527
β (Price level)	-16.045	-0.290	0.000	1.285	-0.148
γ (PPP)	7.769	0.750	-5.830	-0.430	0.289
δ (GDP)	33.050	-5.530	0.000	-0.923	0.688
σ (Household Final Expenditure)	-32.571	7.420	6.999	0.958	-0.365

In addition, the consumption per capita y_t^{cap} is included as the minimum demand for each industrial sectors. Using the same regression approach as in Watari et al.²⁹⁹ who investigated the base metals per capita consumption evolution with respect to GDP per capita, the per capita consumption for cement, chemical and petrochemical industries was also performed using Indonesian data^{106,300,301}. Hence the demand for a certain industry is defined as:

$$y_t^* = MAX(y_t, y_t^{cap})$$

5.2.2. Fuel Switch and Technology Adoption in the Industrial Sector

The historical demand becomes the basis for the long-term demand projection, which in turn relates to the required production capacity. The gap between required and current production capacity induces new capacity addition, along with renewals for capacities that have reached their end-of-life. In case new capacity is required, the decision whether to invest in the electrified production pathway is determined by its relative benefit over conventional. The factors considered in the relative benefit determination are economic, environmental, technological, and organizational. The technology adoption framework is based on the Technology, Organization, and Environment (TOE) framework³⁰². The economic criteria were separated which is normally accounted in either the technology or environment criteria since the effect of economic factors on the adoption of the technology adoption needs to be clarified. For each of the criteria, literature review was conducted to find the suitable adoption factors.

For the economic criteria, investment cost^{303–307}, investment profitability^{304,306–309}, production cost^{302,303,308}, product price^{305,309}, and demand uncertainty^{302,303,306,307} were found to be the most occurring factors. The environmental factors are relatively straight forward where environmental footprint to be the most discussed^{309,310}. This study further specifies the environmental footprint into emissions to air, soil, and water as is calculated in the Life Cycle Assessment (LCA) method³¹¹. In addition, energy supply and land-use are also discussed³⁰⁸. The most occurring technological factors are technology compatibility^{302,303,305,307,308,310,312}, lifetime³¹⁰, effect on product quality^{305,307–309}, and production throughput^{307,309}. Specifically for the power sector, reliability and resilience was found to be an important factor^{313–315}. Finally, for organizational factor the factors are alignment with company strategy^{302,303,305,306,309,312}, inspection frequency³¹⁰, government incentives^{302,303,305}, regulatory support^{302,305,309,310}, and workforce readiness^{302,303,305,306}.

This study interprets energy supply as resource availability, adapting from the energy supply security concept³¹⁶. Supply security is a relevant adoption factor as explained in the Indonesian National Energy Plan¹⁰, and especially in the renewable energy context. Although Indonesia has a large potential for renewables, in some cases it is concentrated¹¹⁹. For example, hydropower is concentrated in Kalimantan, Sulawesi, and Sumatera islands, while geothermal supply is concentrated in Java Island¹¹⁹. For solar power, while the eastern part of Indonesia has higher solar irradiation, they have less land area than the western part^{317,318}. As a result, solar potential is dominant in Sumatera, Kalimantan, and Papua islands. The framework is illustrated in Figure 5.4.

Technology Adoption Factors			
Economic	Investment Cost	Environmental	Resource availability
	Investment Profitability		Land-Use
	Production Cost		Emissions to Air
	Product Price		Emissions to Soil
	Demand Uncertainty		Emissions to Water
Technological	Technology Compatibility	Organizational	Alignment with company strategy
	Lifetime		Inspection frequency
	Effect on Product Quality		Government incentives
	Production Throughput		Regulatory Support
	Reliability & Resilience		Workforce Readiness

Figure 5.4. Technology Adoption Framework

Experts from each respective industry were interviewed to filter out irrelevant adoption factors after which the Analytic Hierarchy Process (AHP) was conducted to weigh the factors. The weights of the relevant factors are presented in Table 5.4. Factors in Figure 5.4 which are not in Table 5.4 means they are not relevant based on the interview result.

Table 5.4. The weights of the adoption factors and criteria. Factors with “N/A” value indicates it was not found to be relevant by the interviewed experts.

Criteria/Factors	Steel	Cement	Non-Ferrous Metals*	Fertilizer	Plastics	Power Sector
Economic	0.295	0.380	0.295	0.304	0.494	0.384
Investment cost	0.405	0.170	0.405	0.333	0.454	1.000
Investment profitability	0.115	0.560	0.115	0.333	0.417	N/A
Production cost	0.480	0.270	0.480	0.333	0.129	N/A
Environment	0.434	0.380	0.434	0.090	0.179	0.097
Resource availability	0.875	0.330	0.875	0.500	0.209	0.75
Emissions to air	0.125	0.670	0.125	0.500	0.791	0.25
Technological	0.212	0.060	0.212	0.526	0.254	0.228
Technology compatibility	1.000	1.000	1.000	1.000	1.000	N/A
Production throughput	N/A	N/A	N/A	N/A	N/A	0.250
Reliability & resilience	N/A	N/A	N/A	N/A	N/A	0.750
Organizational	0.059	0.180	0.059	0.080	0.073	0.291
Alignment with company strategy	0.063	0.430	0.063	0.145	0.300	N/A
Government incentives	0.303	0.170	0.303	0.405	0.214	0.429
Regulatory support	0.358	0.220	0.358	0.405	0.327	0.429
Workforce readiness	0.275	0.180	0.275	0.045	0.159	0.143

*) For Non-ferrous metal industry, steel industry result is used since no respondents were obtained

The technology with the higher perceived benefits would be invested in, reducing the need to add capacity, creating the balancing loops B1 and B2. Both capacities have their lifetime. In time, firms would need to decide whether to extend their life or replace them, signaling capacity investment (loops B3 and B4). Installed capacities affect production energy and resources intensity, and in turn, consumption. The decision to invest in a certain capacity could affect production costs. Changes in production cost could affect the price of goods, which then affects demand for goods (balancing loop B5). The dynamics of technology adoption is depicted in Figure 5.5. As for fuel switching, while it does not necessarily need to be initiated by the required additional capacity, the dynamics remain the same. The external force for fuel switching may be in the form of the increased economic, environmental, technology or regulation benefit of the alternative fuel – the same adoption factors in technology adoption.

The two balancing loops between technology capacity additions (B1 and B2), creates a reinforcing loop (R1), i.e. an investment in one technology could continue if there is no

intervention in the system, a phenomenon called “technology lock-in”³¹⁹. On the other hand, the opportunity to adopt new technology comes from additional demand or capacity decommissioning. Early retirement would cost firms. Policy interventions could modify the reinforcing loop, by modifying the relative benefit of a technology. Indeed, its effect would be contradicting on the different side of technologies. The dynamics is then transformed into Figure 5.6 where the balancing loops B1 and B2 is replaced by R1.

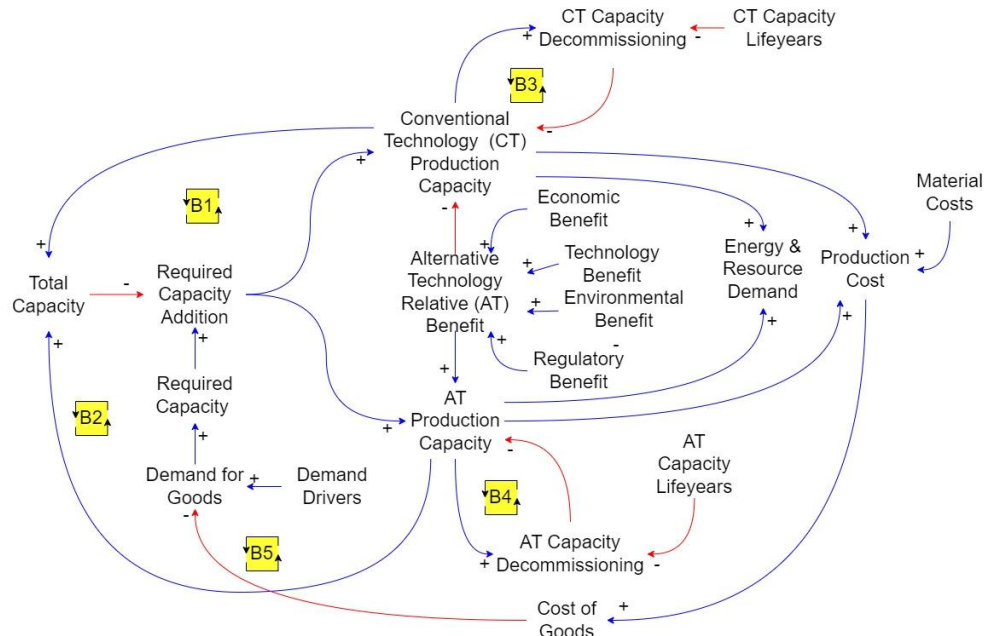


Figure 5.5. General Technology Adoption Model in the Industrial Sector

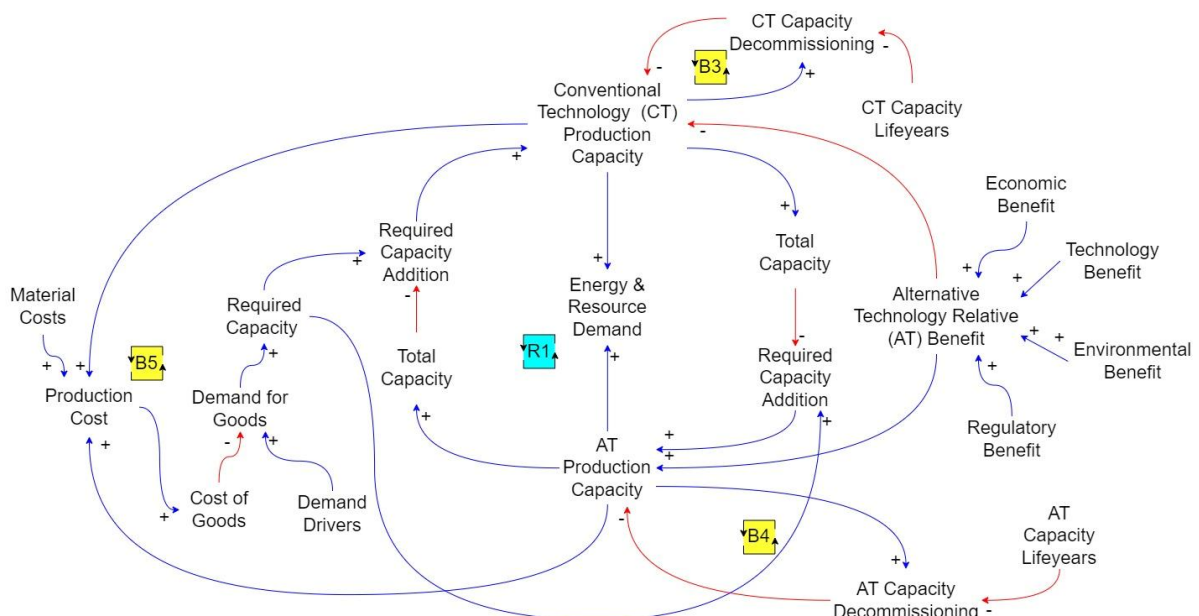


Figure 5.6. The “technology lock-in” phenomenon in the Industrial Sector

5.2.3. Factors affecting energy intensity in the energy-intensive industries

Energy price, industrial mix, and Capacity utilization was reported as a common factor affecting energy intensity. Capacity utilization has the largest impact, where low capacity utilization increases energy intensity with a factor of -0.9³²⁰. Specific to the steel industry,

Katada (1980) concludes that the hot metal ratio in the Basic Oxygen Furnace (BOF) in steelmaking, fuel rate in Blast Furnace (BF) in ironmaking, and production load affect overall energy consumption³²¹. He continues to find that a 1% increase in the hot metal ratio increases energy consumption around 160 to 200 MJ per ton of steel³²¹. In addition, an increase of 10 kg of fuel per kg of pig iron leads to a 210 MJ per ton of steel³²¹.

Production load and energy intensity follow a negative exponential curve. Production curtailment affects energy consumption in two mechanisms. First, it would increase the hot metal ratio, which increases energy consumption. Second, it would increase the need for wasted energy consumption to keep the facility running³²¹.

Similar to the steel industry, capacity utilization is a significant factor to energy intensity with low utilization leading to higher energy intensity³²⁰. The impact of capacity utilization has on energy intensity is exemplified by the cement industry in Indonesia whose energy intensity decreased from 4.23 GJ/ton of cement in 1990 to 2.62 GJ/ton of cement in 2020, while production almost tripled in the same period²⁸⁹.

Processing low raw material quality also leads to a higher energy consumption in metal industry^{284,322}, cement³²³, and chemical and petrochemical industries^{294,324}. Production method also affects energy consumption, for example a shift from wet to dry production in the cement industry improved energy efficiency by 26%-58% since nearly 41% of energy in the wet process is spent in evaporating moisture³²³.

Fuel mix is another common factor shown to affect energy intensity³²⁰. For example, the energy intensity using best available technologies for Natural gas as feedstock is 28 GJ/ton while the intensity is 42 GJ/ton if using coal³²⁵. Propylene from coal was found to consume 2.6 and 2 times more energy than petroleum catalytic cracking. Furthermore, it emits GHG more than 5 times than the conventional route³²⁶.

5.2.4. Fuel mix in the energy intensive industries

Globally, BF-BOF pathway is currently dominated by coal (89%) while the electric arc furnace (EAF) – the electrified production pathway – is dominated by electricity (50%) followed by natural gas (38%)³²⁷. However, Figure 5.7 shows that the Indonesian iron and steel industry saw a drastic change in fuel mix over the last decade due to shift from EAF to BF-BOF as the dominant production pathway²⁹⁷. As the result, now 87% of the energy consumed in the iron and steel industry comes from coal while previously it was only 4%²⁷⁴ as shown in Figure 5.8.

Like the steel industry, the cement industry is also known to be a main consumer of coal (See Figure 5.8). The average coal use in the cement industry fuel mix between 2001 and 2021 is 71% which is actually much higher than the steel industry (52% on the same period)²⁷⁴. As one of the ways to decarbonize, the steel industry has been attempting to replace coal with biomass and refuse-derived fuel (RDF)^{288,289}. This attempt strongly indicates that process electrification is not yet considered as part of their decarbonisation strategy.

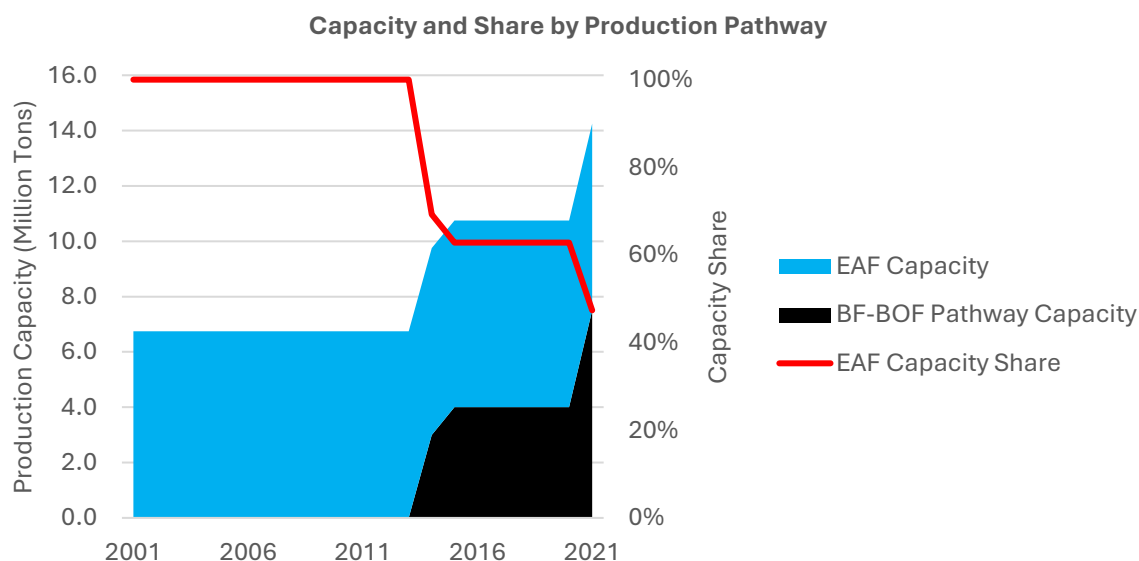


Figure 5.7. Steel Industry Production Pathway Shift^{297,335}.

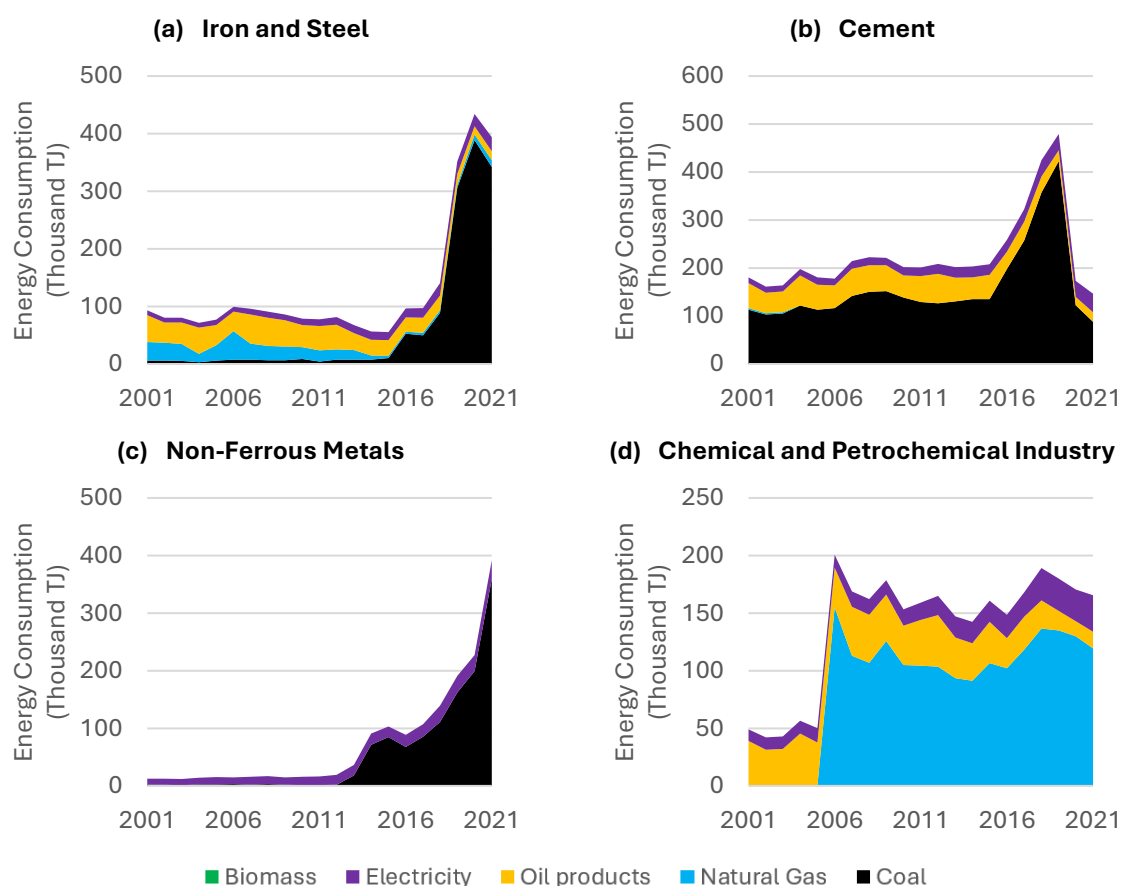


Figure 5.8. Fuel Mix in the other Indonesian energy intensive industries 2001-2021²⁷⁴. Electricity consumption is calculated based on Input-Output Table³³⁵.

The fuel mix in the non-ferrous metals industry varies according to its products and producers. The literature survey found that nickel, copper, and tin refinery used mostly fossil fuel^{279,328,329} in their process while aluminium primarily used electricity³²⁹. In case of Indonesian production, aluminium production obtained all of their energy for smelting and refining from

hydropower³²⁹. Energy for nickel production in Indonesia are almost evenly supplied from coal, diesel, and hydropower²⁷⁹. The copper smelting process uses the Mitsubishi process while the ISA process is used for copper refining^{330,331}. The Mitsubishi process use fossil fuel (57%) and electricity (43%)³³², while the ISA process fully uses electricity as its final energy³³³. Finally, tin production in Indonesia primarily uses fuel oil and electricity both from diesel captive generation and from grid³³⁴.

The chemical and petrochemical industry is a diverse industry, but the major products are fertilizer and plastics²⁹⁴. The fertilizer industry obtains most of its energy from natural gas (65%) since it also serves as the primary feedstock. In addition, coal (20%) and electricity (15%) are also used in the process, for use in boilers and for supporting plant utilities, respectively³⁰⁰. As for plastics production, nearly 90% of their energy input oil products followed by electricity, and a fraction of natural gas³⁰¹.

5.2.5. Model Testing

The model testing method is the same as in Chapter 3, namely MAPE and Theil's statistics. The variables that are validated industrial demand and energy demand. In general, the model simulation results are compared to the historical data from 2005 to 2022. However, for the chemical and petrochemical industry energy demand, the simulation model is compared historical data from 2014 to 2022 due to data limitations.

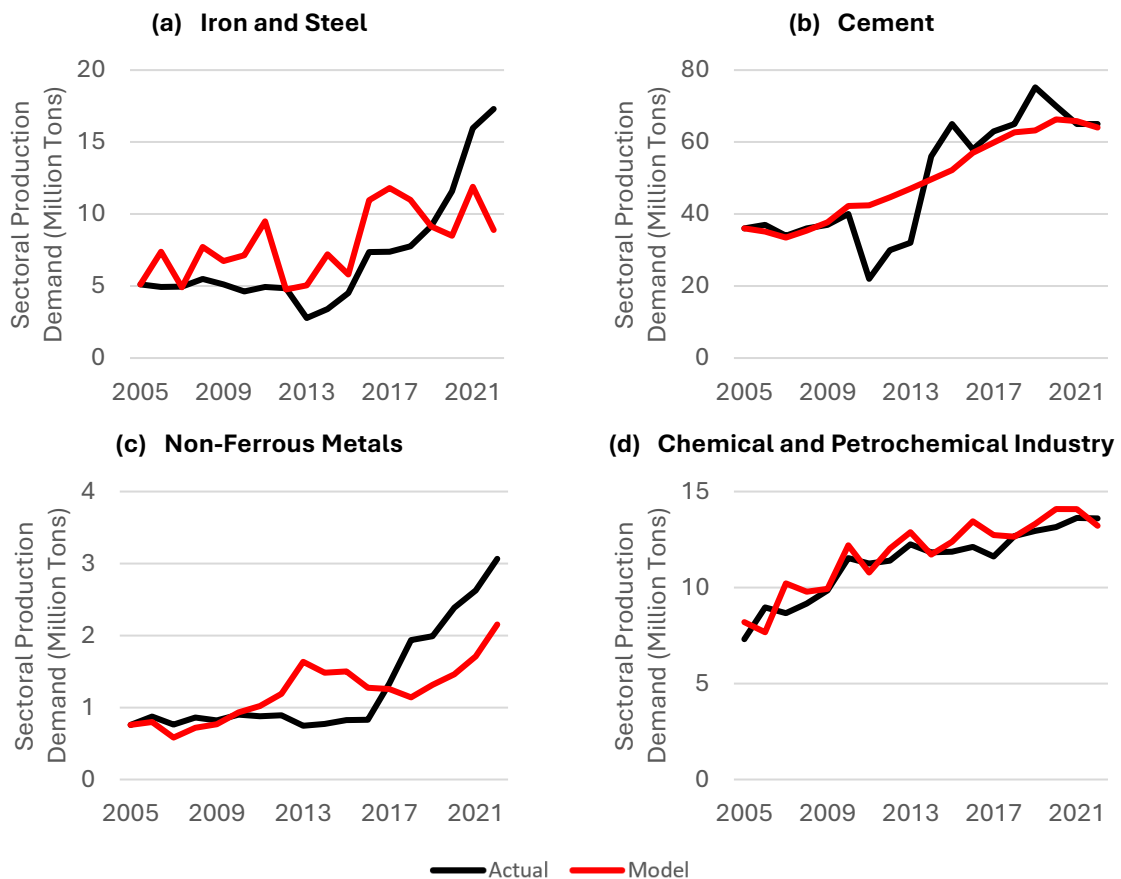


Figure 5.9. Model Demand Validation.

According to the result, the correlation between the historical and the model output for the iron and steel, cement, non-ferrous metals, and chemical and petrochemical industries are 0.58, 0.88, 0.66, and 0.93 respectively, while mean average percent error (MAPE) are 0.41, 0.15, 0.36, and

0.06, respectively. Although the MAPE for iron & steel and non-ferrous metals are relatively large, Theil's statistics test revealed that the error is unsystematic ($U_{iron\&steel}^C = 0.69$ and $U_{non-ferrous\ metals}^C = 0.63$). As explained above, since this model does not study cycles within the actual data and focuses on the trend, the large U^C is not considered systematic, and the model can be considered valid. The comparison between the actual sectoral demand data and its respective model output are shown in Figure 5.9. For the chemical & petrochemical industry, only the fertilizer demand data is shown since plastics demand data was not available.

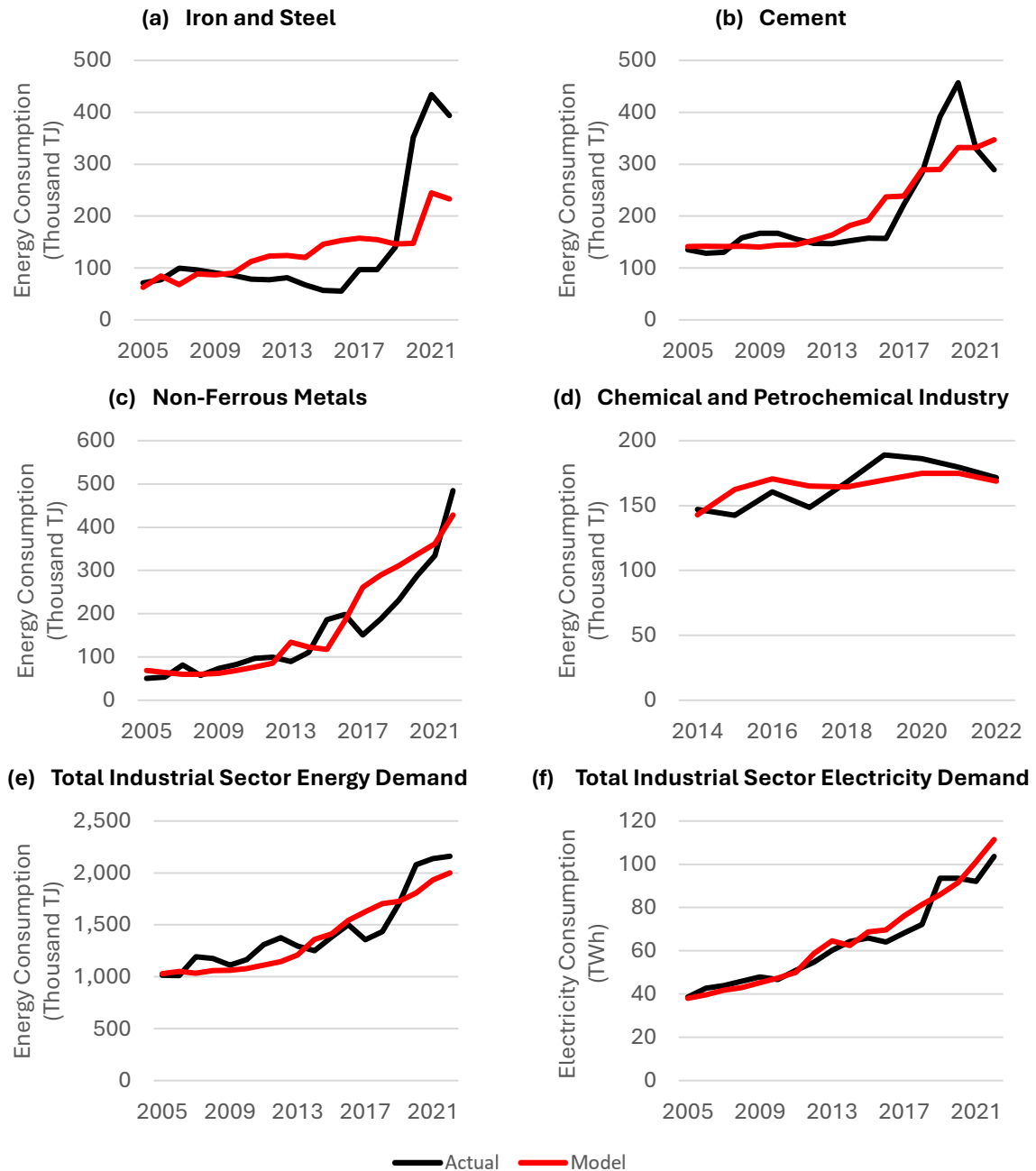


Figure 5.10. Model validation of energy consumption for the industrial sector.

As with the demand modelling, energy demand was also done on energy consumption in each sector. The steel industry energy consumption experienced a declining trend between 2005 and 2016, however the consumption then surged dramatically. This increase can be traced to the increased proportion of the Blast Furnace Basic Oxygen Furnace (BF-BOF) production

pathway which is more energy intensive. The Indonesia steel industry was dominated by the Electric Arc Furnace (EAF) pathway since its inception in the 1970s. The first BF-BOF integrated steel making was introduced in 2013 and then the capacity was doubled in 2019. The model was able to capture the shift in this technology as shown in Figure 5.9(a) although the increase was not as sharp as the actual data. Despite the point-to-point inaccuracy, the model can be considered valid since the correlation and covariance inequality is acceptable ($r = 0.75$, and $U^C = 0.68$). The error relatively large error ($MAPE = 0.51$) is attributed to the demand's error – $MAPE = 0.41$ but unsystematic – indicating the additional error from the energy consumption model was minor.

The cement industry energy consumption follows a rather steady increase from 2005 up to 2017 but then increased rapidly from 2017 to 2019. The cement sector energy consumption model is still sufficient given the statistical validation results ($r = 0.87$, $MAPE = 0.15$, and $U^C = 0.81$).

Energy consumption in the non-ferrous metals industry, which main products in Indonesia are copper, nickel, aluminium, and tin, showed an exponential increasing trend. The increase is attributed to the production increase as shown in Figure 5.9 (c), which was the result of the down streaming policy. The model was able to capture the energy consumption trend ($r = 0.92$) as shown in Figure 5.10(c). The error ($MAPE = 0.25$) is considered to be unsystematic ($U^C = 0.90$).

The chemical & petrochemical industry comprised of, in general, the fertilizer industry and the plastics industry. In Indonesia, the fertilizer industry is dominated by a state-owned company, whose market share is larger than 90%³⁰⁰. On the other hand, the plastics industry market share is more distributed but still dominated by one company. The IEA reports that the chemical & petrochemical industry energy consumption showed a decreasing trend²⁷⁴ despite increasing company reports showed otherwise^{300,301}. However, when comparing with 2014 to 2022 historical data the model showed acceptable results with $r = 0.68$, $MAPE = 0.06$, and $U^C = 0.65$, which tells that the model can, in general follow the actual data behaviour with minimum error, and that error is unsystematic.

5.3. Steel Industry Decarbonisation Case Study

In general, there are two steel production pathways³³⁶. First is the Blast Furnace-Basic Oxygen Furnace (BF-BOF) which produces steel from iron ore that is reduced using coking coal³³⁶. This process is the dominant production pathway globally due to its lower cost and its production of primary steel, rather than dependence on scrap or Direct Reduced Iron (DRI)³³⁶. However, it is also very carbon intensive due to the use of coal for energy and coke for the reduction process. The second pathway is the Direct Reduction Iron-Electric Arc Furnace (DRI-EAF) production pathway. In the process of making iron, it typically utilizes natural gas as a reducing agent, which is less carbon intensive³³⁶. In the EAF steel making process, the main input energy is electricity, which further reduces the direct carbon intensity in the process but is three-times more electricity-intensive³³⁶. While other decarbonisation strategies are available, including the use of carbon capture and storage (CCS) technology and coal substitution, production electrification using DRI-EAF is the most widely considered strategy for decarbonising the sector globally as it would also enable incorporating renewable electricity in steel production.

To further accelerate decarbonization, hydrogen has been considered as an alternative to coal or natural gas, both in the iron ore reduction process and as a fuel³³⁶. It has been shown that hydrogen can be introduced to the existing DRI-EAF production at a 33.3% injection rate without any modifications³³⁷. However, there are several barriers in implementing this strategy in Indonesia. Firstly, most BF-BOF facilities in Indonesia are still relatively new²⁹⁷, thus their early retirement will be costly. Secondly, it must be noted that the hydrogen itself must be from produced via non-carbon routes for it to be a viable decarbonization alternative to coal and natural gas. Blue and green hydrogen are the labels given to zero-carbon-emissions hydrogen production. Blue hydrogen is produced from fossil fuels with carbon capture and storage (CCS) (typically carbon-capture-paired steam methane reforming), while green hydrogen is obtained from water electrolysis using renewable-sourced electricity (RE). Green hydrogen is currently still very costly at around 2.7-2.9 US cent/MJ compared to 0.2 US cent/MJ for natural gas and 0.3 US cent/MJ for coking coal^{217,338,339}. Even if this barrier were to be by-pass through, for example a large subsidy, its availability remains to be addressed³⁴⁰.

In transitioning to hydrogen-based steel production, the steel industry must rely on the availability of hydrogen, preferably domestically from the perspective of energy security. Hence it is important to identify potential producers. The fertilizer industry has been producing hydrogen using natural gas in the production of ammonia, albeit without carbon capture and storage (CCS) technologies. In line with its own decarbonization efforts, the Indonesian fertilizer industry is planning to adopt CCS, enabling them to produce blue hydrogen³⁰⁰. In the longer term, they expect to move towards green hydrogen³⁰⁰. Another potential hydrogen supplier is the power sector, which recently trialled green hydrogen at pilot scale using geothermal electricity³⁴¹.

Even with these potential domestic suppliers, the actual availability of hydrogen is still uncertain. Firstly, the production of hydrogen in the fertilizer industry is mostly captive, being exclusively used for ammonia production within the sector. While they may be able to increase their capacity to fulfil demand from other sectors, this would present a new risk to their ongoing business. As for the power sector, the current pilot plant was made possible due to an increasing over-capacity of electricity generation¹. With the desire to accelerate economic growth³⁴², the heavy electrification in the transportation sector³⁴³, and the expected increase in electricity for a DRI-EAF transition, the power sector may have problems in producing sufficient green hydrogen.

Ledari et al. found that national circumstances and availability of resources constrain decarbonization efforts in the steel industry³⁴⁰. In addition, they suggested that countries with fossil fuel resources would be best to adopt blue hydrogen in the production of steel –which they termed “blue steel” – since using green hydrogen would be too costly³⁴⁰. However, with the cost of green hydrogen expected to fall along with the declining costs of RE³⁴⁴ and electrolyzers³⁴⁵, this situation may change. Watari & McLellan project the global demand for green hydrogen-based steel – green steel – in 2050 could reach 660 Mt which would require 41 Mt of green hydrogen and 561 GW electrolyser capacity³⁴⁶. These requirements amount to 1000 times that of the current level³⁴⁶. The required RE specifically for steel production would also need to be expanded dramatically to 2556 TWh - equal to the total current global solar and wind power generation³⁴⁶. Hence, there are clear resource constraints to green hydrogen availability despite its expected reducing cost. Regarding these resource limitations, Indonesia is an interesting case, since it has potential resources to produce both types of hydrogen.

With this background in mind, the aim of this study is twofold. First is to investigate hydrogen availability – both blue and green – for the steel industry. Secondly, pertaining to the goal to decarbonise the sector, is to identify the potential levers to increase the adoption of hydrogen-based steel production. The structure of the problem entails simultaneous feedback between the steel industry, the potential hydrogen producers, and resources. In addition, a quantitative method is required to be able to simulate the hydrogen-based steel production adoption process. A method that can simulate how different uncertainties affect the model, and to find potential levers for the goal at hand is also essential. For these reasons, system dynamics was selected as a suitable method.

In next section the system dynamics model is presented in detail. The results of the study are presented in two different sections. In Section 5.3.3, the results of the simulation under the baseline settings are presented, then in Section 5.3.4 and 5.3.5, the results of the uncertainty tests are given. In Section 5.3.6, the results are discussed in more detail, focusing on the interaction between the sub-systems involved. Finally, the practical implications and key points for further research will be elaborated together with discussion from the other energy-intensive industries in Section 5.6.

5.3.1. Steel Industry Energy Transition Model Building

5.3.1.1. *Model Structure*

Figure 5.11 shows the conceptual dynamics of the system under consideration. The structure is based on the general model introduced in Section 5.2, but with the specific context for the steel industry. Specifically, the cleaner production pathway capacity is specified as the DRI-EAF capacity. Furthermore, this study added the dynamics of the hydrogen supply for this specific model.

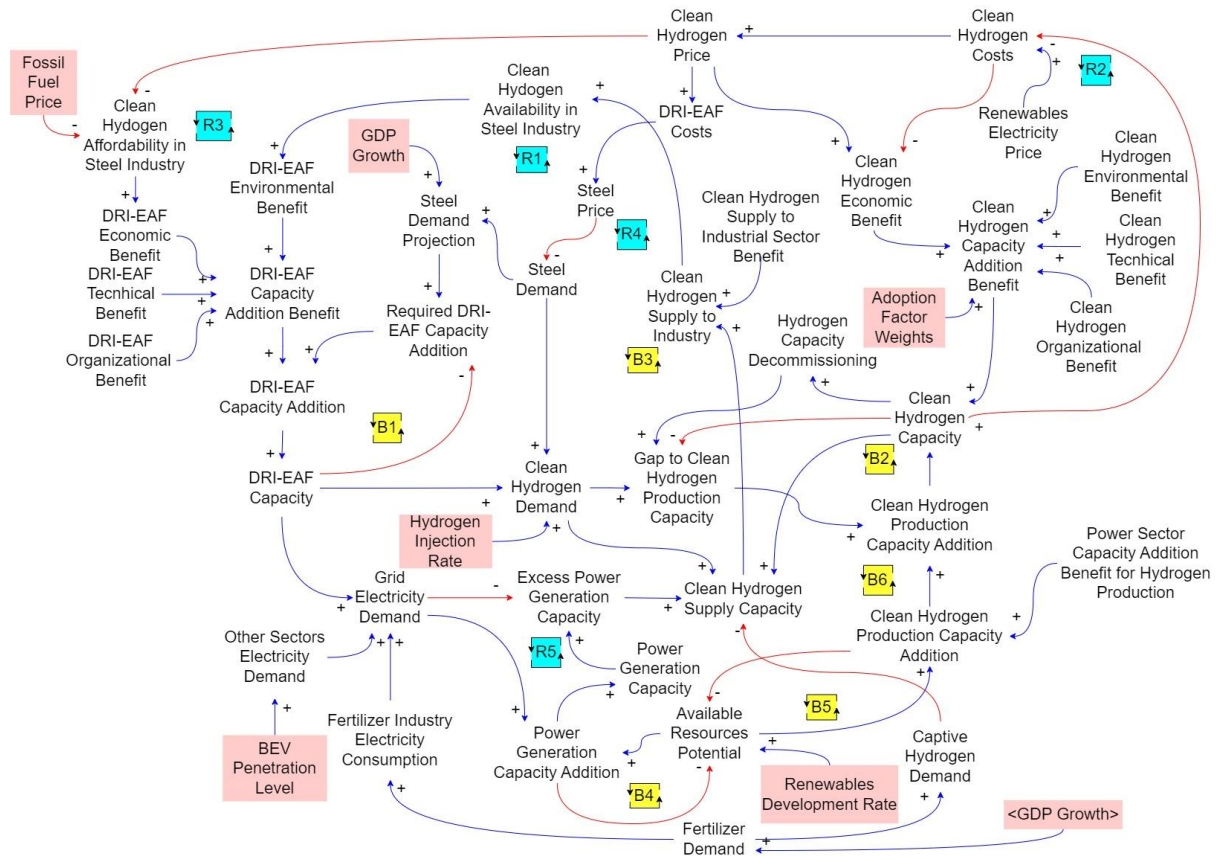
As with the general model, once the decision has been made it will fulfil the required capacity addition, creating the balancing loop B1. An increase in H₂-DRI-EAF capacity would lead to two things. First is the increase for clean hydrogen demand, and second is the increase in grid electricity demand.

The increase in H₂-DRI-EAF capacity initiates the need to add hydrogen production capacity. Whether to produce blue or green hydrogen (or none) is again determined by the economic, environmental, technological, and organizational benefits of the blue or green hydrogen. After the either hydrogen production capacity has been added it will balance out the need for additional capacity (B2). In time, the hydrogen production capacity will be decommissioned, initiating again for capacity investment requirement and then fulfils the demand under the same process.

An addition in the clean hydrogen production increases the supply for the steel industry and its availability. This would have a positive effect on the H₂-DRI-EAF relative benefit, increasing its chance for adoption, creating the reinforcing loop R1. Furthermore, an addition in clean hydrogen production capacity could reduce its cost in the long-run due to the learning effect³⁴⁵. In turn, this would increase the economic benefit of clean hydrogen adoption and their overall benefit, increasing the chance for them to be adopted in the next required capacity addition. This positive feedback serves as the second reinforcing loop (R2) in the system. The declining cost of hydrogen also benefits the adoption of H₂-DRI-EAF, increasing its affordability and then economic benefit, creating the reinforcing loop R3. Furthermore, the cost of hydrogen would also affect the price and demand of steel. The price of steel acts as negative feedback to

its demand³⁴⁷, and to an extension the demand and production capacity of hydrogen. However, the hydrogen production capacity serves as negative feedback to its production cost. This two negative feedback create another reinforcing loop R4, connecting the price of hydrogen to steel demand.

The other consequence of adding H₂-DRI-EAF capacity is the potential increase in grid electricity demand. Since the technology is electricity intensive³³⁶, it could put a heavy burden on the grid if the electricity is not supplied from captive generation. The substantial increase in grid electricity demand would limit the excess power generation capacity which could have been used to produce green hydrogen and limits the availability of hydrogen in the steel industry, thus creating the balancing loop B3. Eventually however, the increasing demand would send a signal for additional power generation capacity installation which could create an excess in power generation and the chance for increased hydrogen production from the power sector. In the end, the increase in grid electricity demand due to the increased adoption of H₂-DRI-EAF could also potentially create the reinforcing loop R5.



Note:

Blue arrows (→+) indicate a positive relationship between two variables, while red arrows (→-) indicate a negative relationship. Loops – a circular relationship between variables – are highlighted in blue and yellow. The two types of loop R and B refers to reinforcing loops (positive feedback) and balancing loops (negative feedback), respectively. The loops can be identified by tracing the loop names indicated on the lines connecting the variables. The variables highlighted in pink are uncertainties to the system as will be described in Section 5.3.2.

Figure 5.11. Causal Loop Diagram in the DRI-EAF Adoption in the Iron & Steel Industry.

Table 5.5. List of loops in the system model.

Loop	Variables involved
B1	Required DRI-EAF Capacity → DRI-EAF Capacity Addition → Required DRI-EAF Capacity
B2	Gap to Clean Hydrogen Production → Hydrogen Production Capacity Addition → Gap to Clean Hydrogen Production
B3	Grid Electricity Demand → Excess Power Generation Capacity → Clean Hydrogen Supply Capacity → Clean Hydrogen Supply to Industry → Clean Hydrogen Availability in Steel Industry → DRI-EAF Environmental Benefit → DRI-EAF Capacity Addition → DRI-EAF Capacity → Grid Electricity Demand
B4	Power Generation Capacity Addition → Available Resources Potential → Power Generation Capacity Addition
B5	Hydrogen Production Capacity Addition → Available Resources Potential → Hydrogen Production Capacity Addition
B6	Power Generation Capacity Addition → Available Resources Potential → Clean Hydrogen Production Capacity Addition → Clean Hydrogen Capacity → Clean Hydrogen Supply Capacity → Clean Hydrogen Supply to Industry → Clean Hydrogen Availability in Steel Industry → DRI-EAF Environmental Benefit → DRI-EAF Capacity Addition → DRI-EAF Capacity → Grid Electricity Demand → Power Generation Capacity Addition
B7	Power Generation Capacity Addition → Available Resources Potential → Clean Hydrogen Production Capacity Addition → Clean Hydrogen Capacity → Clean Hydrogen Costs → Clean Hydrogen Price → Clean Hydrogen Affordability → Clean Hydrogen Affordability in Steel Industry → DRI-EAF Environmental Benefit → DRI-EAF Capacity Addition → DRI-EAF Capacity → Grid Electricity Demand → Power Generation Capacity Addition
R1	Clean Hydrogen Availability in Steel Industry → DRI-EAF Environmental Benefit → DRI-EAF Capacity Addition Benefit → DRI-EAF Capacity → Clean Hydrogen Demand → Gap to Clean Hydrogen Production → Hydrogen Production Capacity Addition → Clean Hydrogen Capacity → Clean Hydrogen Supply Capacity → Clean Hydrogen Supply to Industry → Clean Hydrogen Availability → Clean Hydrogen Availability in Steel Industry
R2	Clean Hydrogen Costs → Clean Hydrogen Investment Economic Benefit → Clean Hydrogen Capacity Addition Benefit → Clean Hydrogen Capacity → Clean Hydrogen Costs
R3	Clean Hydrogen Affordability in Steel Industry → DRI-EAF Economic Benefit → DRI-EAF Capacity Addition Benefit → DRI-EAF Capacity → Clean Hydrogen Demand → Gap to Clean Hydrogen Production → Hydrogen Production Capacity Addition → Clean Hydrogen Capacity → Clean Hydrogen Costs → Clean Hydrogen Price → Clean Hydrogen Affordability → Clean Hydrogen Affordability in Steel Industry
R4	Steel Price → Steel Demand → Clean Hydrogen Demand → Gap to Clean Hydrogen Production → Hydrogen Production Capacity Addition → Clean Hydrogen Capacity → Clean Hydrogen Costs → Clean Hydrogen Price → DRI-EAF Costs → Steel Price
R5	Grid Electricity Demand → Power Generation Capacity Addition → Power Generation Capacity → Excess Power Generation Capacity → Clean Hydrogen Supply Capacity → Clean Hydrogen Supply to Industry → Clean Hydrogen Availability in Steel Industry → DRI-EAF Environmental Benefit → DRI-EAF Capacity Addition → DRI-EAF Capacity → Grid Electricity Demand

Note: Blue arrows (→) indicate a positive relationship between two variables, while red arrows (→) indicate a negative relationship.

Increasing power generation capacity has its own limitations, in the form of renewable resources availability (balancing loop B4). Because of the power sector exploiting the renewables resources to generate RE for their own use, the fertilizer industry's chance to produce green hydrogen would also be limited (balancing loop B5). However, their potential to produce blue hydrogen would not be affected. In the short run, these two balancing loops create a barrier to increasing the overall production of hydrogen, and in turn affect the availability of hydrogen for the steel industry (balancing loop B6). In the long run, the resource availability limitation would also be a barrier to further increase the hydrogen production capacity and the chance gain learning rate effect to reduce the cost of hydrogen, limiting the adoption of H₂-DRI-EAF (balancing loop B7). The loops within the system are summarized in Table 5.5.

5.3.1.2. *System Boundary*

The model was built around the system boundary which sets the scope of the study. This study models the steel industry and fertilizer industry demand drivers – population, inflation, purchasing power parity (PPP), gross domestic product (GDP), and household final expenditures (HFE)²⁹⁸ – as exogenous factors. While it is understood that there could be feedback from the dynamics between the steel industry, fertilizer industry, and power sector back to the economy³⁴⁸, including them could divert the focus from the research question at hand. The price of fossil fuels is also considered to be exogenous since it has its own complex dynamics deserving their own focus.

The demand drivers to the power sector are developed as a mixed model. The demand from the transportation sector and industrial sector is calculated bottom-up but the demand from residential and commercial sector are extrapolations from 2010-2022 historical data¹. The effect of vehicle electrification in the transportation sector is based on the model developed by Zahari & McLellan³⁴⁹. The technology adoption factor weights are also set as exogenous factors. The weights are set based on interviews with experts from the steel industry, fertilizer industry, and power sector. Finally, the renewables development rate is also considered to be exogenous based on the study done by Setiawan et al³⁰.

In this study hydrogen demand from the transportation sector was included. However, to date there are no formal targets for hydrogen-based vehicles in Indonesia. As such, this study assume hydrogen vehicles are introduced from 2030 and will steadily increase to a share of 5% of the total fleet by 2050.

Within the steel industry model, this study focuses on the transition from the BF-BOF production pathway to the H₂-DRI-EAF pathway in this study. The DRI-EAF production pathway is currently being used to only a minor extent in Indonesia. Since hydrogen can be injected into the current DRI-EAF, the direct transition to H₂-DRI-EAF is important for investigation. Nonetheless, the injection rate is exogenous in this study since it is part of the decision factor in incorporating hydrogen into the steel industry production. Thus, the term DRI-EAF and H₂-DRI-EAF will be used interchangeably in this study.

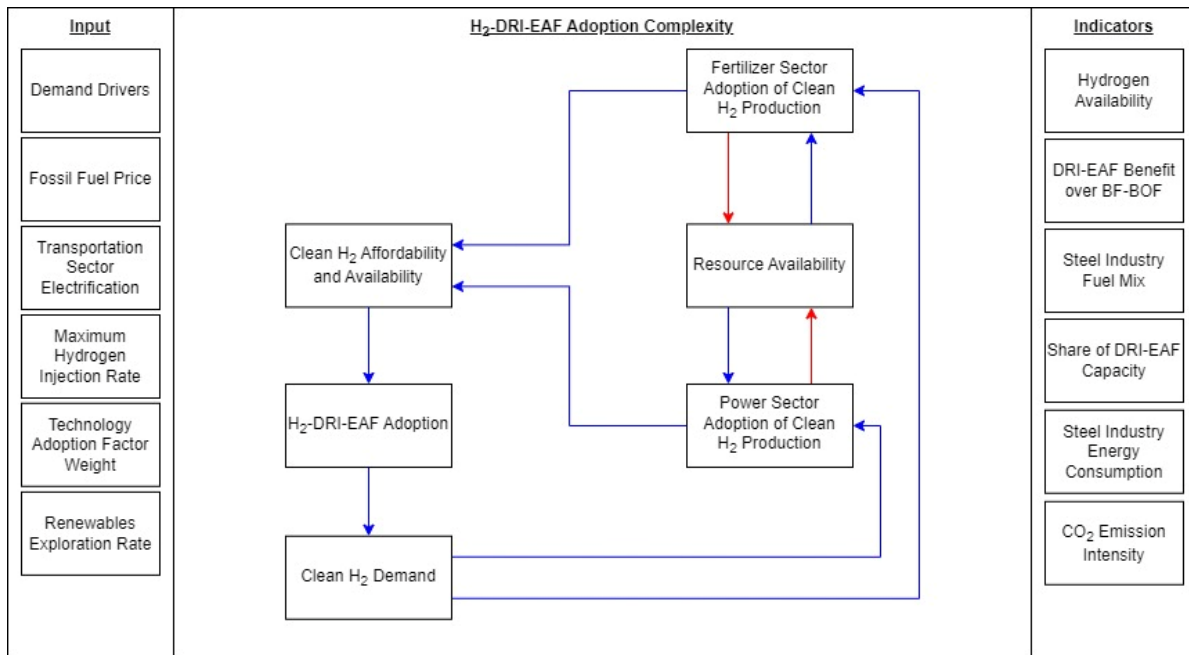


Figure 5.12. System diagram for the transition to the H₂-DRI-EAF steel production pathways.

There are six observed indicators. First is the hydrogen availability as the cumulative effect of supply and demand dynamics between the steel industry, fertilizer industry, and power sector. The hydrogen availability could affect the benefit of adopting H₂-DRI-EAF. The effect of the changing benefit would lead to the next four indicators which are: the steel industry fuel mix, share of DRI-EAF capacity, energy consumption capacity, and finally the carbon intensity. The carbon emissions and resulting intensity considered in the model comprised of direct carbon emissions from production and indirect carbon emissions from the grid electricity because of steel industry production.

The overall system discussed is illustrated in Figure 5.12. The conceptual model shown in the middle is a simplified version of the conceptual model in shown in Figure 5.11.

5.3.2. Model Uncertainties

The exogenous factors determined from the system boundary also function as system uncertainties that could affect the outcome of the model. The uncertainties in the model are represented as variables highlighted in pink in Figure 5.11. The changes in each of these uncertainties will affect the system's output.

This section discusses the uncertainties in more detail and the possible changes of baseline values. The uncertainties were grouped into two sets: supply-demand uncertainties; and uncertainties based on scenarios. While the values of the supply-demand uncertainties can be changed more flexibly due to them being purely exogenous factors, the scenario-based uncertainties are developed based on previous modelling or projections as explained below.

5.3.2.1. *Supply-demand uncertainties*

Since clean hydrogen's availability will be one of the main drivers to DRI-EAF adoption in the steel industry, it is important to understand its supply uncertainties from the potential producers, namely the fertilizer and power sectors. The fertilizer industry is both a producer and consumer of hydrogen. Hence, it is reasonable to assume they would first prioritize their own consumption, with any excess able to be supplied to the market. Similarly, the power sector's primary product is electricity, and they need to fulfil electricity demand first before using it to

produce hydrogen. In this regard, the uncertainties of these sectors' primary product demand – fertilizer and electricity – are explored. While the fertilizer demand is subject to several macroeconomic drivers as mentioned in Section 5.3.1.1, electricity demand in the power sector is also potentially on the verge of a radical change with significant transportation electrification.

If there is sufficient market demand for hydrogen, both potential producers could choose to add production capacity dedicated for that demand. However, this would expose them to market demand risks which are not native to their business operations. To emulate different risk profiles of the potential producers, the weightings applied to the hydrogen production adoption factors were changed. As described in Section 5.3.1.1, the adoption framework consists of four adoption drivers. To what extent the potential producer considers each of the four adoption drivers is determined by the adoption factor weights, as illustrated in Figure 5.11. This study assumes that if the potential producers have a high risk-tolerance, they will have less concern for internal risks including economic and technological factors. Thus, to assume a low risk-tolerance the weight of these two drivers were increased and the weight of the other adoption drivers is distributed proportional to the reference weights. For high risk-tolerance, the weight of the economic driver was halved and perform the same procedure for the other weight factors. The values of the adoption drivers for each risk-tolerance profile are shown in Table 5.6. For the environmental driver the level 2 criteria weights were also changed to better represent the risk-tolerance. Within the environmental driver, resource availability is an internal risk factor while carbon emission is not. Hence, it is important to differentiate the level 2 criteria weights also for the environmental drivers.

Table 5.6. Adoption drivers weights emulating risk-tolerance of the potential hydrogen producers

Adoption Drivers	Risk-tolerance		
	Baseline	High	Low
Economic	Fertilizer: 0.304	Fertilizer: 0.152	Fertilizer: 0.366
	Power: 0.384	Power: 0.192	Power: 0.627
Environmental	Fertilizer: 0.09	Fertilizer: 0.310	Fertilizer: 0
	Power: 0.097	Power: 0.174	Power: 0
Resource availability	Fertilizer: 0.5	Fertilizer: 0.25	Fertilizer: 0.75
	Power: 0.75	Power: 0.25	Power: 0.75
Emissions to air	Fertilizer: 0.5	Fertilizer: 0.75	Fertilizer: 0.25
	Power: 0.25	Power: 0.75	Power: 0.25
Technological	Fertilizer: 0.526	Fertilizer: 0.263	Fertilizer: 0.634
	Power: 0.228	Power: 0.114	Power: 0.373
Organizational	Fertilizer: 0.08	Fertilizer: 0.275	Fertilizer: 0
	Power: 0.291	Power: 0.520	Power: 0

Regarding the supply of hydrogen, there are also uncertainties with the availability of renewables to produce green hydrogen, as well as the carbon storage potential to produce blue hydrogen, which are required for the steel industry's decarbonisation effort. While Indonesia is not short of both potential resources, the actual potential exploitable resource is another matter. Adapting the resource exploitation model developed in Setiawan et al. for geothermal³⁰, the uncertainties of renewable site evaluation lead time and success rates which control the exploitation success rate of these resources were included. These include economic factors for exploration, where if there is not enough assumed economic benefit, exploration will not be undertaken. The total success rate used in the work was 40%, which was derived from the success rate of exploration (50%) and exploitation (80%), and the total lead time is 4 years (2 years for exploration and 2 years for exploitation). For this study, this study uses a lower

resource development success rate than the reference to account for the resources exploration profitability factor since its calculation is not included. The parameters value variation is shown in Table 5.7.

Table 5.7. Renewables and carbon storage potential development rate parameters

Parameters	Resources	Baseline	Fast development	Slow development
Success Rate (%)	Hydro	7.25	14.5	3.75
	Geothermal	5	10	2.5
	Bioenergy	20	40	10
	Solar	0.04	0.08	0.02
	Wind	0.08	0.16	0.04
	Carbon Storage	5	10	2.5
Lead Time (years)		4	2	8

The uncertainty of demand drivers would also affect the system's indicators. As mentioned in Section 5.3.1.1, there are five demand drivers²⁹⁸. However, this study only explore the effects of GDP as it was found to be the most significant in case of the iron & steel industry production in Indonesia. The regression result for the demand projection is presented in Section 5.2.1. The OECD projects Indonesia's real GDP to reach 10 billion USD by 2050, which means an annual growth of 4% from present³⁵⁰. This rate is modest compared to the target set by the National Planning Agency (Bappenas) who target an annual growth of between 5.6% and 7.8% depending on the national development stage³⁴². Nonetheless, the actual GDP growth trend in the last decade, around 3.7% per year, was more similar to the OECD projection. As such, 5.6% annual growth was used as the baseline and symmetrically change the value to 3.6% and 7.6% for the uncertainty test in Section 5.3.4.1.

Another uncertainty related to hydrogen demand in the steel industry is its maximum injection rate. It has been estimated that hydrogen can replace natural gas up to 33.3% in DRI-EAF production without any changes to infrastructure³³⁷. If hydrogen were to replace natural gas completely, then a gas heater would need to be installed to preheat the produced water vapor³³⁷. In this case, a total of 850 m³ of hydrogen per ton DRI is required, where 550 m³/ton is used for the reduction reaction, 250 m³/ton as fuel for the gas heater, and 50 m³/ton to maintain the temperature and carbon content of the DRI. To investigate the effect of changing the maximum injection rate to the observed indicators, the model was assessed with 10%, 33.3%, and 100% of injection rate.

5.3.2.2. Scenario-based uncertainties

The first scenario-based uncertainty is the uptake of BEV in the transportation sector, which could affect the power sector's ability to produce hydrogen from excess capacity. Under the aggressive target for vehicle electrification, the power sector would expect a massive increase in electricity demand. In line with the target, the GOI have provided a number of incentives, including vehicle tax and electricity tariff incentives. Currently only vehicle taxes are exempted, while the electricity tariff is only discounted as regulated in GOI Regulation No. 74/2021. According to the results from Chapter 3, a high BEV penetration was achieved when the maximum battery capacity achieves 350 Wh/kg, potential BEV adopters have a higher consideration for environment than economic factors, there is no improvement in the internal combustion engine efficiency, and there is a low supply of oil and gas which leads to a high fuel price. On the other hand, a low penetration happens when the opposite is true. In addition,

no incentives are provided under the low BEV penetration scenario. The resulting BEV share by 2050 under the high penetration is 33%, 18% under the low penetration, and 26% in the baseline.

The second scenario-based uncertainty is the fossil energy price. As mentioned, the steel industry is energy intensive, with coal and natural gas as the main energy source depending on the production pathway. The fossil energy price is based on the U.S. Energy Information Administration (EIA) who projected fossil fuel prices until 2050²¹⁷. Based on their scenario, oil and gas prices are most negatively affected by supply. As for coal, the price is most negatively affected by the cost of low carbon technologies, while positively affected by oil and gas supply. The variation of annual price changes for each fossil fuel is presented Table 5.8.

Table 5.8. Projected annual price changes of fossil fuels

Fossil Fuels	Reference	Annual price changes (%/year)	
		High oil and gas supply	Low oil and gas supply
Crude Oil	0.38	0.02	0.93
Natural Gas	1.03	0.43	1.66
Coal	2.1	2.4	1.7

5.3.3. Base Run

The base run demonstrates the standard assumptions and performance of the model. Figure 5.13(a) shows the energy consumption will continue to increase as the drivers of demand, particularly GDP. There is a period of slowing down between 2031 and 2039 due to the higher capacity utilization as depicted in Figure 5.14. The higher capacity utilization has a positive impact on the industry's carbon intensity, emphasised by the fast improvement in the same period and continued its trend towards the end of the simulation as presented in Figure 5.13(b). By 2050, the resulting energy and direct carbon intensity were 13,856 MJ per ton of crude steel and 957 kgCO₂ per ton of crude steel, respectively. With this result, the steel industry energy intensity slightly increased from 12,260 MJ per ton of crude steel in 2005, which is within the intensity reported by the U.S. Department of Energy in 2000³⁵¹. The continued decline of carbon intensity is contributed by the improved efficiency in thermal power generation and increasing proportion of renewables in the power sector as will be discussed in detail in Chapter 6.

Under the base run, the share of DRI-EAF production pathway continues to drop as shown in Figure 5.13(c). The reason is because the relative benefit of adopting DRI-EAF remains lower than BF-BOF. In 2023, the share of DRI-EAF production capacity was reported to be around 50% as is also reflected in the model²⁹⁷. This share would drop further to 27% in 2050 if the DRI-EAF benefit continues to be lower than BF-BOF as illustrated in Figure 5.13(e). Nonetheless, the rate at which DRI-EAF decline is slowed down due to the increase DRI-EAF benefit as the result of improved hydrogen availability.

The sharp increase in hydrogen availability in Figure 5.13(d) reflects the supply push from the potential producers, who decide to produce hydrogen despite the absence of demand. This push enables the introduction of hydrogen for the steel industry, which then initiates the reinforcing loops R1 as described in Table 5.5. The consumption of hydrogen supply also triggers reinforcing loop R2 which describes the learning rate effect in lowering hydrogen production cost and thus increasing the economic benefit of investing in hydrogen production capacity. In turn, the reduced hydrogen production cost would affect hydrogen affordability in the steel industry, further increasing the benefit of using DRI-EAF (reinforcing loop R3). The reduced

hydrogen cost would also reduce the steel production cost, which increases steel demand. However, since the DRI-EAF proportion is small, its effect does not significantly influence the overall steel demand.

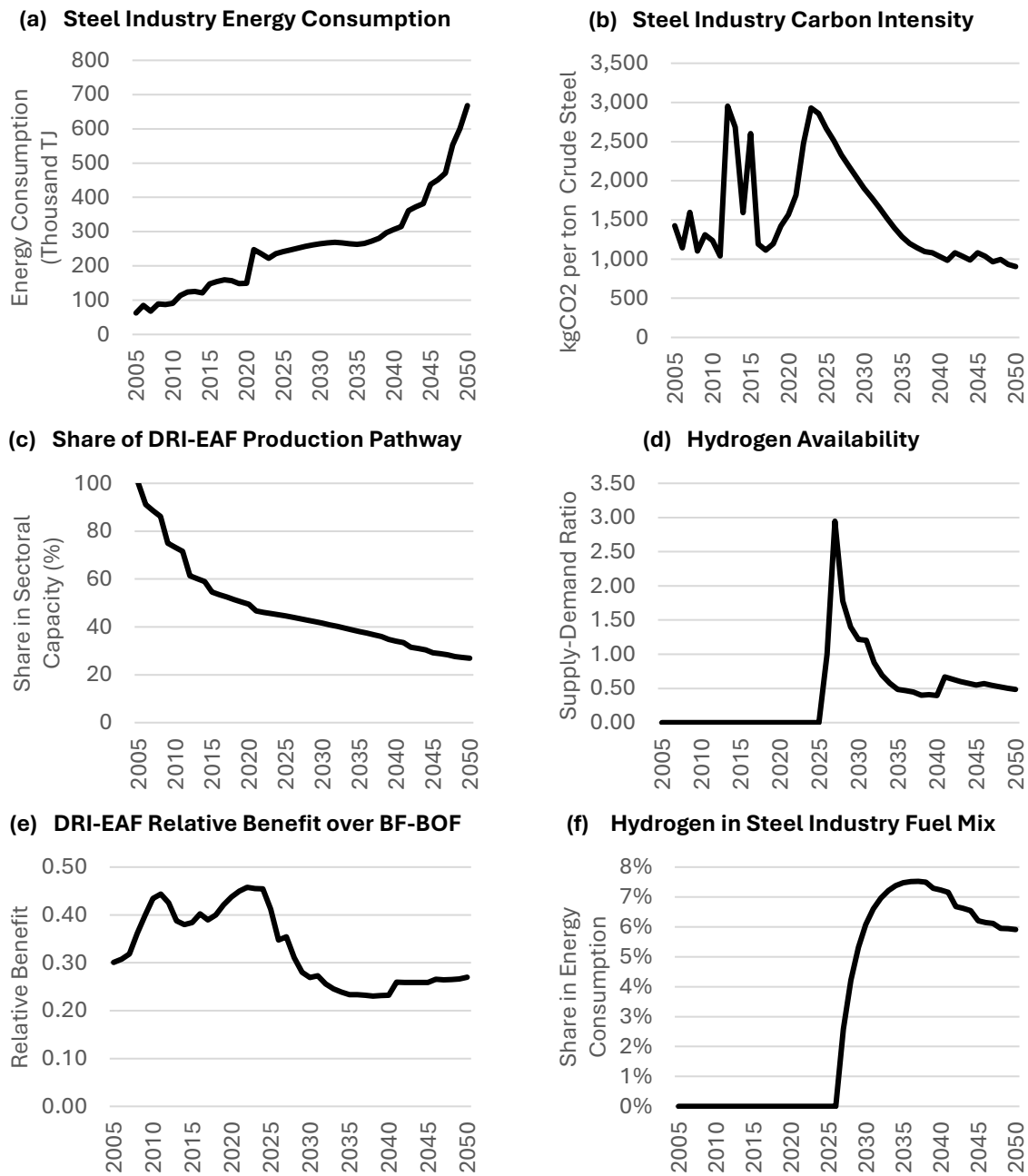


Figure 5.13. Model simulation result under the baseline adoption drive weights as presented in Table 5.6

Although there is a high availability of hydrogen in the initial stages, it soon stabilizes at around 50% following the share of DRI-EAF production pathway proportion, driven by the balancing loop B1. As the result of the dynamics, the hydrogen would account for around 6% of the steel industry fuel mix as shown in Figure 5.13(f), which is equal to 407 thousand tons in 2050.

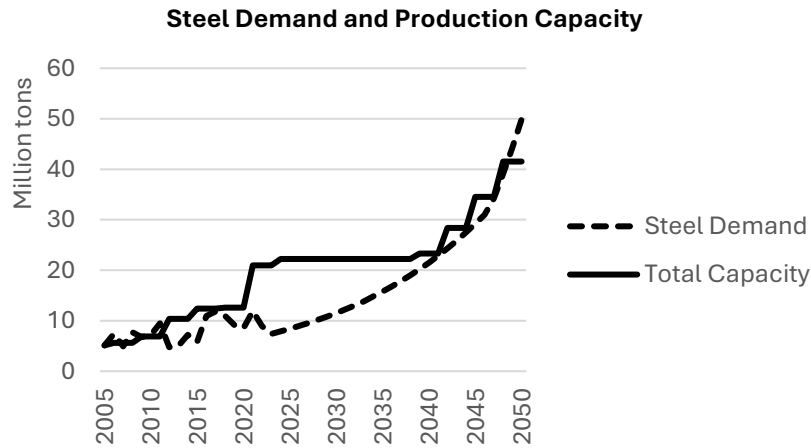


Figure 5.14. Total Steel Capacity and Production

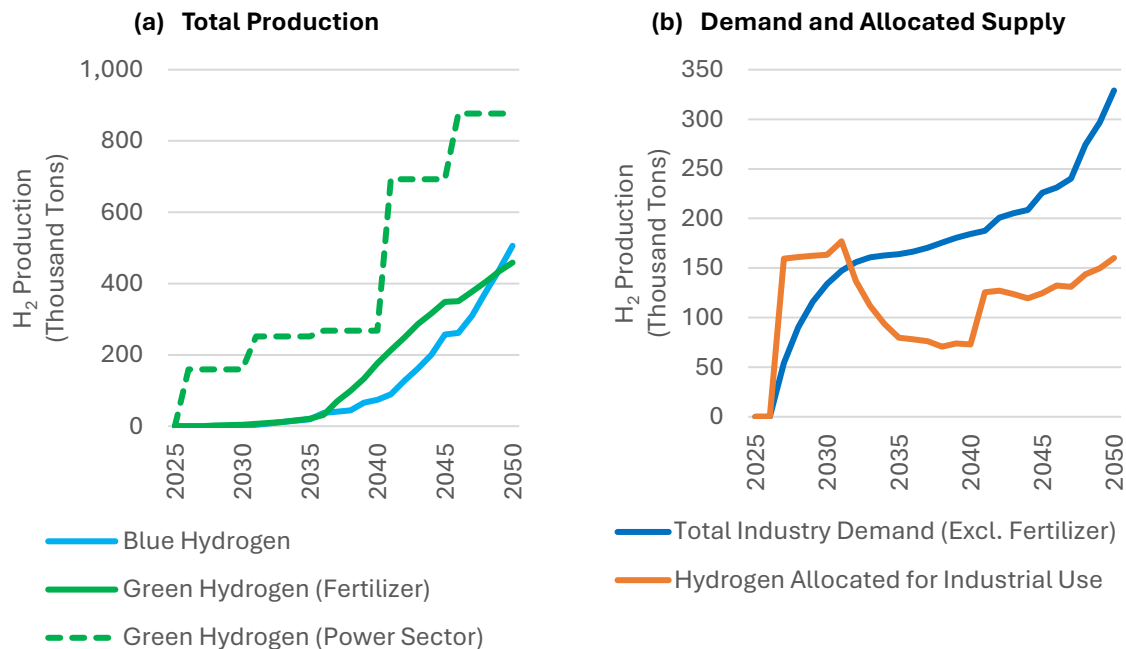


Figure 5.15. Clean hydrogen total production, demand from and allocated hydrogen supply to the steel industry under the baseline scenario

The hydrogen produced would initially be green hydrogen since the excess capacity occurs earlier in the power sector (Figure 5.15(a)). While blue hydrogen is only produced by the fertilizer industry, the power sector produced more green hydrogen compared to the fertilizer industry. Overall, the fertilizer industry would provide 73% of the total hydrogen supply by 2050. However, not all hydrogen is allocated to the industrial sector since it is also being allocated to the transportation sector proportionately to the total market availability. The introduction of hydrogen vehicles explains the significant drop in hydrogen availability in 2030 to 2040 since the allocation is reduced as depicted in Figure 5.15(b).

The stabilizing demand for hydrogen interacts with the balancing loop B2, slowing down the hydrogen capacity addition. The effect of available resources potential is a limiting factor described by the balancing loops B3 and B4 which is further discussed in the sensitivity test in Section 5.3.4.4.

5.3.4. Supply-Demand Sensitivity Test

5.3.4.1. GDP Growth

Since GDP is the key driver to steel demand, GDP growth serves as an uncertainty on the demand-side. The effect of GDP growth on the identified indicators is shown in Figure 5.17 (a) through (f). GDP growth clearly has an impact on the energy consumption within the steel industry as shown in Figure 5.17(a), since it was shown to have the highest effect on demand as presented in Table 5.3. Consequently, it also has a significant effect on capacity utilization, which in turn affects energy consumption and carbon intensity. Figure 5.16 shows lower GDP growth than previously anticipated would lead to a very low capacity utilization. Conversely, a high GDP growth leads to relatively high capacity utilization. The resulting carbon intensity is shown in Figure 5.17(b).

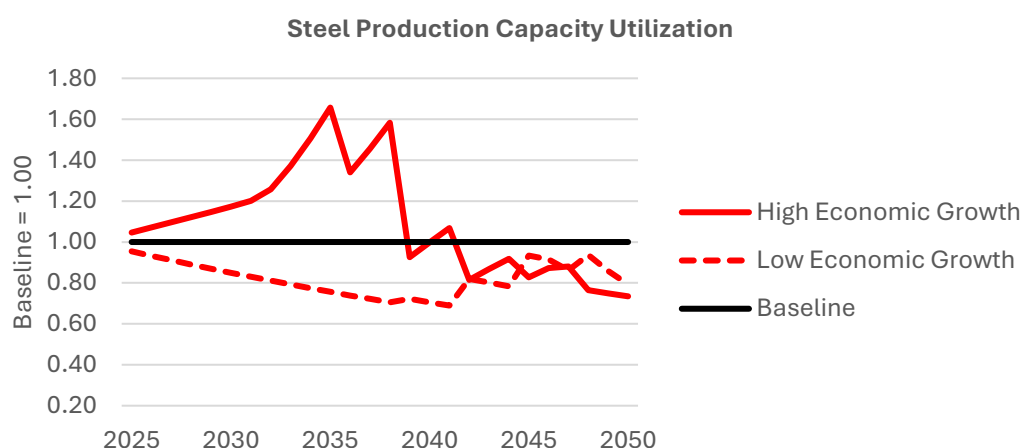


Figure 5.16. Capacity Utilization in the Steel Production under Different Economic Growth

While low GDP growth leads to an unfavourable carbon intensity, it also leads to a higher adoption of DRI-EAF as shown in Figure 5.17(c), driven by the higher hydrogen availability at the initial stages of its introduction as depicted in Figure 5.17(d). The reason behind this is because investments for hydrogen production capacity in both the fertilizer and power sectors, as in the steel industry, is modelled based on projected demand based on historical trends. Hence, there will be more captive demand for hydrogen in the fertilizer industry and more electricity demand when there is higher economic growth, leaving less hydrogen to be supplied to the market. Conversely, hydrogen production capacity will be more underutilized when the economic growth is lower than anticipated, providing more hydrogen to be supplied.

The effect of GDP growth on hydrogen in the steel industry fuel mix can be observed in Figure 5.17(f). In the high GDP growth case, the use of hydrogen increased with the increasing overall steel industry and the start of hydrogen injection. However, the share soon drops when the required additional capacity is invested in BF-BOF instead as depicted in Figure 5.17(c) and remains lower than the baseline until the end of simulation. In contrast, the low economic growth led to lower use of hydrogen following the overall steel industry production but then it increased since the benefit of using DRI-EAF is higher in this case.

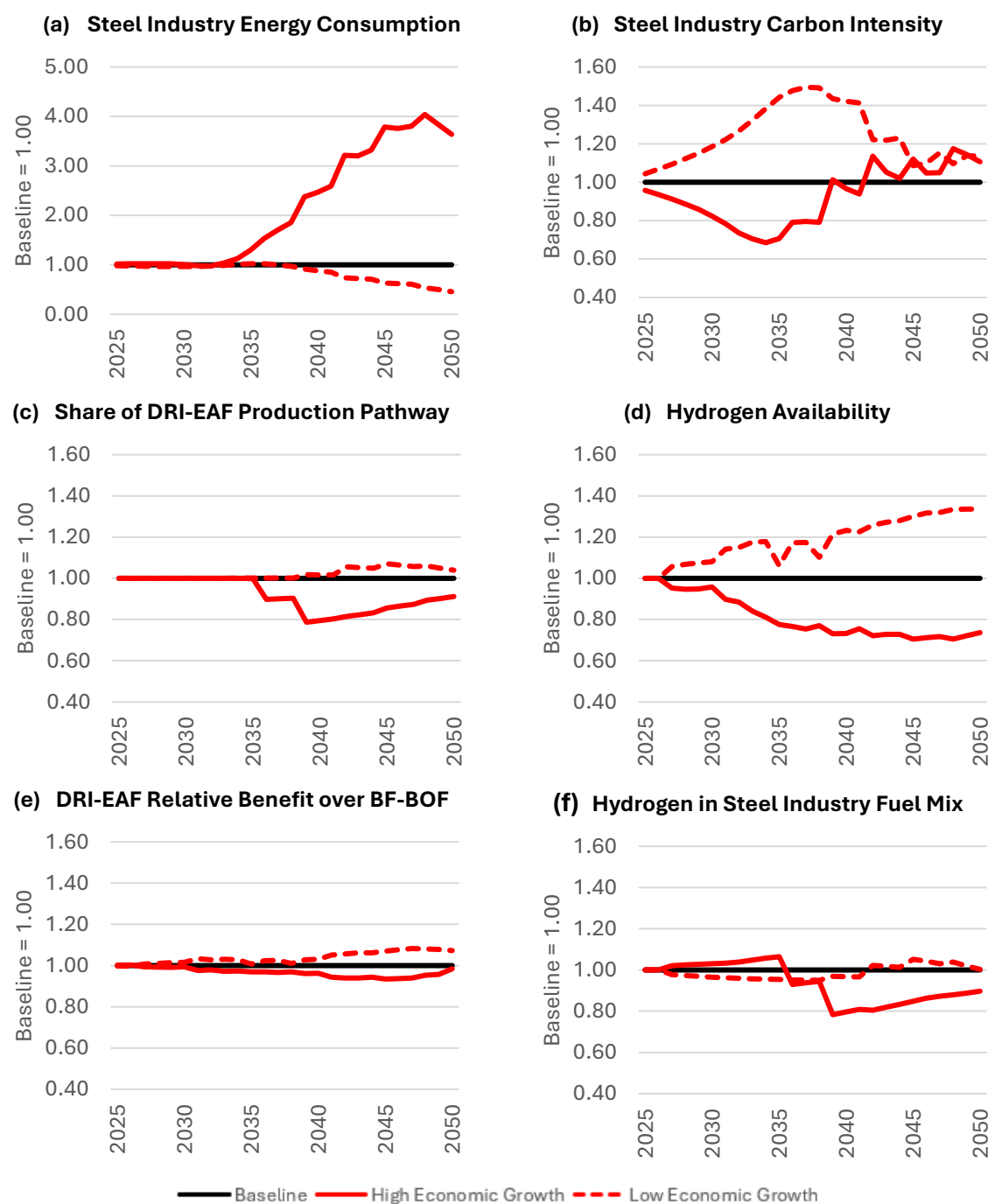


Figure 5.17. Effect of GDP growth on the selected indicators

Figure 5.18 shows the change in coal, natural gas, and electricity energy mix in the steel industry. In the case of high economic growth, coal use increased following the increase in BF-BOF as shown in Figure 5.17(c) and is supported by the lower DRI-EAF relative benefit compared to the baseline in Figure 5.17(e). The use of coal peaks in around 2040 and then steadily declines, approaching the baseline level, replaced by the increase in natural gas and hydrogen use attributed to DRI-EAF. As for the low economic growth case, the energy mix shifts to grid electricity. The shift is again attributed to the share of DRI-EAF which is around 5% higher than the baseline and around 4 times more electricity intensive than BF-BOF^{280,336}.

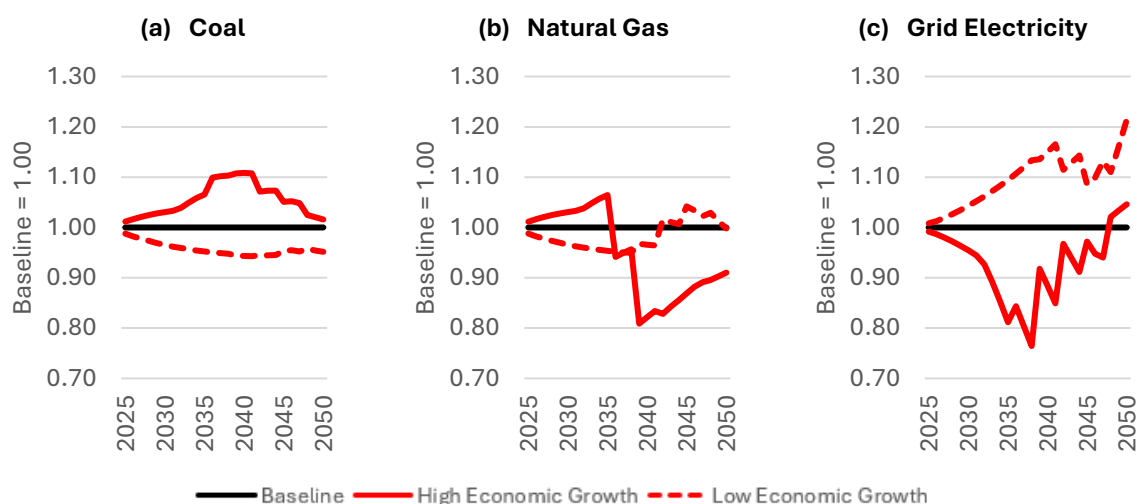


Figure 5.18. Changes in Coal, Natural Gas, and Grid Electricity in the Steel Production Energy Mix under Different Economic Growth

5.3.4.2. Maximum Hydrogen Injection Rate

The maximum hydrogen injection rate directly affects the demand for hydrogen from the steel industry. As shown in Figure 5.20 (a) and (b), a higher injection rate leads to lower energy consumption and lower carbon intensity, due to the increase in DRI-EAF share as seen in Figure 5.20 (c). The increase in DRI-EAF share can be explained by the increasing benefit of adopting DRI-EAF in Figure 5.20 (d). However, looking at the hydrogen availability in Figure 5.20 (e), it cannot explain this increasing relative benefit. While the hydrogen availability under the higher maximum injection rate was below the baseline, the overall relative benefit of DRI-EAF still increased.

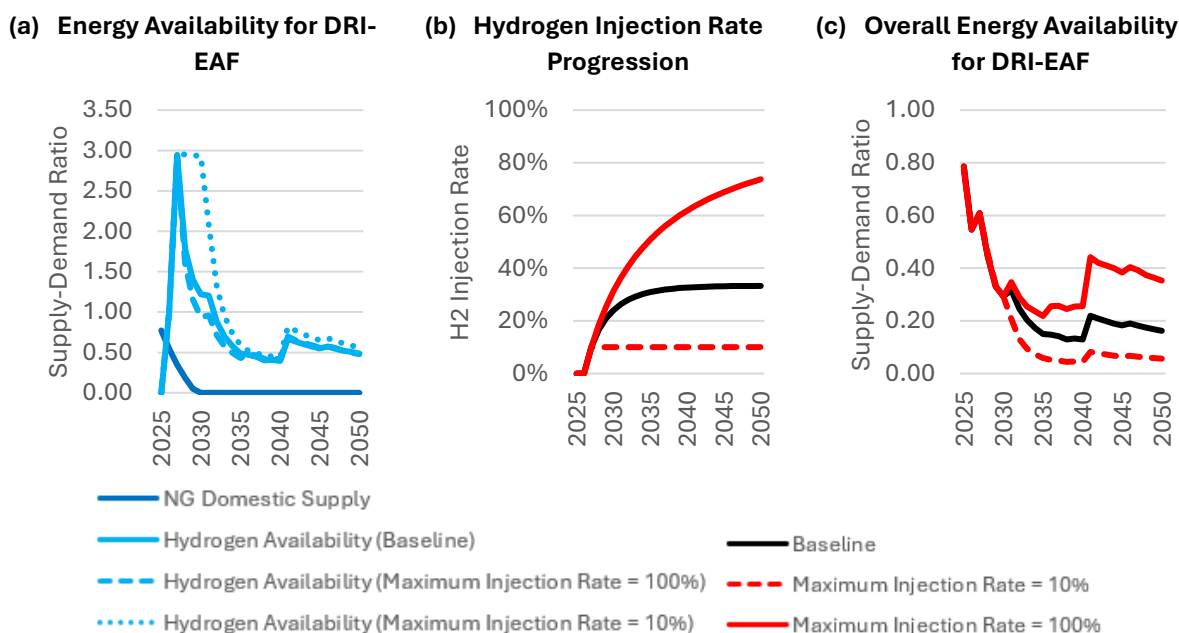


Figure 5.19. Energy Availability and Hydrogen Injection Rate in DRI-EAF

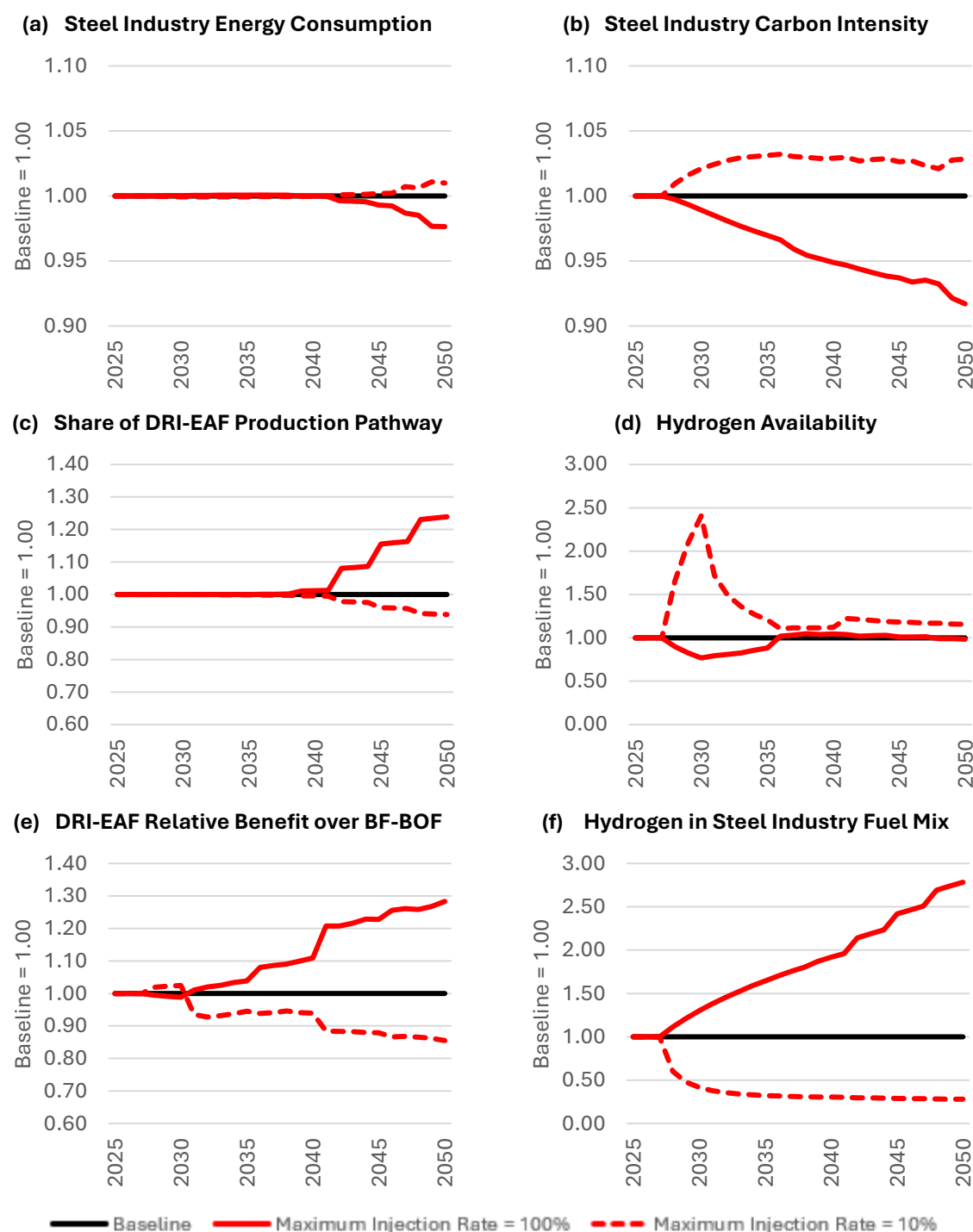


Figure 5.20. Effect of maximum injection rate on the observed indicators

5.3.4.3. Risk-tolerance

Changing the risk-tolerance has a significant effect on hydrogen availability. As defined in Table 5.6, a high risk-tolerance is characterized by low emphasis on economic and technological adoption drivers. Under this case, potential hydrogen producers have higher chance of adopting blue and green hydrogen technology. As shown in Figure 5.21(d), in general, hydrogen availability is higher than the baseline under the high risk-tolerance case while it is lower under the low risk-tolerance case. The higher hydrogen availability leads to higher DRI-EAF benefit over BF-BOF (Figure 5.21(e)), which then increase the share of DRI-EAF (Figure

5.21(c)), lowering the energy consumption (Figure 5.21(a)), and carbon intensity simultaneously (Figure 5.21(b)).

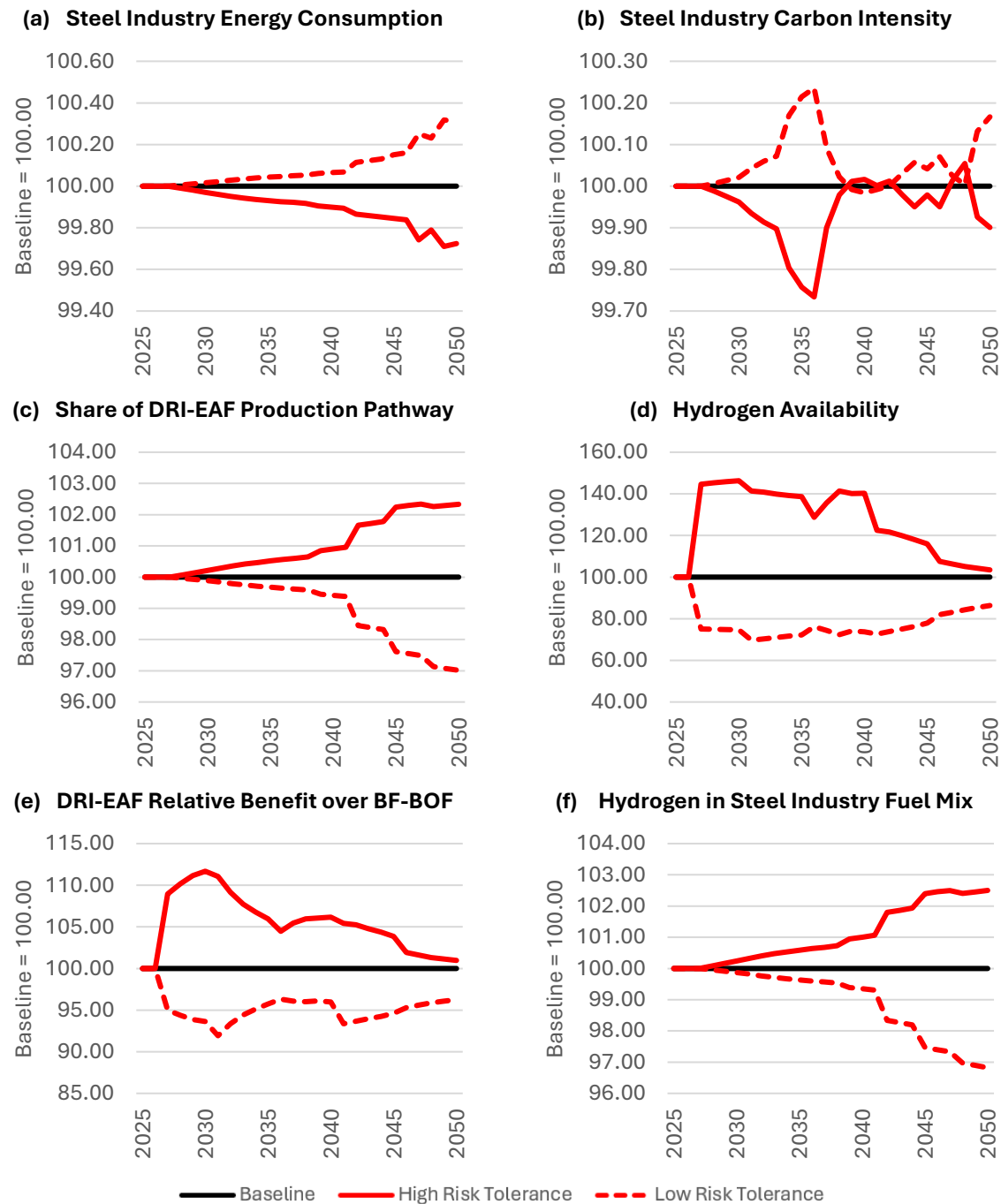


Figure 5.21. Effect of risk-tolerance on the observed indicators

While there is a deviation from the baseline, the hydrogen availability soon returns towards the baseline level in both cases, in particular the high risk-tolerance case where the hydrogen availability becomes almost equal to the baseline in 2050. The sudden changes in hydrogen availability were the result of a drastic change in hydrogen production from the power sector compared to the baseline. The approach towards the baseline level in both cases can be explained by Figure 5.23 which shows that, while changes in risk-tolerance leads to changes in both demand and allocation, the degree of change is not proportional. As can be observed, the change in allocation deviates -14% (low risk-tolerance) and 2.94% (high risk-tolerance)

from the baseline at the maximum points, while the change in demand is -3.1% (low risk-tolerance) and 1.8% (high risk-tolerance). The lack of allocation in the low risk-tolerance case can be explained by the significantly reduced total hydrogen production, which is cumulatively reduced by 29% or 4.8 million tons between 2025-2050 (Figure 5.22).

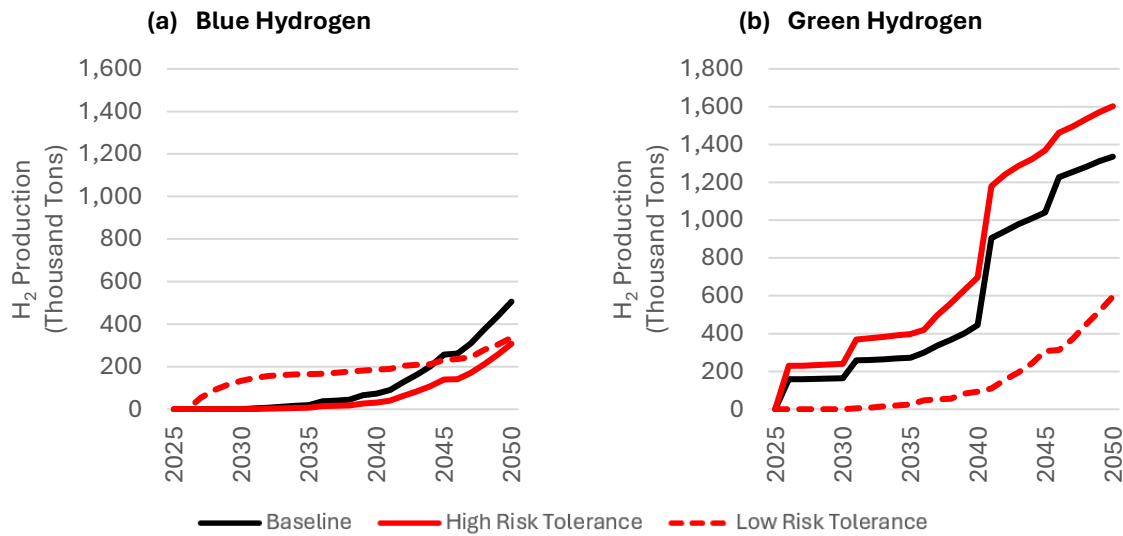


Figure 5.22. Effect of risk-tolerance on hydrogen production

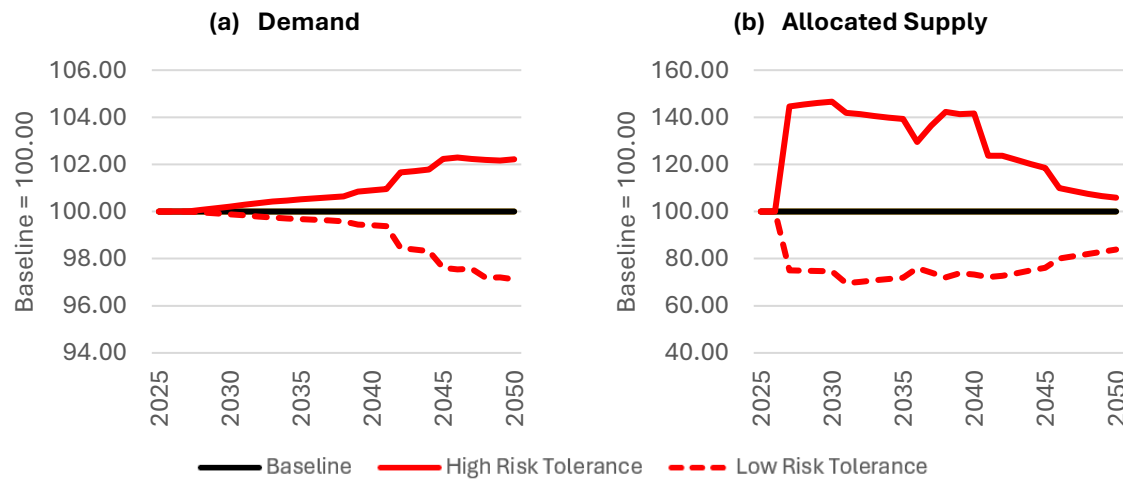


Figure 5.23. Effect of risk-tolerance on steel industry hydrogen demand and allocated supply

5.3.4.4. Renewables Development Rate

As with risk-tolerance, renewables development rate also serves as an uncertainty in the hydrogen supply. Its effect on the availability of hydrogen is profound as can be seen in Figure 5.24(d). Similar to the case in increasing the risk-tolerance in Section 5.3.4.2, the changes in hydrogen availability positively affects the benefit of adopting DRI-EAF (Figure 5.24(e)) and in turn the share of DRI-EAF production pathway (Figure 5.24(c)), which then negatively affect the energy consumption and carbon intensity in the steel industry as shown in Figure 5.24(a) and in Figure 5.24(b), respectively (higher share of DRI-EAF decreases energy consumption and carbon intensity, and vice versa).

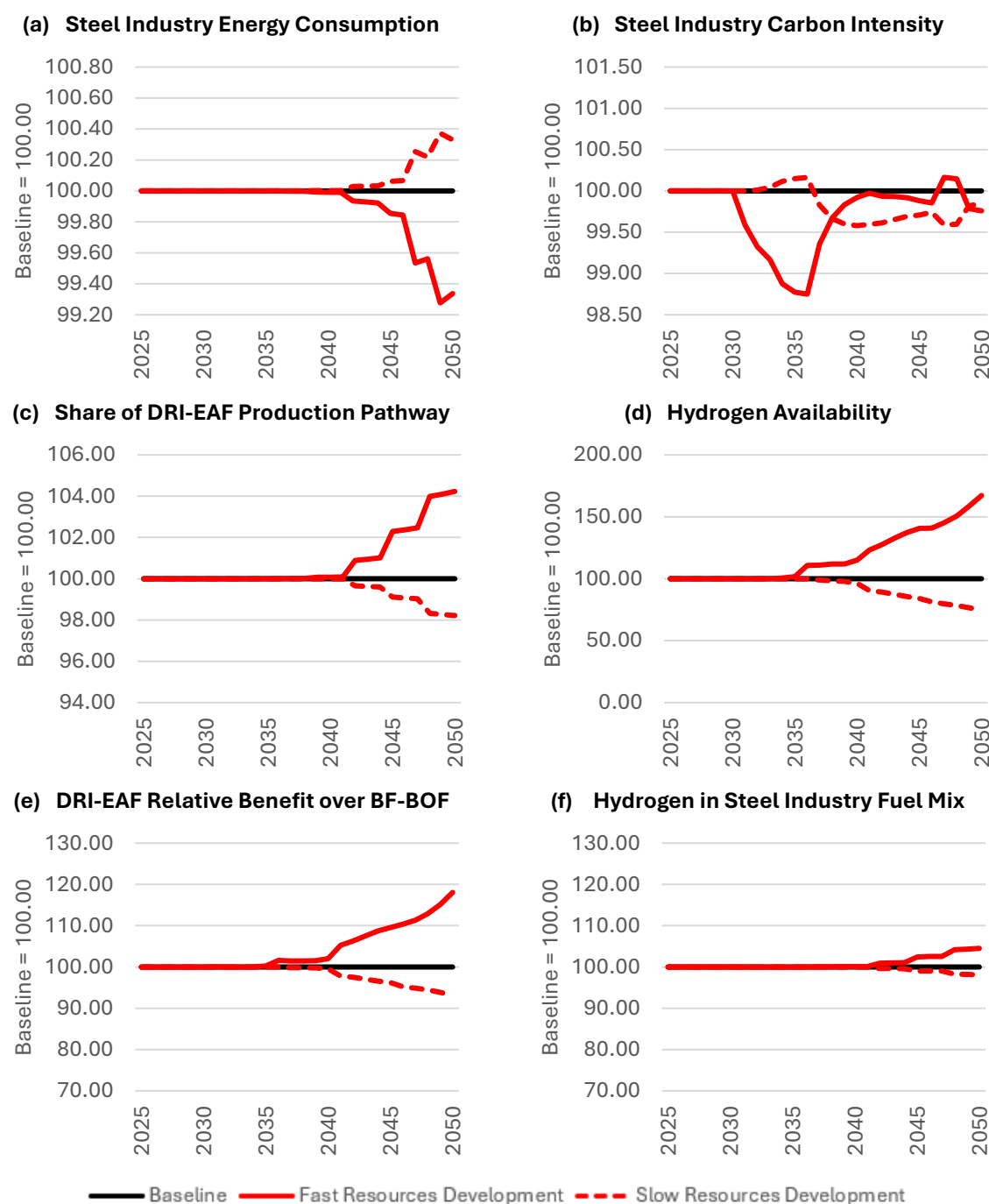


Figure 5.24. Effect of renewables development rate on the observed indicators

Figure 5.24 (d) further shows the effect of doubling or halving the development rate, by doubling the success rate and period as described in Table 5.7, is not symmetrical. The explanation lies in the availability of carbon storage compared to the availability of renewable energy as depicted in Figure 5.25. The explanation can be further traced back to the carbon storage potential in Indonesia, which is much higher compared to renewables in Indonesia. In addition, the overall benefit of adopting blue hydrogen production is higher than green hydrogen, especially due to the lower cost and lower technological barrier to adopt. The resulting hydrogen production is shown in Figure 5.26 where the production of blue hydrogen increased significantly from the baseline under the fast development rate case, cumulatively more than two-fold between 2025-2050. On the other hand, green hydrogen production increased only 20% compared to the baseline over the same time span.

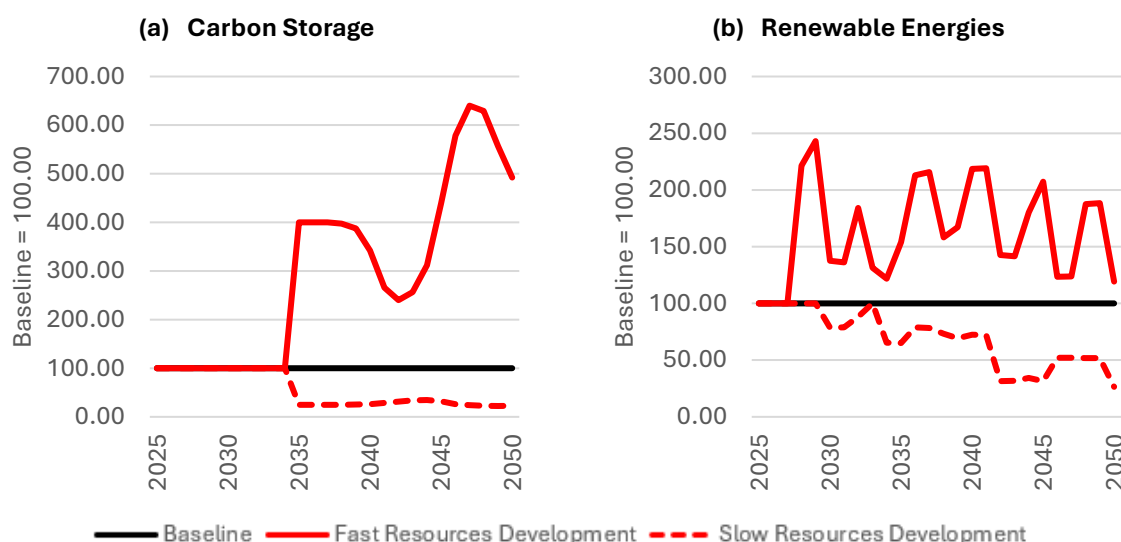


Figure 5.25. The effect of resources development rate on the carbon storage and renewables availability.

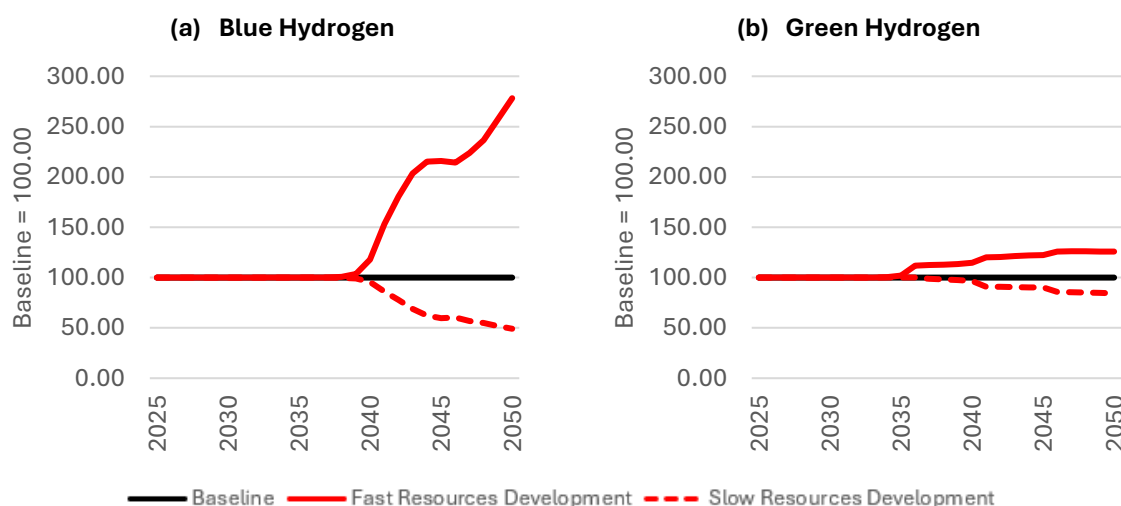


Figure 5.26. The effect of resources development rate on the production of clean hydrogen.

5.3.5. Scenario-driven Sensitivity Test

5.3.5.1. Fossil Energy Price

Fossil energy is used throughout the system being observed – coal in BF-BOF and power generation, natural gas in DRI-EAF, blue hydrogen production, fertilizer industry, and power generation. Thus, the effect of its price changes would be systemic. As seen in Figure 5.27, changes in the fossil fuel price projection, driven by the supply of oil and gas as described in Table 5.8, affects all the observed indicators.

An increased DRI-EAF proportion should have decreased energy consumption in the steel industry, but that is not the case with the changes in fossil energy price as can be seen in Figure 5.27(a). Although small, the increase in oil and gas prices led to an increase in steel industry energy consumption, and the source of the increase is attributed to the increase in demand. The price of fossil fuel is linked to general price level, which is one of the drivers to steel demand albeit negatively as shown in Table 5.3. A lower in oil and gas price would lead to lower inflation rate which increases steel demand. Fortunately, the increase in demand increases capacity utilization also, hence it resulted in a lower carbon intensity as shown in Figure 5.27(b).

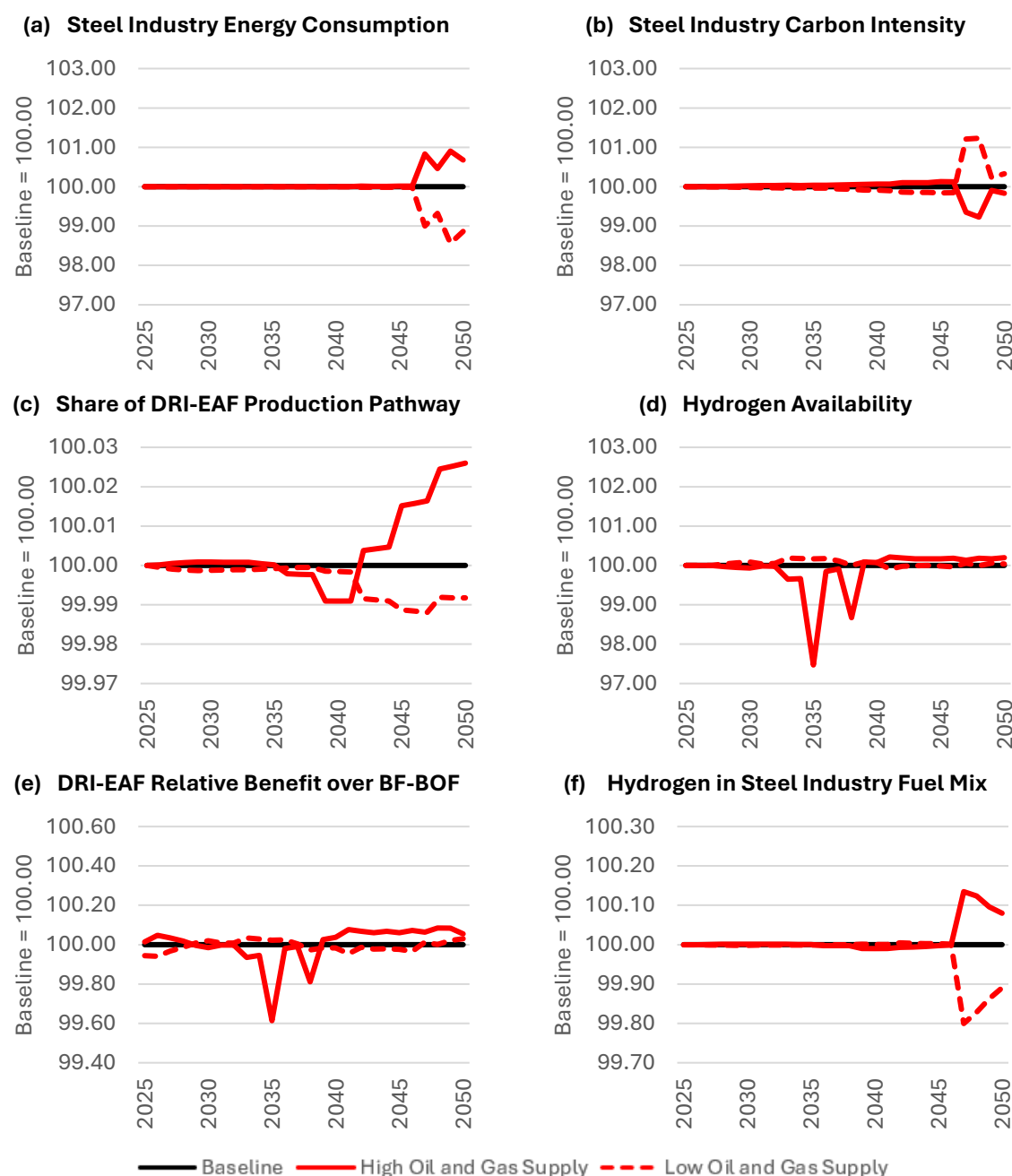


Figure 5.27. Fossil energy prices effect on the observed indicators

Figure 5.27(e) shows that the DRI-EAF relative benefit over BF-BOF under the high oil and gas supply is higher than the baseline in general. The higher oil and gas supply leads to a lower oil and gas price but higher coal price increase, while a lower supply does the opposite. As the result, a high oil and gas supply increases the share of DRI-EAF as seen in Figure 5.27(c) since coal is the main fuel in BF-BOF while DRI-EAF primarily use natural gas. Relating the relative DRI-EAF benefit in Figure 5.27(e) and the availability of hydrogen in Figure 5.27(d), the initial relative benefit deviation from the baseline is not due to the availability of hydrogen but instead due to the increasing gap between natural gas and coal price.

The effect of hydrogen availability on the relative DRI-EAF benefit starts to manifest in 2036. Under the high oil and gas supply case, the production of hydrogen drops below the baseline and then suddenly increased around 2036 as depicted in Figure 5.28. The initial drop can be traced to the hydrogen production decrease in the fertilizer industry because the demand was

lower than the baseline as the result of inflation driven demand changes. Afterwards, the hydrogen production in the fertilizer industry increased due the self-reinforcing supply initiated by the hydrogen demand from the steel industry.

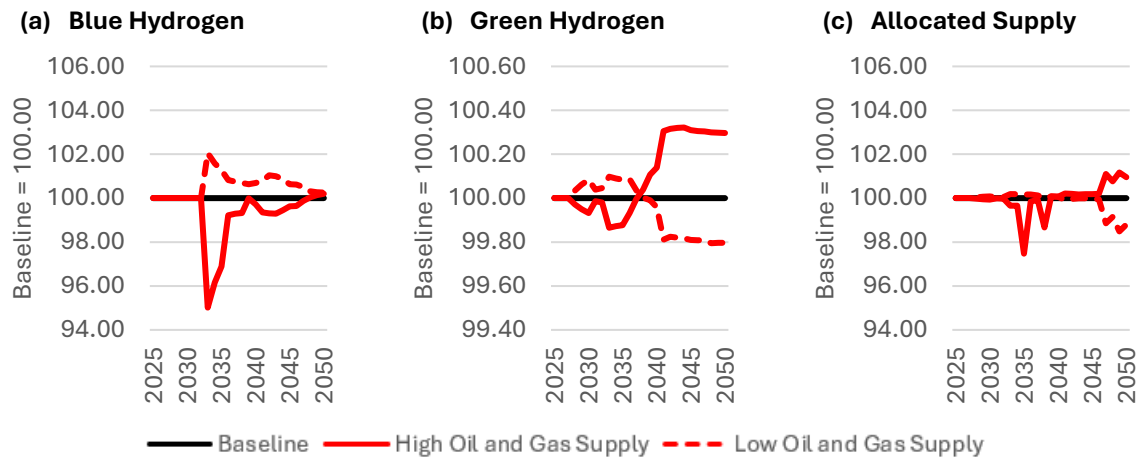


Figure 5.28. Fossil energy prices effect on hydrogen production and supply to the steel industry

5.3.5.2. BEV Penetration Level

While BEV penetration does not seem to be an obvious uncertainty factor for the steel industry, the results showed otherwise. BEV penetration level affects, although minor, all the observed indicators.

Firstly, a lower BEV penetration level, 15% versus 26% for the baseline, led to a higher energy consumption in the steel industry and lower carbon intensity. Conversely, a higher BEV penetration level at 33% led to the opposite result as can be observed in Figure 5.29(a) and Figure 5.29(b). These deviations from the baseline are not the direct effect of changes in BEV penetration, rather what caused the BEV penetration to change, particularly changes in fossil fuel price. As mentioned in Section 5.3.5.1, a higher fossil fuel price decreases steel demand which decreased steel industry energy consumption but higher carbon intensity due to lower capacity utilization.

The more direct effect of BEV penetration on the steel industry is shown in the hydrogen production in the power sector shown in Figure 5.30(b). When BEV penetration is low, the power sector could produce more hydrogen due to the larger excess in capacity. In contrast, a high BEV penetration leads to lower hydrogen production. Nonetheless, the decrease in green hydrogen production from the power sector is compensated by the fertilizer industry because a high BEV penetration was the result of high oil and gas price – lowering the demand for fertilizer as explained in Section 5.3.5.1 and thus increasing their excess capacity. Cumulatively, the green hydrogen production is 0.50% higher than the baseline under the 15% BEV penetration level. The high BEV penetration case also resulted in very minor increase in and 0.08% lower in the 33% BEV penetration level.

The production of hydrogen translates to the allocated supply to the industrial sector, which reflects on the hydrogen availability Figure 5.29(d). In addition to the hydrogen availability, the circumstances that led to the BEV penetration level, namely fossil fuel price, also affects the benefit of adoption DRI-EAF as shown in Figure 5.29(e).

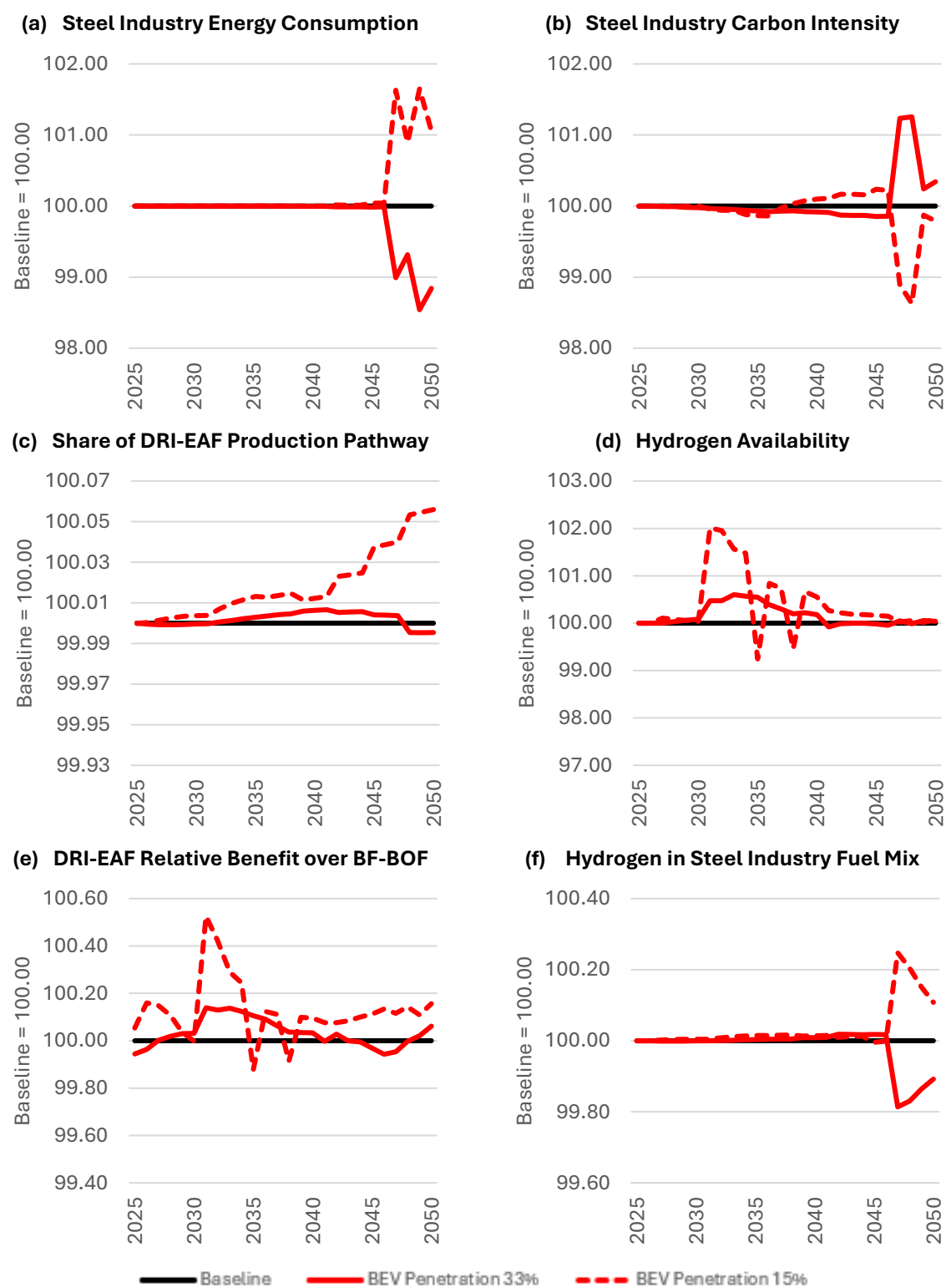


Figure 5.29. BEV penetration level on the observed indicators

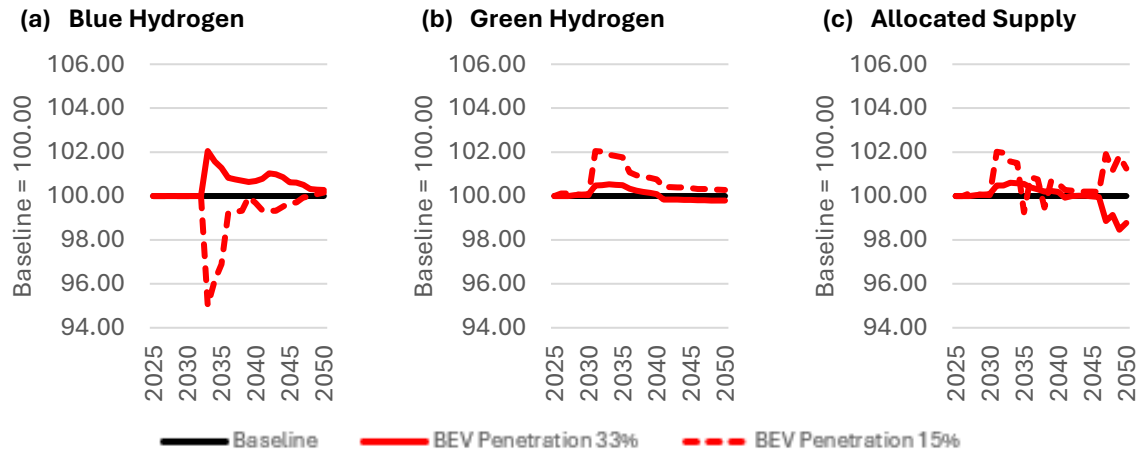


Figure 5.30. BEV penetration level effect on hydrogen production and supply to the steel industry

5.3.6. Interactions between the sub-systems involved

The summary of all the uncertainty tests is presented in Figure 5.31. Different indicators are affected differently by the uncertainties. However, the indicators are more sensitive to several uncertainties than others. The result concludes that GDP growth, hydrogen maximum injection rate, hydrogen producers' risk tolerance, and renewables development rate as the key uncertainties to the adoption of hydrogen in the steel industry, and to the effort in decarbonizing the sector. The effect of the scenario-driven uncertainties is minor compared to the supply-demand uncertainties because the change happens gradually.

The uncertainty test results highlight the dynamic interactions between the sub-systems, namely the steel industry, the fertilizer industry, the power sector, and the environmental system. The steel industry acts as the demand generator for hydrogen, the fertilizer industry and power sectors are the producers of hydrogen, and the environmental system is the limiting factor for hydrogen supply. The results show that a small production of hydrogen could stimulate the confidence in incorporating it in the steel production, which sends positive feedback to the hydrogen production and availability – creating a supply-driven reinforcing loop of the hydrogen utilization in the steel industry. However, the reinforcing loop is faced with a balancing loop in the hydrogen supply itself, limited by the availability of renewables and carbon storage potential.

The dynamic interaction between the hydrogen supply and demand are best observed by linking the maximum hydrogen injection rate and renewables development rate tests in Section 5.3.4.2 and Section 5.3.4.4, respectively. Under normal economic growth, simply increasing the demand of hydrogen in the steel industry – by increasing the injection rate – did not result in higher hydrogen availability since it is limited to the availability of renewables and carbon storage potential. Quite the opposite, solely increasing the hydrogen demand resulted in a reduced hydrogen availability as shown in Figure 5.19(a). Thus, increasing the hydrogen demand in the steel industry and the development of their enabling resources should be promoted simultaneously.

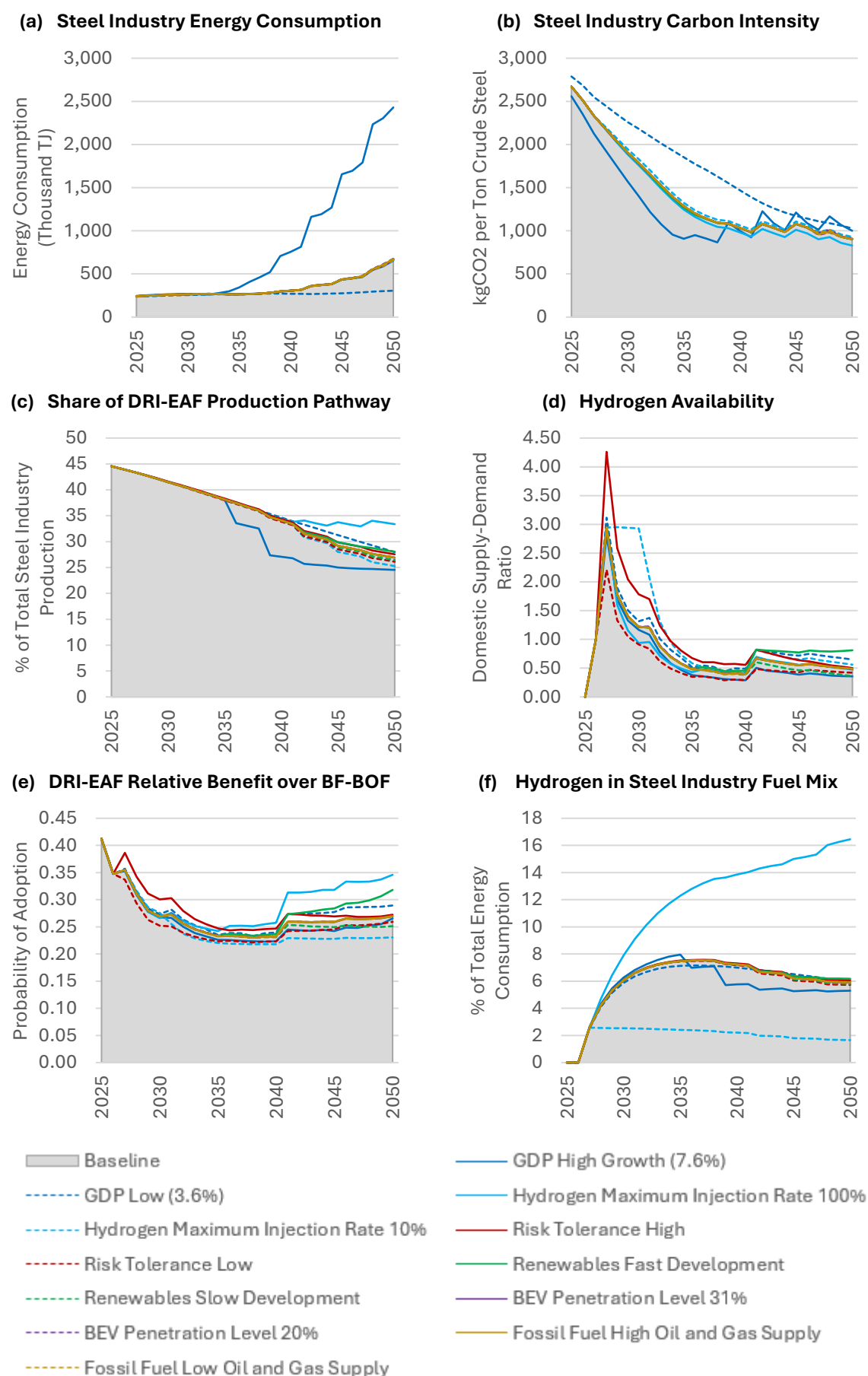


Figure 5.31. Summary of uncertainty results on the observed indicators

We also demonstrated how the transition in the power sector is hard linked to the transition in the industrial sector, as shown in the case with the steel industry in this study particularly in the context of green hydrogen. As explained in 5.3.5.2, the demand for RE required to produce green hydrogen competes with its use in the power sector itself, again linked to renewable resource availability. As for the steel industry link with the fertilizer industry, it was shown in the baseline result that the fertilizer industry has a higher potential to be a hydrogen supplier for the steel industry, primarily blue hydrogen, due to the lower competition for carbon storage resources.

This paper adds to the knowledge built from previous research. Watari & McLellan projected that 30% of the total steel demand would be met by hydrogen-based steel. In Indonesia's case, The result shows that the share of H₂-DRI-EAF could be between 25-33%. However, the previous paper did not mention at what injection rate is the hydrogen was. In this study, the share of H₂-DRI-EAF was evaluated using 10%, 33.3%, and 100% injection rate and obtained different results as shown in Section 5.3.4.2.

This study added the calculation of hydrogen availability for the steel industry which had not been investigated in literature. This study found that the availability range would be very wide between 36% to 81% of the demand. This study also includes the potential hydrogen producers and their production levels for each type of hydrogen. This study also found that the fertilizer industry has a higher potential than the power sector as for hydrogen supply in Indonesia as demonstrated in most cases except when there is a low development of renewables in which case both potential producers produced hydrogen at about the same level. In addition, focusing on one country instead of multiple countries resulted in a more in-depth and contextualized analysis.

The use of Indonesia as the case study presents a unique case since the nation has the potential resources to produce both blue and green hydrogen. As mentioned by Ledari et al., a country rich with fossil fuel should adopt blue steel production instead of green steel. While Indonesia has both fossil and renewable resources, the result demonstrates that the cumulative supply of green hydrogen between 2025-2050 could be higher than blue hydrogen as shown in Section 5.3.3. But it can also be the case that blue hydrogen is produced more when the potential producers have low risk-tolerance as seen in Section 5.3.4.3.

5.4. Aggregate Energy Demand and Grid Electricity Demand in The Industrial Sector

In this section, the aggregate effects of industrial sector energy transition on the energy demand and grid electricity demand are explored. Before moving into the main output, first technology adoption in the other major energy intensive industry shall be discussed.

5.4.1. Technology adoption in the other energy-intensive industries

Each energy-intensive industries have their own electrified production pathway. The cement industry currently uses thermal kilns for calcining process – the most energy intensive process in cement production²⁸⁹ – as their dominant production pathway²⁸¹. Electric kilns is being developed as an alternative²⁸¹. Currently, electric kilns are more 30% energy intensive than thermal process²⁸¹. One electric kiln project commissioned recently in Sweden around 2023 by SaltX in 2023³⁵².

In the non-ferrous metals industry, the current production pathway has already been using electricity as their main final energy source. For example, the nickel industry have employed

rotary kiln electric furnace (RKEF) since 1959²⁸², and the copper industry have even been using it since early 20th century³⁵³. However, these production pathways are highly energy intensive^{282,353} relying mostly on fossil fuels as their primary energy³⁵⁴, thus alternative production pathways have been developed. For nickel, a less energy intensive production pathway is through atmospheric acid leaching hydrometallurgy which offers around 30% less energy intensity²⁹⁰. Unfortunately, the commercial availability remains unclear³⁵⁵. Heap leaching hydrometallurgy, on the other hand, is commercially available and may reduce energy consumption by 10%²⁹⁰. Nonetheless, both atmospheric acid leaching and heap leaching have a much lower yield than pyrometallurgical process²⁹⁰. One hydrometallurgical process called the high-pressure acid leach (HPAL) offers about the same yield but with 15% higher energy intensity than the conventional process²⁹⁰. As for copper, the Mitsubishi process uses less than half of the energy required in the electric furnace, hence making the electric furnace less desirable³⁵³. Hydrometallurgical process can also be used to recover copper, but the direct energy intensity is even higher than electric furnace³⁵³.

Process electrification alternative is also being developed in the plastics industry to replace the current thermal production³⁵⁶. A study demonstrated a 15% energy intensity reduction by using electric steam cracker. Although the production process design can reduce cost by 5.5%, the production process has yet to be commercialized³⁵⁶.

While the technologies have different readiness level, in general however, ‘transformative’ electrification technology is expected to be deployed from 2030²⁸⁷. Thus, this study assumes the alternative electrified production pathway technology will be readily available in 2030 except for the steel industry who has been using EAF technology since 1970²⁹⁶. The resulting adoption of the respective electrified technology is shown in Figure 5.32.

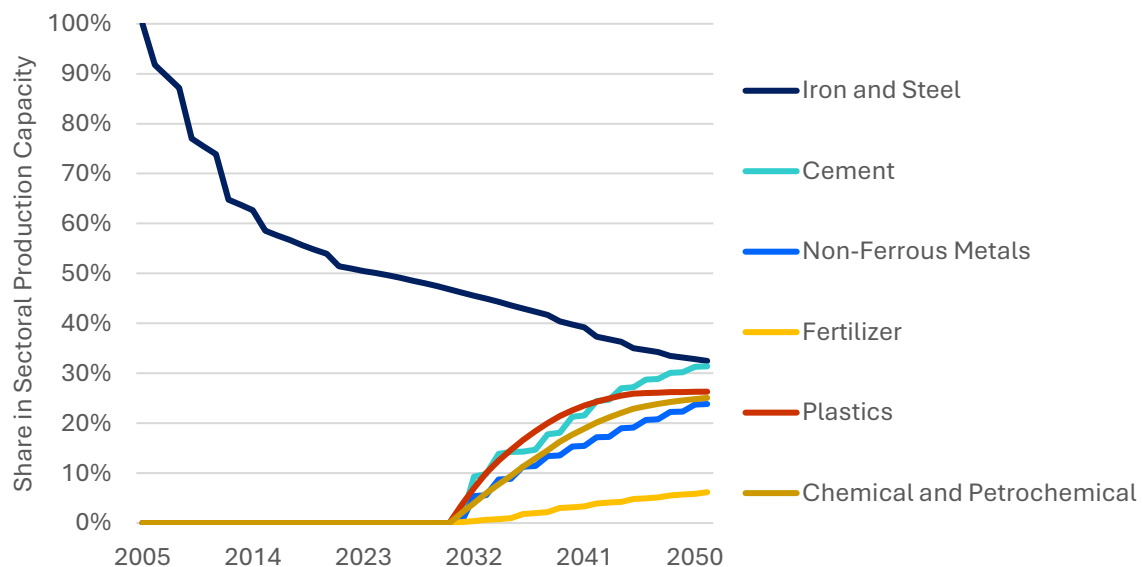


Figure 5.32. Share of electrified production technologies in each industry

Based on the surveyed adoption weights presented in Table 5.4, the cement industry would be the most possible industry to adopt an electrified production pathway. Although the high energy intensity would lead to higher cost, the industry has an equally high consideration for environmental criteria especially carbon emission and electric kilns enables the use of renewable energy which could reduce carbon emissions significantly. On the other hand, fertilizer industry would have the lowest potential to adopt the cleaner production pathway

since they emphasis on the compatibility of the technology to current process. Indeed, adopting clean ammonia production would require a major change in fertilizer production. Similarly, non-ferrous metals industry would also need to completely change their production process if they were to shift to hydrometallurgy process. However, their priority is resource availability when adopting a technology, and with the declining availability of fossil fuel – particularly coal as will be elaborated in Chapter 6 – the benefit to use electrified production pathway increased.

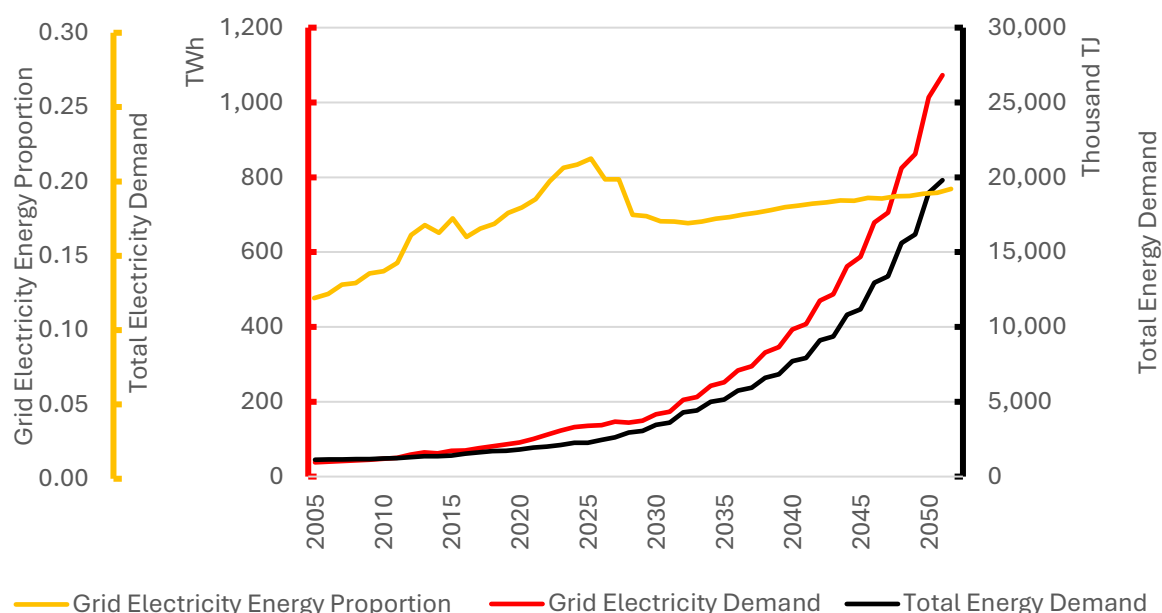


Figure 5.33. Baseline energy and electricity demand, and the proportion of grid electricity in the industrial sector

The total energy and grid electricity demand from the industrial sector baseline result are shown in Figure 5.33. By 2050, the energy demand could reach 19.8 million TJ which is 8.7 times and 17.6 times larger than the 2025 level and 2005 level, respectively. Among the industries, this found that non-ferrous metals industry would be the dominant energy consumer in the industrial sector followed by the cement industry. Using the demand projection formulated in Section 5.2.1, the demand in the non-ferrous metals could be 54 times larger than 2005 level, highest among other industries (iron and steel industry 12 times, cement industry 9 times, plastics industry 4 times, fertilizer industry 3 times). In addition, the non-ferrous metals industry is the most energy intensive industry among all. In case of the cement industry, although the increase in demand is less than the iron and steel industry, the adoption of electric kilns which has a higher energy intensity than the conventional technology led to a significant energy demand.

Like to result in steel industry energy transition presented in Section 5.3, there are uncertainties as to how the energy demand would evolve in the future. The energy demand of the whole industrial sector is investigated in Section 5.4.4 using the same uncertainties as used in the steel industry case study except for maximum hydrogen injection rate since it is only relevant to the steel industry.

For the risk-tolerance in each industry, the weights of adoption drivers were modified like what was done in the steel industry case study. Table 5.9 showed each industry have a different initial risk-tolerance profile. The criteria weights of level 2 of the environmental driver the level were also changed to better represent the risk-tolerance. The reason can be explained if comparing

the cement industry and base metals industry. While both have a high consideration for environmental drivers, the base metals emphasized on resource availability – an internal risk factor – and not carbon emissions. Hence, it is important to differentiate the level 2 criteria weights also for the environmental drivers.

Table 5.9. Weights of adoption drivers to emulate different risk-tolerance of the industries

Adoption Drivers	Risk-tolerance					
	Baseline		High		Low	
Economic	Steel	: 0.295	Steel	: 0.148	Steel	: 0.582
	Cement	: 0.380	Cement	: 0.190	Cement	: 0.760
	NFM	: 0.295	NFM	: 0.148	NFM	: 0.582
	Fertilizer	: 0.304	Fertilizer	: 0.152	Fertilizer	: 0.366
	Plastics	: 0.494	Plastics	: 0.247	Plastics	: 0.660
Environmental	Steel	: 0.434	Steel	: 0.657	Steel	: 0.000
	Cement	: 0.380	Cement	: 0.530	Cement	: 0.081
	NFM	: 0.434	NFM	: 0.657	NFM	: 0.000
	Fertilizer	: 0.090	Fertilizer	: 0.310	Fertilizer	: 0.000
	Plastics	: 0.179	Plastics	: 0.445	Plastics	: 0.000
Resource availability	Steel	: 0.875	Steel	: 0.125	Steel	: 0.875
	Cement	: 0.330	Cement	: 0.330	Cement	: 0.670
	NFM	: 0.875	NFM	: 0.125	NFM	: 0.875
	Fertilizer	: 0.500	Fertilizer	: 0.250	Fertilizer	: 0.500
	Plastics	: 0.209	Plastics	: 0.209	Plastics	: 0.791
Emissions to air	Steel	: 0.125	Steel	: 0.875	Steel	: 0.125
	Cement	: 0.670	Cement	: 0.670	Cement	: 0.330
	NFM	: 0.125	NFM	: 0.875	NFM	: 0.125
	Fertilizer	: 0.500	Fertilizer	: 0.750	Fertilizer	: 0.500
	Plastics	: 0.791	Plastics	: 0.791	Plastics	: 0.209
Technological	Steel	: 0.212	Steel	: 0.106	Steel	: 0.418
	Cement	: 0.060	Cement	: 0.030	Cement	: 0.120
	NFM	: 0.212	NFM	: 0.106	NFM	: 0.418
	Fertilizer	: 0.526	Fertilizer	: 0.263	Fertilizer	: 0.634
	Plastics	: 0.254	Plastics	: 0.127	Plastics	: 0.340
Organizational	Steel	: 0.059	Steel	: 0.089	Steel	: 0.000
	Cement	: 0.180	Cement	: 0.250	Cement	: 0.039
	NFM	: 0.059	NFM	: 0.089	NFM	: 0.000
	Fertilizer	: 0.080	Fertilizer	: 0.275	Fertilizer	: 0.000
	Plastics	: 0.073	Plastics	: 0.181	Plastics	: 0.000

As in the steel industry case study simulation, a high BEV penetration was achieved when the maximum battery capacity achieves 350 Wh/kg, potential BEV adopters have a higher consideration for environment than economic factors, there is no improvement in the internal combustion engine efficiency, and there is a low supply of oil and gas which leads to a high fuel price. On the other hand, a low penetration happens when the opposite is true. In addition, no incentives are provided under the low BEV penetration scenario. The resulting BEV share by 2050 under the high penetration is 33%, 18% under the low penetration, and 26% in the baseline.

5.4.2. Effect of uncertainties on industrial sector demand

The demand in all industries is positively affected by GDP, except for fertilizer as depicted in Figure 5.34. Nonetheless, GDP was shown to have the highest impact on demand in all industries. Under the high economic growth, the cumulative demand between 2025-2050 for steel, cement, non-ferrous metals, and plastics is 2.7, 2.9, 1.5, and 4.2 times larger than the

baseline, respectively. Conversely, the cumulative demand is 0.62, 0.48, 0.64, and 0.3 from the baseline in the low economic growth. The demand in the fertilizer industry, who have the opposite effect, is 0.95 and 1.05 from the baseline under the high and low economic growth, respectively. Specifically for the non-ferrous metals, the adoption of BEV also affects demand. Under the high BEV penetration – which led to a 33% penetration – the cumulative demand between 2025-2050 in the non-ferrous metals industry is 7% higher than the baseline while under the low penetration level it is 2% lower. Nonetheless, the BEV penetration effect on the cumulative demand is far below the effect of GDP.

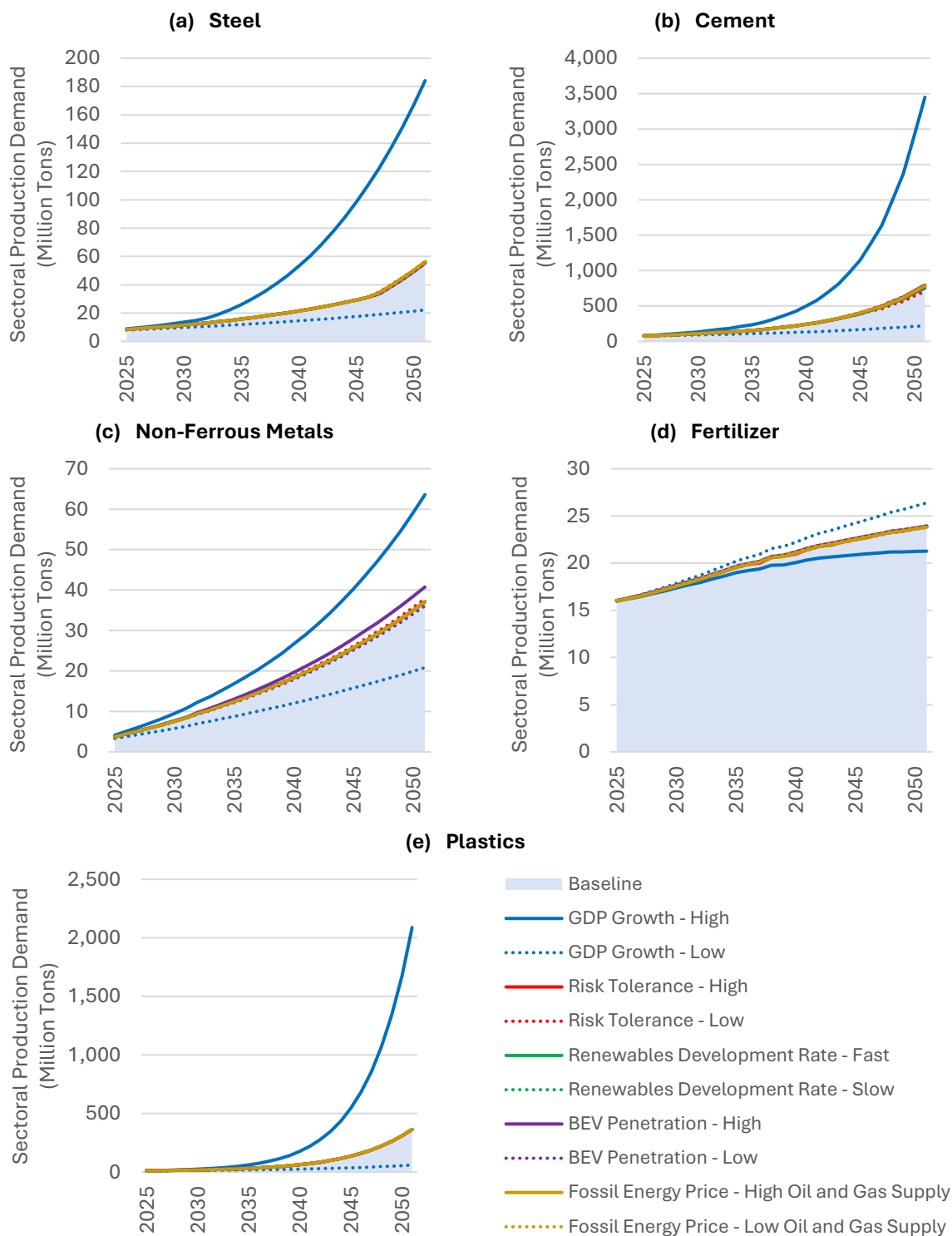


Figure 5.34. Energy-intensive industries demand under different uncertainties

5.4.3. Effect of uncertainties on electrified production pathway adoption

GDP growth also affects electrified production pathway adoption significantly as seen in Figure 5.35. In addition, risk-tolerance is also shown to have substantial effect on technology adoption. However, again, the effect is different in each industry. In the steel industry and fertilizer industry, a high risk-tolerance led to a higher chance of electrified production pathway since both of these industries initially tend to have a risk-averse characteristic, indicated by their high considerations on internal risks factors such as economic factor, resource availability, or technology compatibility. Conversely, the cement industry has an equally high weight on carbon emissions and very low weight on technology compatibility. Unfortunately, in the case of the cement industry, the alternative production pathway has a higher carbon emission. In addition, while the overall cost of electric kilns is higher than thermal ones, the relative environmental benefit is still lower than the economic benefit. As a result, the adoption rate in the cement industry could be less if the weight for environmental drivers is higher than the economic driver like in the high risk-tolerance case.

A rather unique behaviour can be observed in the non-ferrous metals where in both high and low risk-tolerance, the adoption rate is lower than the baseline. In the case of high risk-tolerance, the weights are shifted to carbon emissions. However, as with the case in the cement industry, the relative benefit in carbon emissions is much lower than resource availability, which led to a lower adoption rate. On the other hand, the weight of the economic and technological drivers is dominant under the low risk-tolerance. While within the non-ferrous metals industry nickel production continues to dominate and hydrometallurgical process offers lower energy intensity, the cost of energy is still higher due to the electricity price. In addition, since the majority of production uses pyrometallurgical process, shifting to hydrometallurgy could put the producers with operational risks. Hence, the adoption rate of electrified production pathway becomes lower than the baseline.

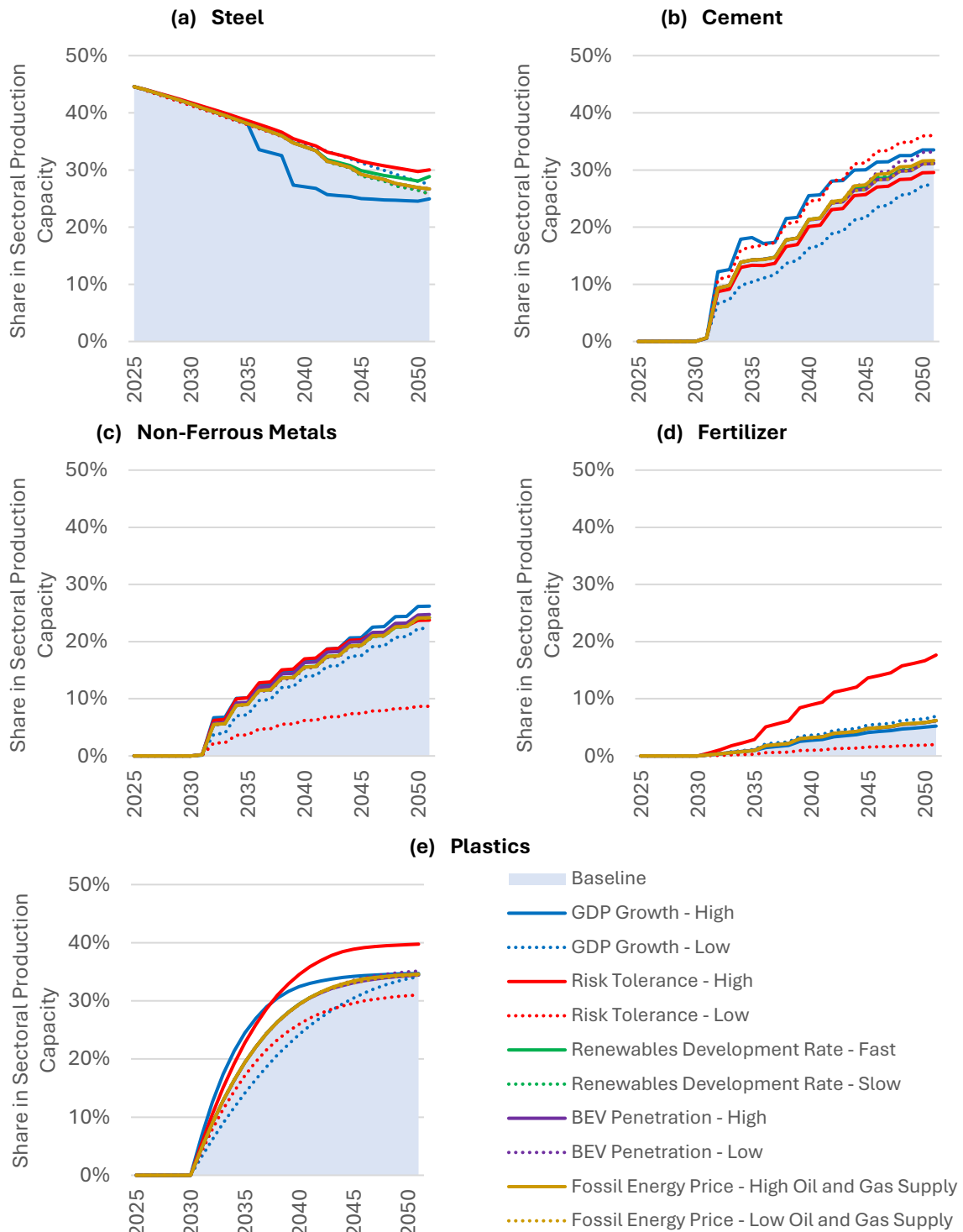


Figure 5.35. Electrified production pathway adoption in the industrial sector under different uncertainties

5.4.4. Energy demand and grid electricity demand in the industrial sector

The resulting total energy and grid electricity demand is presented in Figure 5.39. Following the effect on demand, GDP is also the most significant uncertainty on energy and grid electricity demand in the industrial sector. By 2050, the energy demand could reach 72 million TJ if the GDP growth is high which is 32 times and 64 times larger than the 2025 level and 2005 level, respectively. Conversely, the energy demand would only increase to 6.8 million TJ if the economic growth is low.

The annual energy demand and the cumulative energy demand comparison to the baseline by industries is presented in Figure 5.36 (steel and non-ferrous metals industries), Figure 5.37 (cement industry), and Figure 5.38 (fertilizer and plastics industries). For the cumulative energy demand, the comparison with the GDP growth tests was excluded due to the different magnitude with the other uncertainties. It can be noted that risk-tolerance is the second most important determinant in the industrial energy consumption, particularly in the case of cement industry, non-ferrous metals industry, and plastics industry. Risk tolerance also excites a rather counterintuitive results in the three industries.

The low risk-tolerance in the cement industry led to a higher electric kiln adoption as shown in Figure 5.35. While the higher share of electric kilns should have resulted in a higher energy demand, Figure 5.37 showed the opposite. The high energy intensity of electric kilns caused the production cost of cement. This in turn affects cement demand significantly (see Figure 5.34). The 2025-2050 cumulative cement demand in with the higher electric kiln adoption is 3.6% lower than the baseline, while the demand is 1.2% higher in the low electric kiln adoption case. Hence, the overall result is a higher energy demand despite low electric kiln adoption.

In case of the plastics industry (Figure 5.38), although the energy intensity of electric production pathway has a lower energy intensity, its higher electricity intensity means a higher electricity consumption. Unfortunately, based on the preference characterised in Table 5.4, plastics industry would tend to use captive generation from fossil fuel and particularly coal which have a low efficiency. Hence, the overall energy consumption become higher.

Specific to non-ferrous metals industry (Figure 5.36), both high and low risk-tolerance led to a higher energy consumption despite it also led to lower adoption rate of electrified production pathway as in Figure 5.35. In the case of low risk-tolerance, in addition to continuing with pyrometallurgy, the industry would tend to reduce their dependence on grid electricity. Instead, they would and rather increase their captive generation according to the adoption weights in Table 5.4. Like the plastics industry, however, it leads to a higher use of coal generation which explains the higher energy consumption than the baseline. The energy consumption increase is even higher in the high risk-tolerance case, because of the higher use of captive coal generation. A high risk-tolerance non-ferrous metals industry would reduce their dependence on the grid for the potential of using a lower carbon emission power generation – a different reason with the low risk-tolerance case. However, in the end they would still have a higher tendency to use thermal power generation although the possibility of using captive renewables was found to be higher than the baseline. The share of captive renewables in the high risk-tolerance case was 31%, while the share was 30% and 29% in the baseline and low-risk scenario, respectively.

The total grid electricity demand is shown on Figure 5.39(b). Overall, industrial sector's demand for grid electricity could range from 387 TWh to 2,303 TWh in 2050 – a very high uncertainty due to the GDP growth. In addition, a high risk-tolerance also presents a high uncertainty to the grid electricity demand as the result of the electricity sourcing preference explained previously.

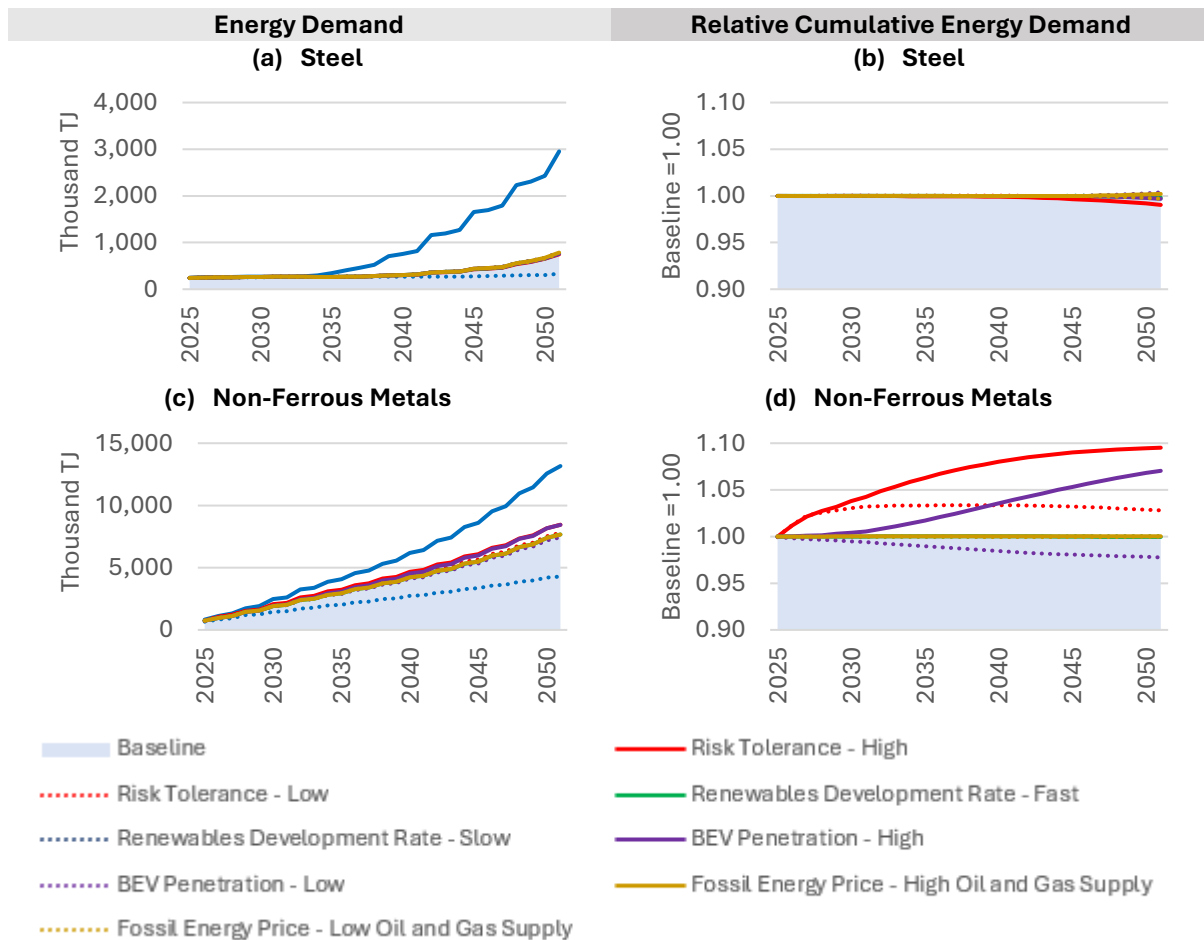


Figure 5.36. Energy demand in the base metals industry under different uncertainties.

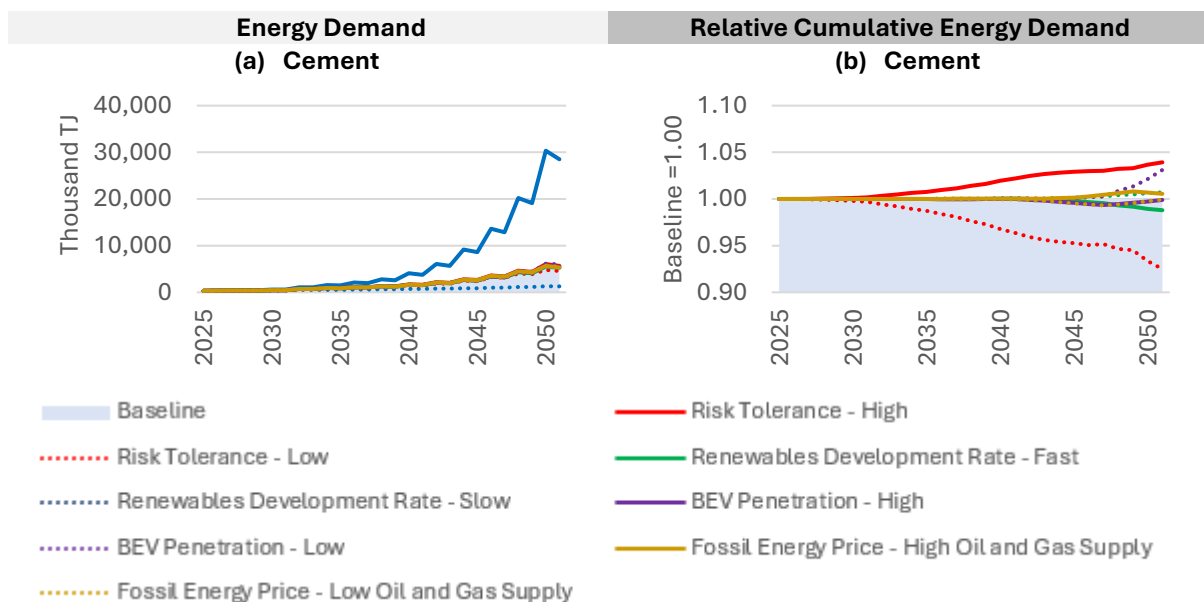


Figure 5.37. Energy demand in the cement industry under different uncertainties.

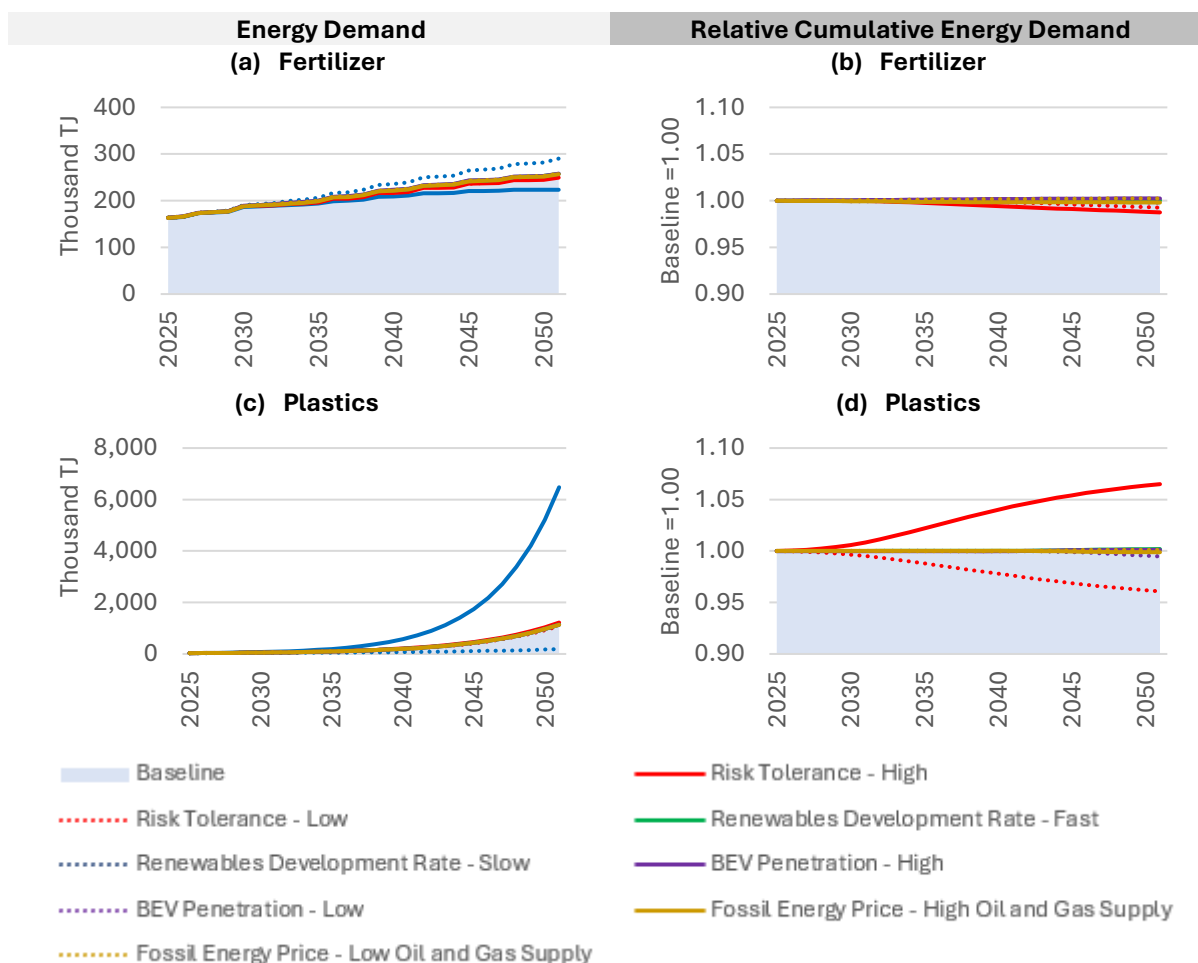


Figure 5.38. Energy demand in the chemical and petrochemical industry under different uncertainties

The industrial sector's dependence on grid electricity is illustrated in Figure 5.39(c). While a high GDP growth led to a high grid electricity demand, its effect on the grid electricity proportion in the industrial sector energy demand is the opposite. The explanation lies with the industrial demand mix shown in Figure 5.40. In the high GDP growth case, for example, on average 42% of the industrial sector energy demand comes from the cement industry followed by non-ferrous metals 37% and both industries have the highest use of captive generation. On the other hand, the non-ferrous metals hold 54% of the energy demand in the low economic growth case, followed by other industries 19% and cement industry 15%. The other industries – including paper and pulp industry, textile industry, food industry, and others which are not specifically investigated in this study – have a relatively high use of grid electricity which explains the higher overall share of electricity grid compared to the high economic growth case. But the most significant factor to the share of grid electricity was shown to be risk-tolerance, as explained by the adoption of captive generation by the non-ferrous metals.

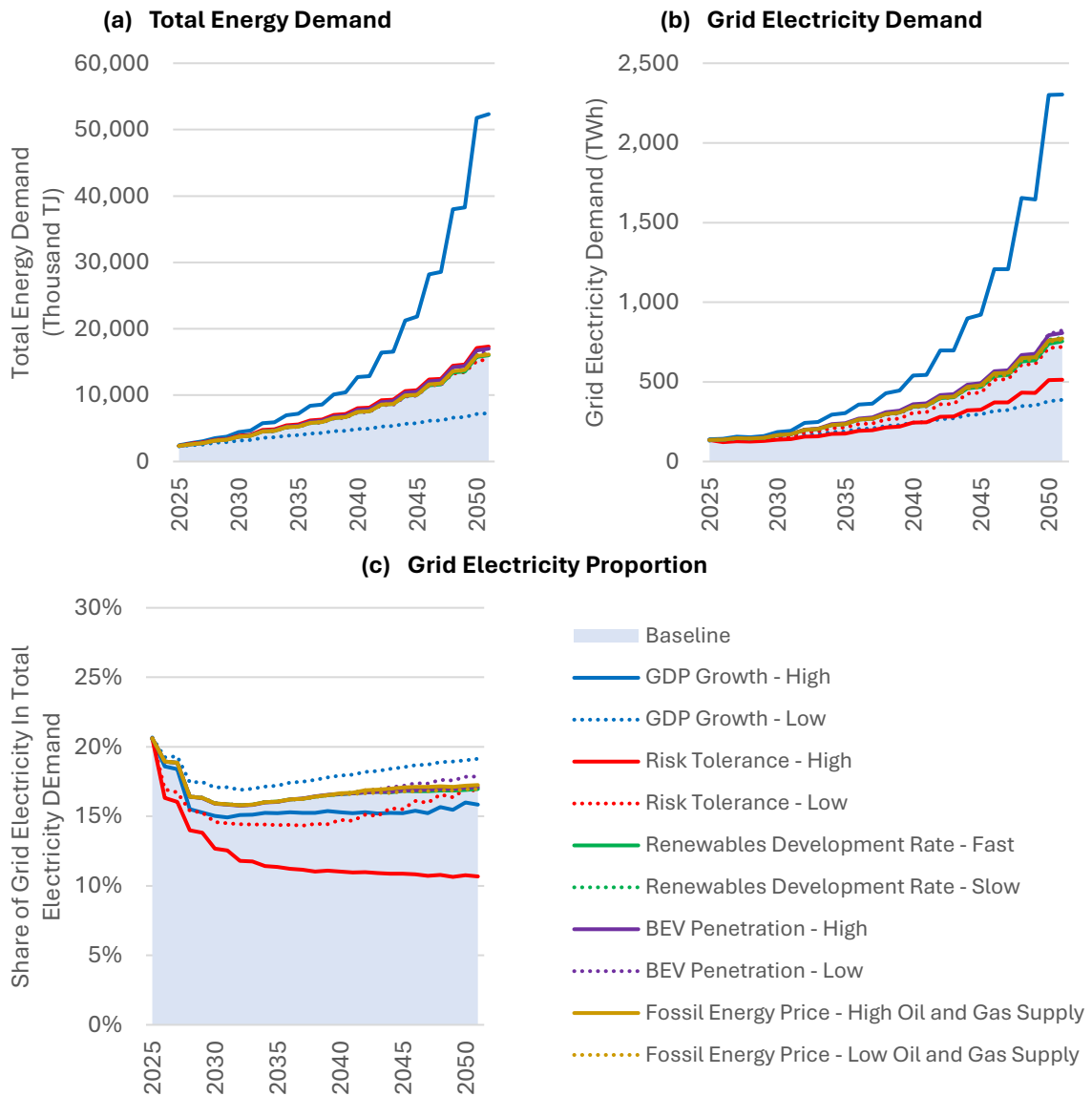


Figure 5.39. Total energy and grid electricity demand, and the proportion of grid electricity in the industrial sector under different uncertainties

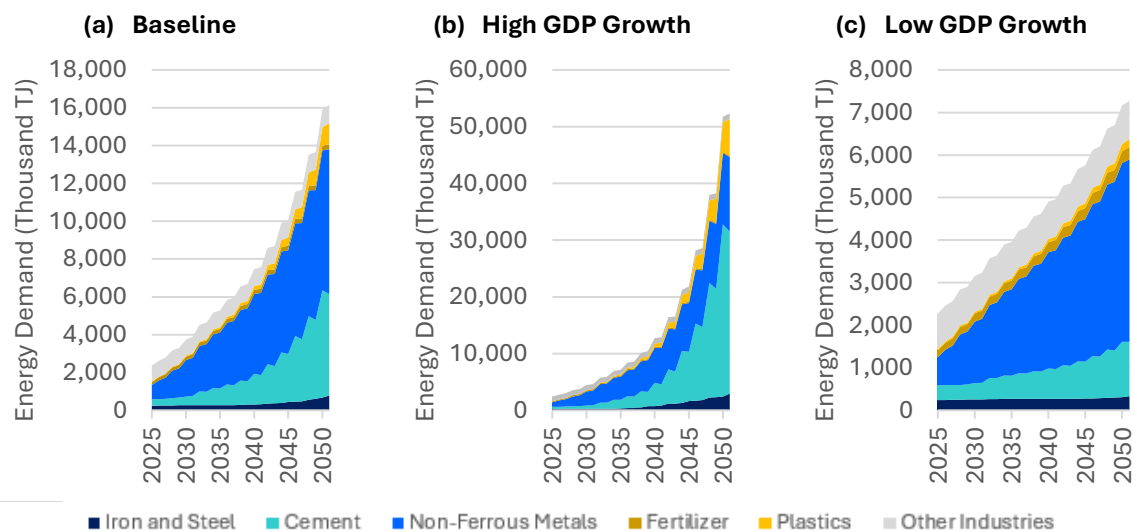


Figure 5.40. Industrial mix and energy demand under different economic growth

5.5. Implications of the Industrial Sector Energy Transition

Being the central of the productive activity, the energy transition in the industrial sector would have a profound effect on the economy and the environment. The sustainability of a transition can be measured by three economic indicators prescribed in Chapter 2, namely GDP growth, inflation, and state budget. Since GDP growth was treated as an exogenous factor in this chapter, this section shall focus on the effect of the energy transition on inflation and state budget. For the environmental impacts, this section shall focus on resources demand and carbon emissions.

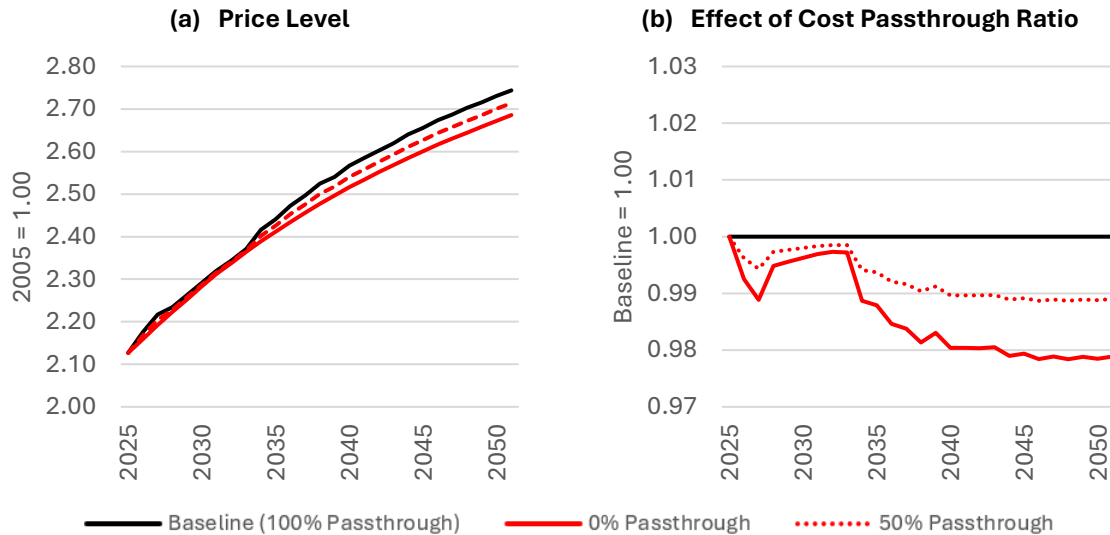


Figure 5.41. Effect of transition cost on price level of goods

Changes in the production pathway may significantly alter the production costs in the industrial sector. However, the effect would depend on whether how much the costs are passed through to the consumers as illustrated in Figure 5.41. If it were to be passed through completely as assumed in the baseline, the general price level of goods by 2050 could increase to 2.74 times from the initial level in 2005. However, if all the costs of transitioning are absorbed by the producers, the price level of goods in 2050 would only increase to 2.69 times. Hence, the contribution of production pathway transition in the industrial sector is around 2.8%. If half of the transition cost increase is passed through to consumer, the technology transition contribution would also be halved, and the price level would increase 2.71 times from the 2005 level. Note that only cost changes in the selected industries were included, hence the effect of the transition on the price level should be smaller than actual. Figure 5.42 shows the effect of industrial sector technology transition on state budget. While the effect fluctuates, in general it is showing a negative trend (higher state budget deficit ratio). The additional strain on the state budget comes from the hydrogen incentives and electricity subsidy, particularly for the feed-in tariff for the renewables. The lower price level with less transition cost being passed through could lead to slightly higher industrial sector demand which resulted in a higher energy demand and its associated subsidies.

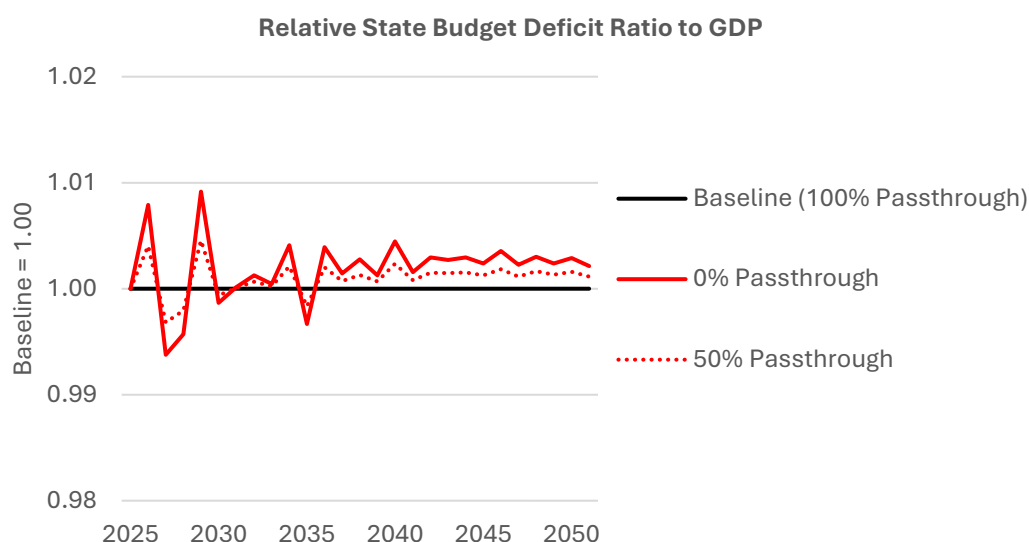


Figure 5.42. Effect of transition cost on state budget deficit ratio to GDP

From the results in Figure 5.39, energy demand is most sensitive to GDP growth and risk tolerance, which would translate to the primary resources required. Figure 5.43 shows that, in 2050, the demand for coal, natural gas, and crude oil could reach 452 million tons, 40 billion m³, and 418 billion litres, a 10.8, 1.8, and 24.3 times increase from 2025 level. Crude oil demand would be the most uncertain – ranging from 4.5 times higher than the baseline to 128.3 times higher – attributable to the demand uncertainty in the plastics industry due to GDP growth. On the other hand, natural gas demand would change the smallest (1.6-3.5 times larger than 2025 level). Natural gas demand decreased with higher risk tolerance due to the more rapid adoption of hydrogen in the fertilizer industry and shift to electrified production pathway in the plastics industry. The cumulative natural gas demand between 2025-2050 could be 3% lower than the baseline in the high risk-tolerance case. On the other hand, coal demand increased with higher risk tolerance due to the use of it for captive generation to power electrified production pathways especially in the cement and non-ferrous metals industry. Under the high risk-tolerance setting, the cumulative coal demand between 2025-2050 could be 15% larger than the baseline.

The consequence of the fuel mix is reflected in the carbon emissions shown in Figure 5.44. Under the high GDP growth where the cement industry would dominate the industrial sector in terms of energy consumption, the carbon emissions could reach 4 million tons CO₂ which is an increase of 6.6 times from the baseline and 20 times increase from the 2025 level. In both cases of risk tolerance, the carbon emissions can be reduced. On one hand when risk tolerance is high, carbon emissions can be reduced due to the increased use of captive renewables generation although coal consumption also increased from the increase overall captive generation. On the other hand, a lower risk-tolerance led to lower electricity consumption and thus also reducing the emissions from coal power generation (both captive and grid generation). In either case, the cumulative carbon emissions between 2025 to 2050 from the industrial sector could be reduced by 2% from the baseline.

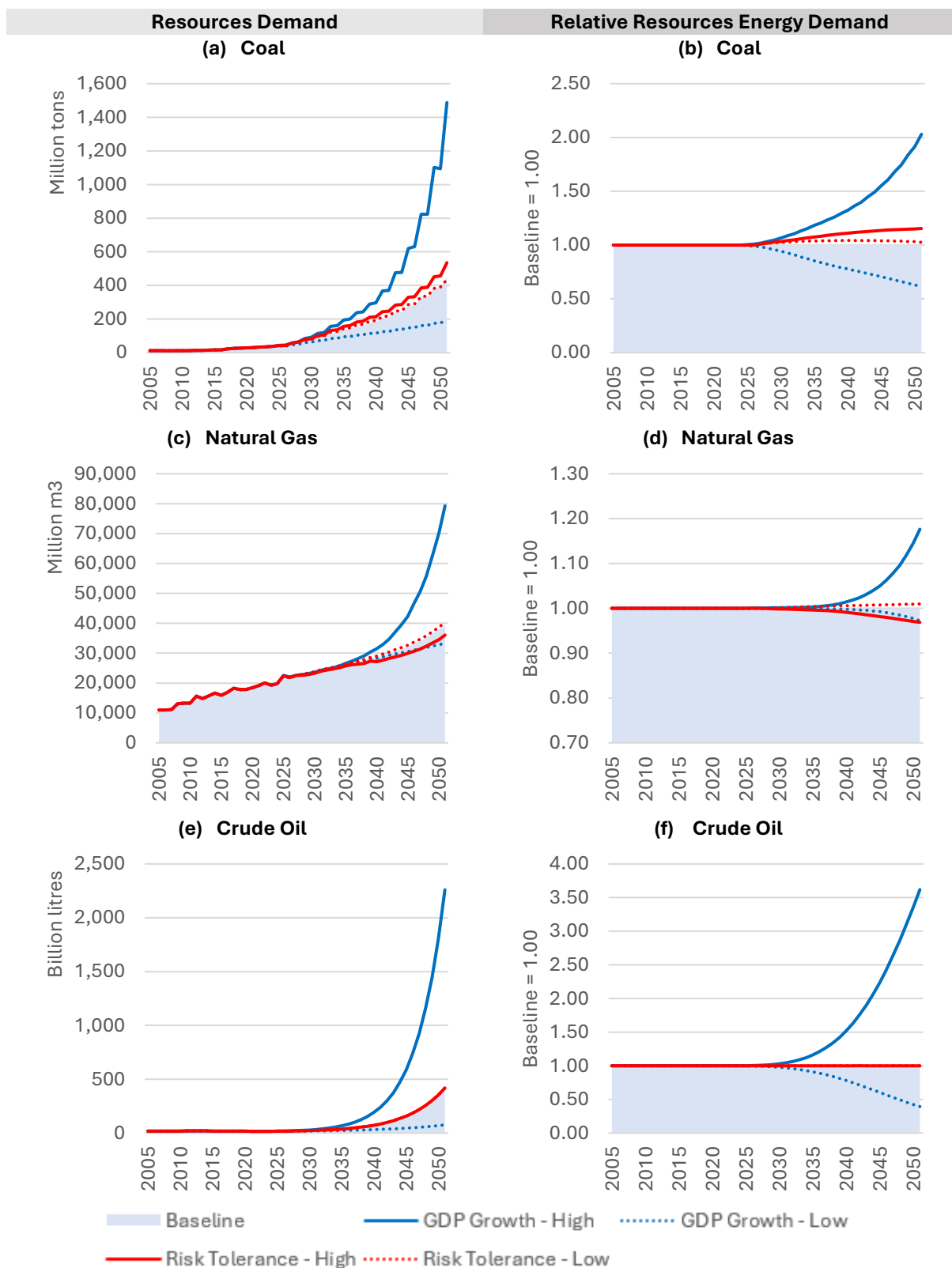


Figure 5.43. Effect of transition on industrial sector primary resources demand.

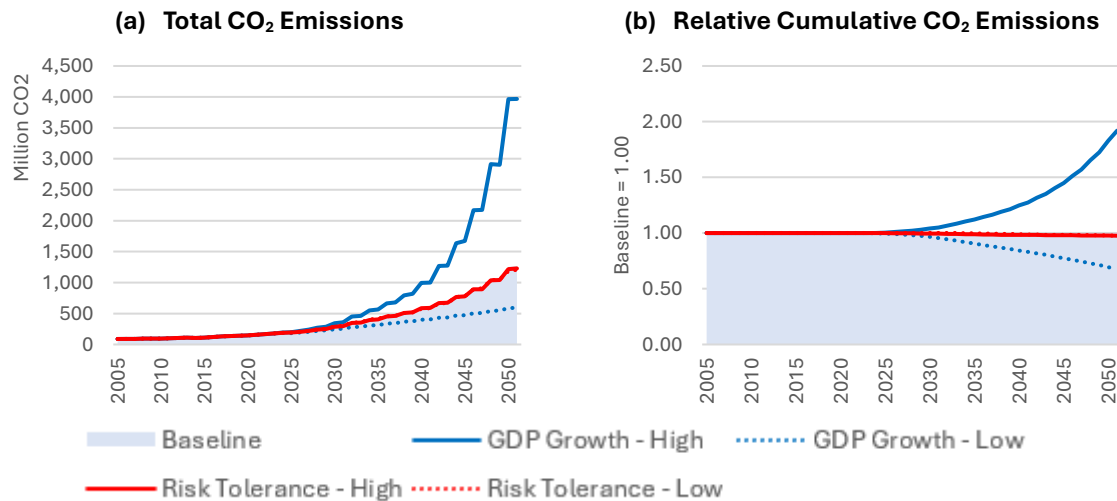


Figure 5.44. Effect of transition on industrial sector carbon emissions.

5.6. Conclusion

The industrial sector is the largest energy consumer, and its consumption continues to increase. Four industries, namely the iron and steel industry, non-ferrous metal industries, cement industry, chemical and petrochemical industries is responsible for 80% the industrial sector energy demand. Unfortunately, these industries are energy-intensive and relying mostly on fossil fuels. Electrification of production pathways has come as one alternative to decarbonise the sector. However, this could strain the electricity grid, on top of the substantially increasing electricity consumption in the industrial sector. The steel industry adoption of the hydrogen-based DRI-EAF is used as a case study before moving into the other energy-intensive industries.

From the steel industry case study, it was found that resource availability is a key factor in transitioning to a cleaner production pathway. Since hydrogen is a prerequisite in the H₂-DRI-EAF, its availability would drive the production pathway adoption pathway. This study found domestic hydrogen production can fulfil between 36% to 81% of the demand in the Indonesian steel industry. The key uncertainties to availability, and ultimately to the effort in decarbonizing the sector, were found to be GDP growth, hydrogen producers' risk tolerance, hydrogen maximum injection rate, and renewables development rate. This study adds to the knowledge of the uptake of hydrogen in the steel industry. In Indonesia's case, the result shows that the share of H₂-DRI-EAF could be between 25-33% and the share of hydrogen in the fuel mix could vary widely from 1.7% to 16.4%. The result also demonstrates that the dominant hydrogen type would be determined by the risk-tolerance of the potential producers.

GDP growth and industries' risk tolerance was also shown to be a key uncertainty in the aggregate industrial sector energy demand. However, it affects each industry differently. The energy demand of all industries except the fertilizer industry is positively affected by GDP growth. While the effect of risk tolerance to the energy demand in the steel industry and fertilizer industry is straightforward – high risk tolerance led to a higher adoption of electrified production pathway and lower energy demand, it is not as clear as in the cement, non-ferrous metals, and plastics industries. In the non-ferrous metals and plastics industry, while a higher risk tolerance led to a higher adoption of the electrified production pathway, the still-dominant use of coal power captive generation led to a higher energy demand. In the cement industry, a high risk-tolerance led to a lower electric kilns adoption instead. However, the resulting energy

demand is still higher than the baseline since low electric kilns adoption lowers the total production cost and, in turn, a higher cement demand.

By 2050, the aggregate energy demand in the industrial sector could reach 72 million TJ if the GDP growth is high. Conversely, the energy demand would only increase to 6.8 million TJ if the economic growth is low. The industrial sector's demand for grid electricity could also have a wide range from 387 TWh to 2,303 TWh in 2050 due to the GDP growth. In addition, a high risk-tolerance also presents a high uncertainty to the grid electricity demand as the result of the electricity sourcing preference where a high risk-tolerance among the industries could reduce grid electricity demand by 25% thanks to the higher adoption of renewables captive generation.

The results of the study also provide practical implications. Exemplified in the steel industry case study, to ensure the supply-driven reinforcing loop of resource availability hydrogen utilization in the steel industry is initiated, the government could initiate and incentivize pilot production of H₂-DRI-EAF based steel learning from the pilot-scale hydrogen production in the power sector. The key uncertainties found in this study are also potential leverages to increase the adoption of H₂-DRI-EAF. Using the findings, steel producers should find ways to increase the hydrogen injection rate in the DRI-EAF production pathway, which would dramatically increase the demand for hydrogen, which in turn stimulates its production from the potential producers and maximizes the hydrogen availability. The increase must be supported by progressing a faster development of renewables and carbon storage by the government, for example, by providing fiscal incentives or streamlining the permit process. However, environmental and social impact assessment should be considered with highest regard. Finally for steel demand, the government could push domestic steel production by mandating local content in products using steel. Promoting the production of “green” steel globally could also attract exports.

Up to this point this chapter has only evaluated single uncertainties one at a time while changes in these uncertainties could happen at the same time. This limitation will be explored further in Chapter 6.

Chapter 6

A Sustainable Transition in The Power Sector from the Whole System Perspective

6.1. Background

Indonesia's final energy demand in each of the major demand sectors – discussed in detail for the transportation sector in Chapter 3, the residential sector in Chapter 4, and the industrial sector in Chapter 5 – could increase exponentially in the next decades. The proportion of electricity in the final energy mix would continue to increase, primarily from the transportation sector due to the adoption of BEV. By 2050, the electricity demand from the transportation sector could exceed 200 TWh which is more than 17 times its current level. This demand would exceed the electricity demand from the residential sector which was the largest electricity consumer in the last decade¹. The electricity demand in the residential sector itself would increase steadily by 2%, reaching 190 TWh in 2050. But the sector with the largest electricity demand would be the industrial sector, which could reach 767 TWh under – a 6.9% increase from the current level. The energy demand and grid electricity demand increase in the industrial sector is driven by economic growth which was 5.6% per year – exogenously simulated in Chapter 5.

With the increase in electricity consumption, it is imperative for the power sector to decarbonise. As shown in the previous chapters, carbon emissions increased following the energy demand. The Government of Indonesia (GOI) has issued their Enhanced Nationally Determined Contribution (NDC) to reduce greenhouse gases (GHG) by 29% unconditionally by 2030⁶. If all sectors are to be burdened equally, this necessitates the grid emission factor being reduced from 0.78³⁵⁷ in 2019 to 0.55 kg CO₂ per kWh in 2030. Unfortunately, the share of coal powered generation instead increased between 2019 to 2022, from 62.6% to 66.6%¹ as shown in Figure 6.1. The ambitious plan to increase the renewables uptake in the power sector to at least 31% in 2031⁶ and up to 80% by 2050² remains questionable.

Chapter 2 identified the main factors that may have hindered the progress to include more renewable electricity generation into the grid. These might include the larger land footprint than fossil energy⁷ and the negative effect of massive variable renewable electricity (VRE) integration on the grid electricity price^{8,12–14}. In addition, grid reliability may be compromised when more VRE is included into the grid²⁶⁷. Chapter 3 quantitatively assessed the land required for renewable energies, and indeed the land requirement is massive – reaching 90 thousand hectares in 2050. Although the land required is mostly for biofuels production in the transportation sector, it coincides with the physical land availability for power generation also. Not to mention the 30% required land area for conservation²¹⁵. An increased electricity price will not only burden households as was shown in Chapter 4 but may also hinder decarbonisation efforts in the energy demand sectors as demonstrated in Chapter 3 through Chapter 5. In a wider context, transitioning away from coal may negatively impact the economy as the commodity provides almost 18% of the Indonesian government's revenue through tax and non-tax revenues¹¹.

The GOI is planning to employ an array of energy policies to support the transition in the power sector. However, some policies show negative impacts on the economy. For example, the application of a Feed in Tariff (FIT) could lead to a spike in electricity price^{16,17}, while a carbon emission trading system (ETS) increases fossil energy prices and the production costs of various industries, leading to a decline in real GDP¹⁰⁷. Taking applications of the Feed-in Tariff (FIT) and Renewables Purchase Obligation, Zahari & McLellan qualitatively explain that both policies will be limited to the state budget but expanding the fiscal space could mean reallocation of other subsidies which may cause a systematic issue or through debt which may lead to future economic burden³⁴⁸. Many of the complications in energy policy implementation, as previously mentioned, involve linkages and feedback between different systems—the economic system in particular—which creates complexities in the energy transition. Thus, energy transition policy in the power sector must be viewed from a wider context, involving the economic system^{34,348}.

One study projected the pathway towards a 100% renewable energy in Indonesia²⁶⁶. Using TIMES least cost-optimisation, they found nuclear and solar power could form 86% of the total electricity production. They also found that by excluding nuclear, the land requirement would increase up to 83% and generation cost by almost 10%, which confirms the concern of relying on VRE²⁶⁶. While providing detailed projections on the power mix, the study has not included the wider socio-economic and environmental implications of the transition. Another study has qualitatively assessed the power sector energy transition issue from a wider perspective³⁵. Although they have considered the link with economic growth, they view the problem predominantly from the perspective of the state-owned electricity company PT Perusahaan Listrik Negara (Persero) (PLN), which limits the discussion with regards to structural feedback on the economic system and the other stakeholders, particularly the energy demand sectors as have been discussed in Chapter 3 through Chapter 5. With the non-linearity and uncertainty of transition as demonstrated in previous chapters, this chapter shall continue to apply system dynamics to accommodate the complexity of the power sector transition from the perspective of the whole system energy transition.

The objective of this chapter extends the objectives in Chapter 2. In the conceptual model, the first aim was to understand the underlying system structure that could hold back the energy transition in the power sector to Chapter 2 have qualitatively addressed. Secondly, Chapter 2 presented the policies the GOI have prepared to promote the energy transition, as well as the stakeholders involved in the transition. Chapter 2 also qualitatively explored “what would happen” and “how does it happen” when these energy transition policies are implemented. Thus, this chapter shall quantitatively investigate the structural barriers of the energy transition in the power sector and simulate the effect of the identified policies. As the binding chapter between the previous chapters, this chapter aims to quantitatively investigate the necessary policies to sustainably transition in the power sector – measured by the indicators defined in Chapter 2 – and to identify the roles of each stakeholder in the transition.

The next section of this chapter will present the model building process for the power sector transition. The developed model will be run in the baseline scenario in Section 6.3, observing the indicators defined in Chapter 2. In Section 6.4, the model is simulated under uncertainties identified in Section 6.2 to identify the leverage points as the basis in developing policies in Section 6.6, in which the model will be run again for different scenarios. Section 6.8 summarises the findings and compares the results with previous research. Finally, Section 6.8

concludes the study and provides practical policy implications as well highlighting the role of each stakeholder within the system transition.

6.2. Model Building

6.2.1. The State of the Power Mix in Indonesia

The Indonesian power mix has been relying on coal generation over the last two decades, and its share is growing - as can be seen in Figure 6.1. The increasing dominance of coal-fired power plants (CFPP) since the 2000s can be traced to the Chinese's government "Going-out" strategy where Chinese Engineering, Procurement, and Construction (EPC) Contractors expanded overseas³⁵⁸. In the power sector, this strategy was met with GOI's preference towards coal as the least-cost energy for generating electricity – banking on the domestic abundance of coal³⁵⁹. This inclination towards coal was exacerbated with GOI's tolerance towards subcritical power plants which are the cheapest but least efficient, thus leading to more coal consumption and more adverse environmental impacts³⁶⁰. The Belt and Road Initiative (BRI) further extends Chinese government investments for CFPP particularly to support minerals smelting activities which are also owned by Chinese companies³⁶⁰. Gu found that there were at least 25 CFPP projects with Chinese involvement, 21 of which were for grid electricity generation – five of which are mine-mouth CFPP – and 4 captive generation CFPP – all for mineral smelting³⁵⁸. This recent investment in CFPP may lead to a "technology lock-in" phenomenon owing to the long lifetime of the assets^{319,358}.

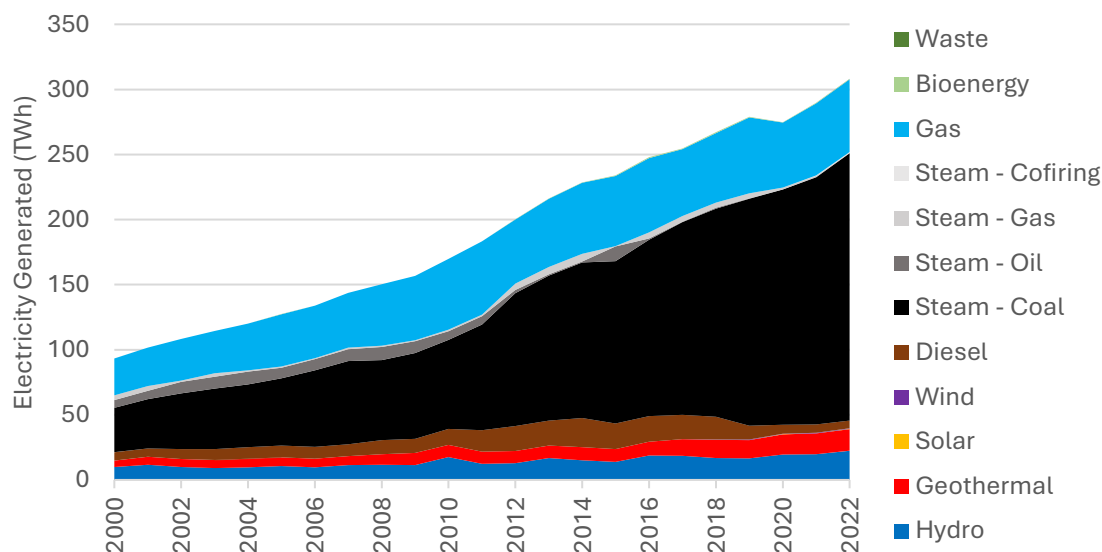


Figure 6.1. Indonesian Power Sector Generation Mix from 2000 to 2022.

Other fossil-based generation has not increased. The increasing reliance on CFPP has resulted in the stagnation of gas-fired power plant (GFPP) capacity despite their initially close share in the power mix. Diesel power plants (DPP) have been used in remote areas where grid interconnection is difficult³⁶¹. However, the necessity to use diesel power generation has become less as the grid electricity distribution increased³⁶². In addition, reducing diesel power generation is favourable in terms of energy security since a large proportion of diesel is imported^{1,363}. Similarly, natural gas allocation for the power sector competes with the industrial sector¹⁰ with the domestic natural gas reserves declining¹.

Table 6.1. Renewable potential, its planned utilization by 2050¹⁰ and capacity factor⁸.

Renewables	Potential (MW)	Planned Project (MW)	Planned Potential Utilization	Capacity Factor
Hydropower (incl. small hydro)	94,476	45,000	47.63%	44-46%
Geothermal	17,546	17,546	100.00%	85-87%
Bioenergy	32,654	26,000	79.62%	72%
Solar	207,898	45,000	21.64%	14-17%
Wind	60,647	28,000	46.17%	27-37%
Total	413,221	161,546	39.09%	

Indonesia is home to more than 400 GW renewable energy potential, around half of which is solar energy¹⁰. However, hydropower and geothermal remain the most utilised renewables up to the present day, producing on average 13% of the grid electricity¹. Geothermal generation has increased through the years as shown in Figure 6.1, and by 2050 all its potential is expected to have been used¹⁰. Hydropower along with solar power is planned to be the largest renewable electricity capacity in 2050 as stated in the National Energy Plan¹⁰ as shown in Table 6.1. When including capacity factor and conversion efficiency into consideration, however, hydropower would remain the largest contributor of clean electricity to the grid followed by bioenergy and geothermal^{8,21}.

6.2.2. Renewables adoption in the power sector

The electricity demand can be segregated based on the demand sectors: residential (Chapter 4), industrial (Chapter 5), and transportation (Chapter 3). All sectors' demands are driven by population and GDP growth. Chapter 4 explains that electricity demand in the residential sector is driven by the number of households in each income-level which shift between class is driven by GDP. Similarly, Chapter 3 explains that energy demand in the transportation sector is driven by the number of commuters and vehicle ownership, which is also affected by GDP. In Chapter 5, population and GDP are used to calculate the demand in each industry which in turn translates to energy demand subject to production pathway adoption.

If the current power generation capacity is insufficient to meet the demand, there will be a required capacity addition. Like in the production pathway adoption in the industrial sector, power producers have the option to invest in new fossil-sourced electricity (FE) capacity or renewable electricity (RE) capacity. Also as in the industrial sector, the adoption decision is affected by economic, technological, environmental, and organisational benefits based on the TOE framework.

Economic factors are well-documented to be an important driver to technology adoption in the power sector. The economic factors include investment cost^{313,364-368}, investment profitability^{314,315,364}, generation cost³⁶⁸⁻³⁷⁰, electricity price^{365,369,371}, and demand uncertainty^{313,365,370}. While these factors are common with technology adoption factors in the industrial sector as elaborated in Chapter 5, Lenhart and Araujo added economic development outcomes in the context of microgrid adoption in rural areas³¹⁴. Since the power sector in Indonesia is under the government's jurisdiction, the economic multiplier effect becomes important to be considered since it is the role of the government to improve the whole economy. Previous research also emphasised the importance of organizational and regulatory factors in technology adoption in the power sector. These factors can be categorized into four factors, namely: alignment with company strategy^{313,365,368}, government incentives^{313,364-366}, regulatory support^{313,365-368,370,372}, and workforce readiness^{365,366}. Researchers have stressed the importance of regulatory support for technology adoption in the power sector, pointing out the

lack of regulations^{365,366,368,370,372}, political commitment³⁶⁵, and corruption³⁶⁵ as key barriers to renewables adoption. Factors including readiness level^{364,365,373}, technology compatibility^{364-366,368,373}, production throughput³⁷³, and reliability and resilience³¹⁵ are highlighted as key technological factors in renewables adoption. Reliability and resilience are of particular importance due to the negative effect of VRE integration on system performance²⁶⁷. Lastly, emissions to the environment^{314,366}, resources supply security^{313,365,366,368,371}, and land-use³⁶⁸ are reported to be the key environmental factors. The adoption factors are summarised in Figure 6.2.

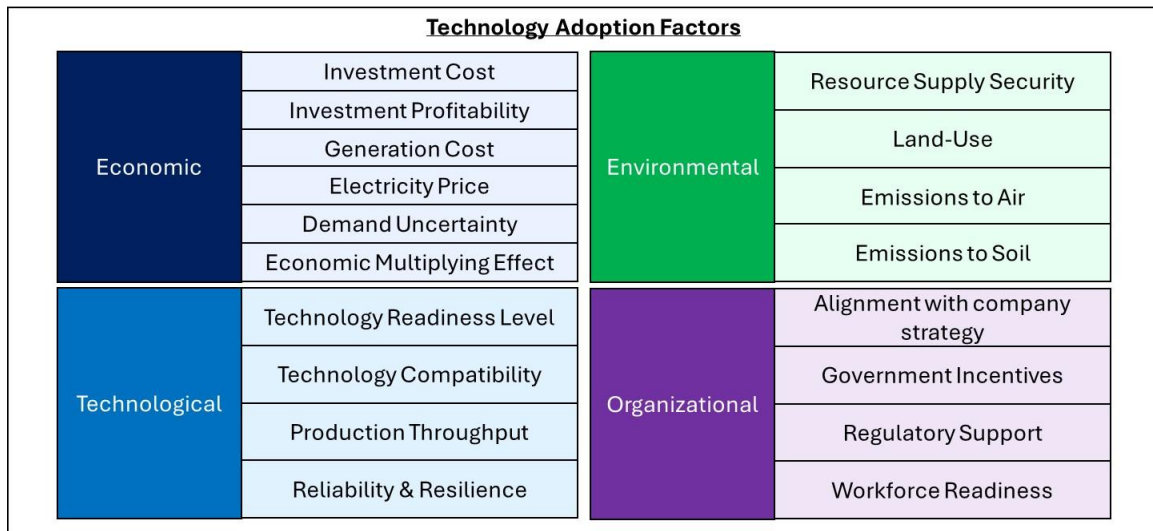


Figure 6.2. Technology adoption factors in the power sector.

Using the Analytical Hierarchical Process (AHP), power sector experts were interviewed to determine the relevant factors and then the weights of each factor were determined. The resulting factor weightings are presented in Table 6.2. The factors mentioned in Figure 6.2 but missing in Table 6.2 were considered irrelevant according to the experts.

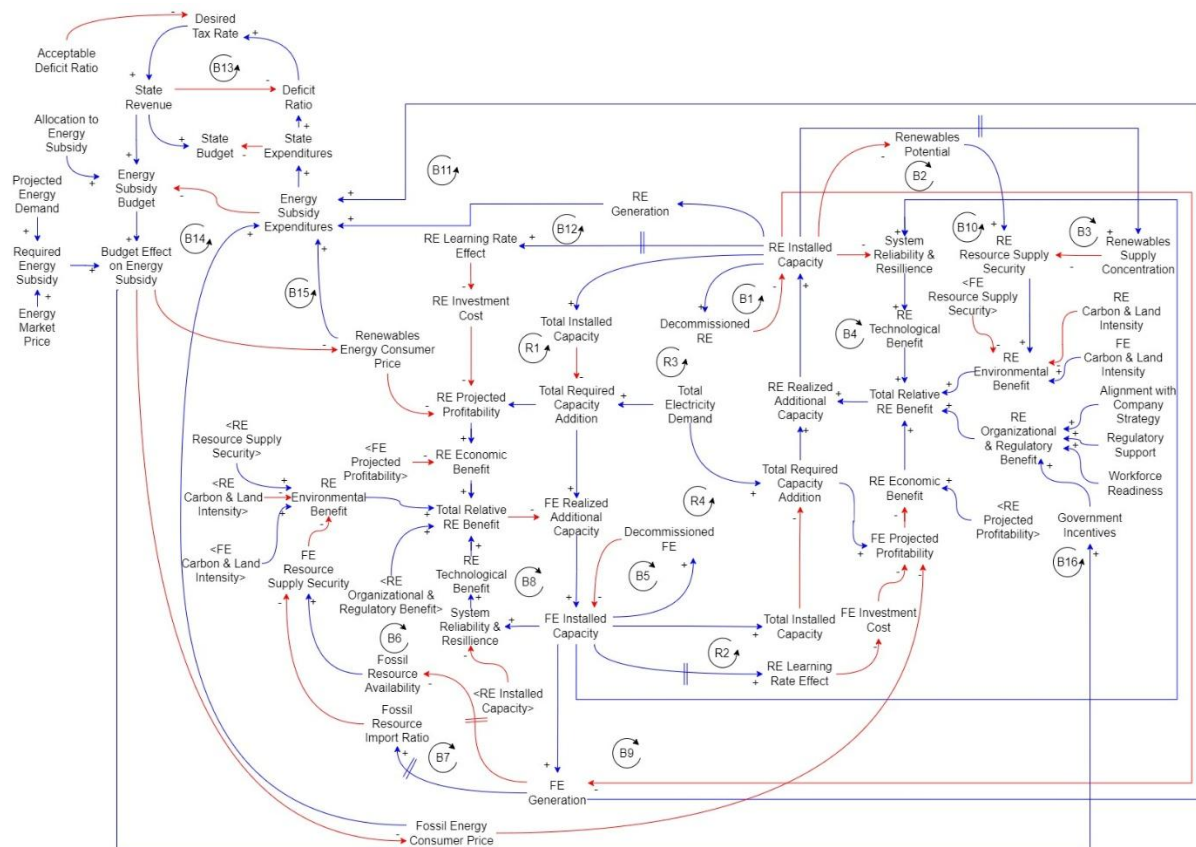
Table 6.2. The weights of the adoption factors and criteria.

Criteria/Factors	Weight
Economic	0.384
Investment cost	1.000
Environment	0.097
Resource availability	0.750
Emissions to air	0.250
Technological	0.228
Production throughput	0.250
Reliability & resilience	0.750
Organizational	0.291
Government incentives	0.429
Regulatory support	0.429
Workforce readiness	0.143

Using these adoption factors, the technology with higher benefits was assumed to be invested in. This capacity addition signals the demand fulfilment loop in both technologies. Thus, should one technology consistently have the higher benefit, investment in that technology could persist in the future and create the reinforcing loop R3 in Figure 6.3. This reinforcing loop describes the “technology lock-in”³¹⁹ which may also explain the persistent investment in CFPP in Indonesia in the last two decades.

Both types of power plant have a limited lifetime. Over time, power producers would need to decide whether to extend their life or replace them, signalling capacity investment. If the benefit of replacing them is higher, it would open up the possibility for bi-directional shift to the other technology (either from FE to RE, or RE to FE). If extending the use of the current technology is higher, then it would create the balancing loops B1 and B5.

Research has pointed out the importance of learning rate in estimating the reduction of technology costs¹²⁰, including renewable electricity³⁷⁴. The adoption of RE would be expected to induce learning effects and drive investment costs down, reinforcing its economic benefit over FE (reinforcing loop R1). To a lesser extent (as they are more mature technologies), the same thing could also happen to fossil generation (reinforcing loop R2) particularly in case of more advanced thermal power generation such as the advanced ultra-supercritical CFPP²⁵⁹ or combined-cycle generation³⁷⁵. Like the “technology lock-in” described by reinforcing loop R3, reinforcing loops R1 and R2 compete, and the one with higher economic benefit would win the learning rate effect race (reinforcing loop R4). This reinforcing loop shows the endogeneity of power generation technology adoption relative benefit.



Note:

Blue arrows ($\rightarrow +$) indicate a positive relationship between two variables, while red arrows ($\rightarrow -$) indicate a negative relationship.

Figure 6.3. Renewables adoption dynamics in the power sector.

Another economic benefit endogeneity can be observed when including the fact that energy – both fossil and renewable – is subsidised in Indonesia. An increase in either FE or RE would increase their generation and hence energy subsidy expenditures, a part of the state expenditures. If the state expenditures are higher than the state revenues, the government may

increase tax rates to boost revenues and minimize deficits in the coming fiscal year (balancing loop B13). With higher state revenue, the amount of energy subsidy budget could be increased to maintain the subsidy rate. In turn it would affect the economic and organisational benefits of adopting either technology. However, the budget may not be able to be increased further if the tax rate is excessively large since it could put too large a burden on the wider economy. Thus, ultimately the economic benefit (balancing loops B11, B12, B14 and B15) and organisational benefit (balancing loop B16) would be limited to the state budget. This argument has been pointed out in Chapter 2 in the macroeconomic loop of the energy transition.

The environmental benefit endogeneity is illustrated by balancing loops B2 and B3 in case of RE, as well as B6 and B7 in case of FE. Adding RE capacity ‘consumes’ its potential, and in turn limits its future exploitation (B3). In parallel, adding RE capacity could increase its supply concentration and reducing its supply security (B4). While adding FE capacity do not immediately affect its resource supply security, utilizing its capacity will. Consequently, it could reduce fossil resource availability and its security of supply (B7). It could also increase the import ratio when domestic supply is limited (B8). The adoption of the two technologies also interacts from the perspective of resources availability as demonstrated by balancing loop B9. An increase in RE capacity would reduce FE utilization which reduces fossil resource consumption. However, this would also mean increased fossil resource supply security, which then reduces RE benefit. This resource limitation concurs with the conceptual model presented in Chapter 2.

Endogeneity is also present in technological factors. An increase in variable renewables, such as solar and wind, in the grid would reduce system reliability and resilience²⁶⁷, which reduces the benefit of using RE (balancing loop B4). Conversely, increasing FE would increase system reliability and resilience²⁶⁷ (balancing loop B8). The increased system reliability and resilience from adopting FE allows for more RE to be installed on the grid, and ultimately fulfilling required capacity addition (balancing loop B10).

6.2.3. Indicators

The indicators used to evaluate the sustainability of the energy transition are based on the indicators defined in Chapter 2. The indicators are grouped into economic, social, and environmental dimensions. Each dimension consists of three indicators – GDP growth, inflation, and state budget for economic dimension; the share of electricity in household expenditures, jobs created, and unemployment for social dimension; emissions to air, land use, and resource depletion for the environment dimension.

As illustrated in Figure 6.3 and explained in the previous section, the state budget is hard linked to energy since energy is subsidised. Applying subsidies for fossil fuel and government incentives for renewables strains the state budget, and thus limits the GOI’s ability to continuously provide subsidies. Chapter 2 has explained the cross-sectoral impact of energy transition on the economy. Chapter 5 has further demonstrated the effect of energy transition on inflation. This chapter extends the analysed effects of transition by including changes in grid electricity as the result of renewables adoption. Price levels will then affect aggregate demand, affecting GDP growth.

The share of electricity in household expenditures has been shown in Chapter 4. Like the case with inflation in Chapter 5, this chapter will include the effects of RE adoption on electricity

price. Jobs creation and unemployment will be used to investigate the larger picture of the transition, using feedback from GDP²⁹.

With the current and potentially future dependence on coal generation, the inclusion of NOx, particulate matter, and SO₂ on top of CO₂ would be essential, since coal generation has high emissions intensity of these substances¹⁰¹. The emissions of these pollutants were also used in Chapter 3 for the same reason. Also demonstrated in Chapter 3, transition to renewables requires substantial land and resources demand due to the high land intensity of solar PV, extensive use of biofuel, and minerals for EV battery in the transportation sector – the subject of Chapter 3. In this chapter, the same indicators shall be used for the case of power sector transition. In addition, the depletion of fossil fuel resources shall also be investigated since coal is extensively used in the power sector.

6.2.4. Model Tests

As with the previous chapters, the model was statistically tested using model correlation, mean absolute percent error (MAPE), and Theil's inequality statistics. For the Theil's inequality statistics, the model does not have a systematic error if the main source of error is the unequal covariation U^C or the bias error U^M is low. In this case, the model captures both the mean and the trend of the actual data but does not capture its point-by-point value, which is what this long-term modelling aims to understand.

The comparison between the actual and modelled total installed capacity is presented in Figure 6.4. The model showed a high correlation with the historical data ($R^2 = 0.96$), low error (MAPE = 0.06), and the error is mainly due to covariation ($U^C = 0.88$, $U^M = 0.12$). Looking into the power mix, Figure 6.5 shows that the model can also capture the share of each power plants. The model, however, resulted in a slightly higher GFPP proportion compared to the actual value, at the expense of CFPP. Nonetheless, the error is minor and unsystematic. The correlation of the CFPP proportion with historical data is high ($R^2 = 0.95$), has an acceptable error (MAPE = 0.09), and the error is mainly due to covariation ($U^C = 0.52$, $U^M = 0.32$), as with the case for GFPP ($R^2 = 0.96$, MAPE=0.05, $U^C = 0.07$, $U^M = 0.07$).

The model testing confirms that the adoption factors and their weights are sufficient to describe the factors considered when adopting power generation technology. In this case, the power sectors' preference for the least-cost technology with high resource availability and providing system reliability and resilience is reflected in their inclination towards CFPP.

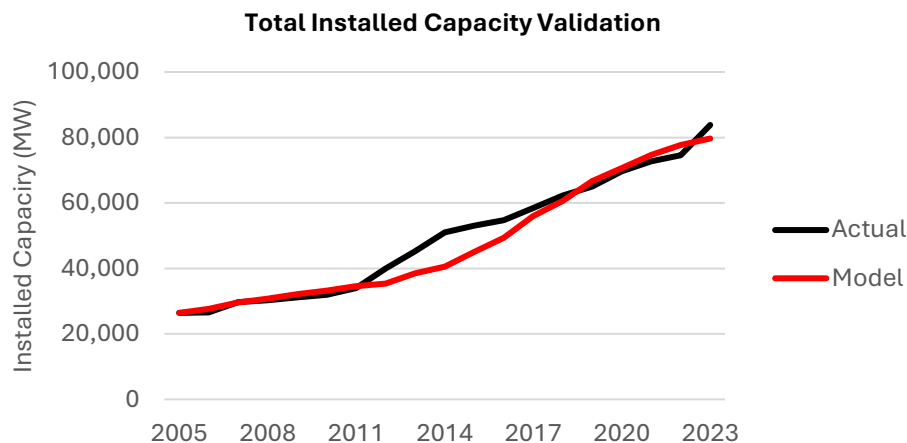


Figure 6.4. Comparison between the actual and modelled total installed capacity in the power sector.

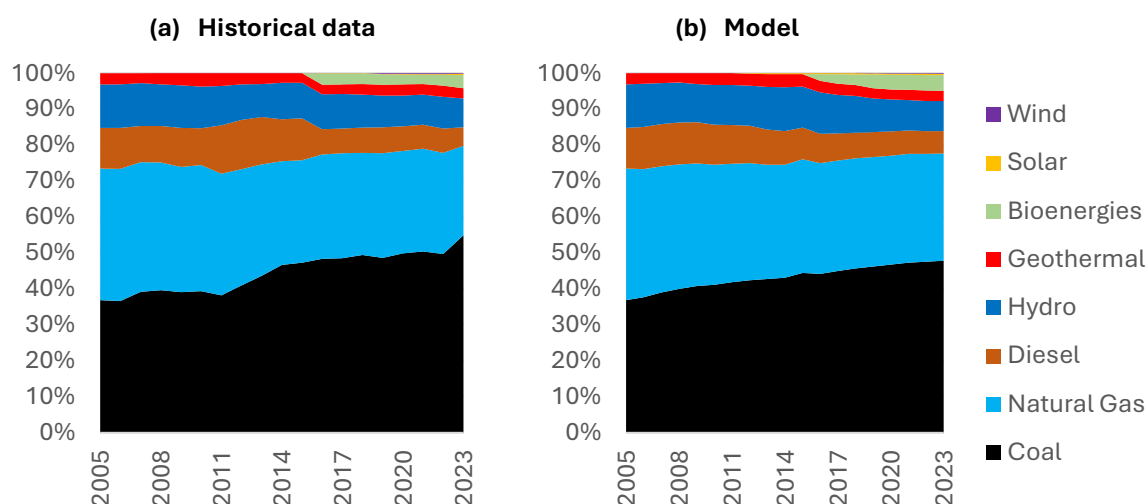


Figure 6.5. Power mix in the power sector comparing the actual and simulation results

6.3. Base Run

After being confirmed to be sufficient, the model is then simulated – under the baseline assumptions used for model testing – from 2005 until 2050 according to the national energy plan. The simulation is divided into four parts, where the first discussion will be about the adoption of renewables in the power sector. The second until the fourth section will discuss each of the three sustainable transition indicators separately.

6.3.1. Renewables adoption in the power sector

Figure 6.6 shows the possible power mix progression from 2025 to 2050 if there are no changes in the system. CFPP capacity would continue to increase and by 2050 could be close to 109 GW or 2.75 times larger than the current capacity. Installed-capacity-wise, it would be 55% of the total capacity in the grid. CFPP would be the only fossil-based generation that increases in proportion where GFPP and DPP would decrease 16% and 9%, respectively.

Among the renewable energy generation, bioenergy power plant (BePP) could increase significantly reaching more than 16 GW by 2050 which would surpass diesel generation capacity of 10 GW. Both hydropower and geothermal installed capacity increases steadily by around 1% per year, but proportion-wise could be outshined by bioenergy power plants. The installed capacity of hydropower and geothermal by 2050 could be 9.8 GW and 3.2 GW which is 36% and 29% larger than current capacity, respectively. Unfortunately, the share of solar and wind remains small even among the renewables, but their share increased significantly compared to 2025 level in the baseline simulation. The installed capacity of solar power plants and wind power plants could reach 520 MW and 319 MW in 2050. This solar power installed capacity is equal to almost 4 floating solar power plant in the Cirata reservoir, the biggest floating solar power plant in Southeast Asia in 2024³⁷⁶.

The RE installed capacity under the baseline simulation shows that their potential could be underutilized, in particular for solar and wind. Comparing to the planned project as in Table 6.1, solar and wind potential could only be used 1%. Hydropower and geothermal fared better at 22% and 18%, respectively. But the most utilized potential could be BePP since 63% of their potential is used under the baseline simulation. BePP has the advantage of resource site evaluation rate compared to other renewables which enables it to be exploited more quickly even though the technology itself does not have the highest economic, environmental, technological, or organisational benefits among the renewables.

The increasing use of bioenergy in the power sector can be attributed to the increase in biodiesel use in the transportation sector¹. The wastes from crude palm oil conversion to biodiesel, namely palm waste, palm kernel shell, and empty fruit bunches, are the primary fuel for BePP in Indonesia³⁷⁷. Chapter 3 has shed light on how the use of biodiesel will continue to increase since electric vehicles (EV) will not completely replace internal combustion engine vehicles (ICEV), which could help to secure the resource availability of BePP. In addition, the government has opened up a 1.3 million hectares area dedicated for energy crops to be used in BePP where among the primary energy resources are wood chips³⁷⁸. Considering these extensive plans, the increase in BePP, as in the baseline simulation results, seems to be reasonable.

The resources site evaluation rate, which in this research is defined as the rate at which resources potential can become exploitable, for other renewables are relatively low. The site evaluation rate for geothermal is based on the research done by Setiawan et al. who used a rate of 5% in their model³⁰. Using their rate the geothermal installed capacity progression showed a very high correlation ($R^2=0.96$) and low error (MAPE = 0.06). Using the same approach to fit the historical data, the site evaluation rate for hydropower, solar, and wind are 7.25%, 0.04%, and 0.08%, respectively.

Considering the very low rates for the other renewables, the parameter will become one of the key uncertainties in the utilization of renewables potential in the power sector which will be discussed in detail in Section 6.5. The weights of the adoption factors are also a key uncertainty since it is shown contribute to the ‘stickiness’ of CFPP dependence.

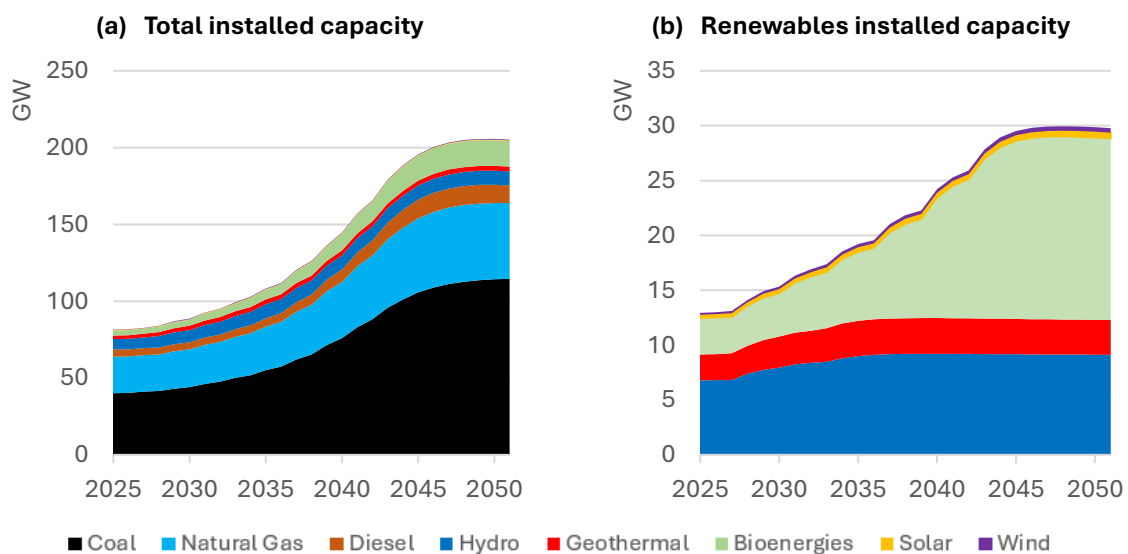


Figure 6.6. Power mix in the power sector baseline simulation result.

6.3.2. Economic Indicators

One of the direct outcomes of the power mix is electricity price. The electricity price for a certain year is estimated using the estimated LCOE for each generation technology, multiplied by the share of that generation technology in that year. However, since electricity is subsidised like other energy sources in Indonesia, the end-price will be subject to the state budget capacity. Figure 6.7. showed that indeed the state budget limitation manifests towards the end of the simulation around 2034 onwards, indicating the state can no longer maintain the desired subsidy rate for electricity hence causing the electricity price to increase more sharply. Under the baseline, the electricity price could be around 0.11 USD per kWh in 2050, increasing 1.4%

per year from 2025. The rate of increase accelerates when the state budget can no longer provide enough subsidy – from an annual increase of 0.7% from 2025 to 2034, to 2.5% from 2034 to 2050. The sudden increase in electricity price could affect energy affordability at the household level as will be discussed in Section 6.3.3.

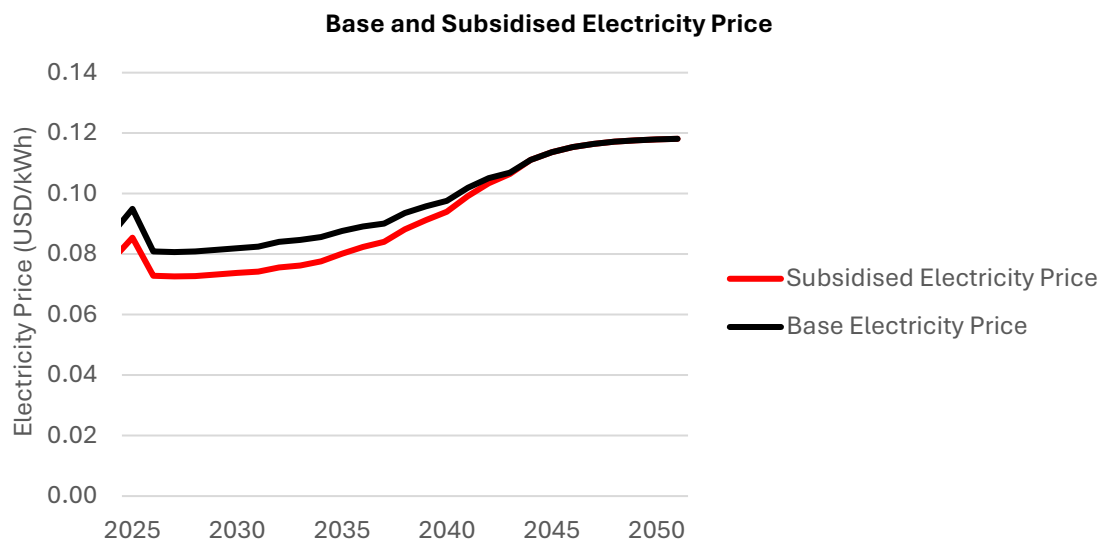


Figure 6.7. Electricity price under the baseline simulation result.

The increasing amount of energy subsidy including for electricity have put pressure on the state budget that it continues to decrease the deficit ratio to GDP as shown in Figure 6.8. However, Figure 6.9 explains that the main burden in the energy subsidy is not for the electricity itself but rather fossil fuels for as the primary energy sources, which is also used in the transportation and industrial sectors. Although reducing subsidies for liquid fossil fuels, for example gasoline and diesel, may increase fiscal space for subsidizing electricity, it would lead to higher their prices which could induce inflation especially if the economy is still reliant on them. The effect of this policy shall be discussed in Section 6.4.

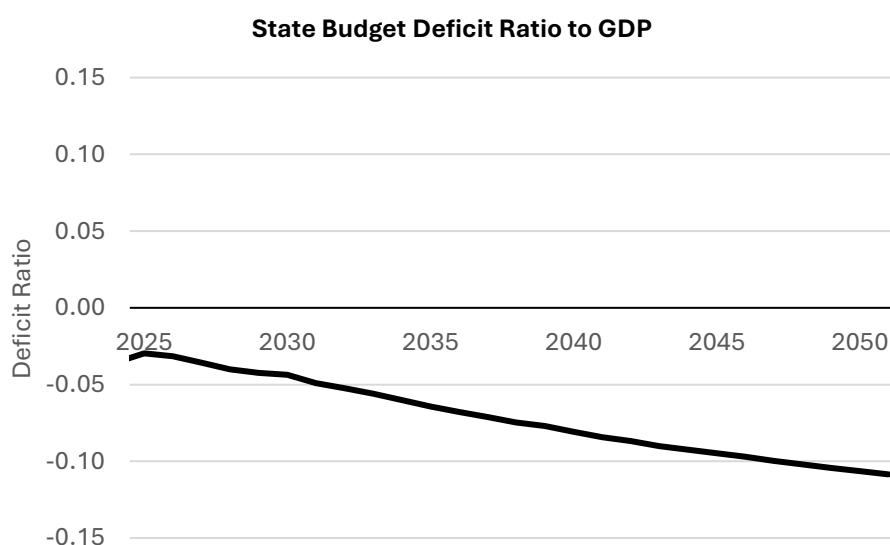


Figure 6.8. State budget deficit ratio to GDP under the base run.

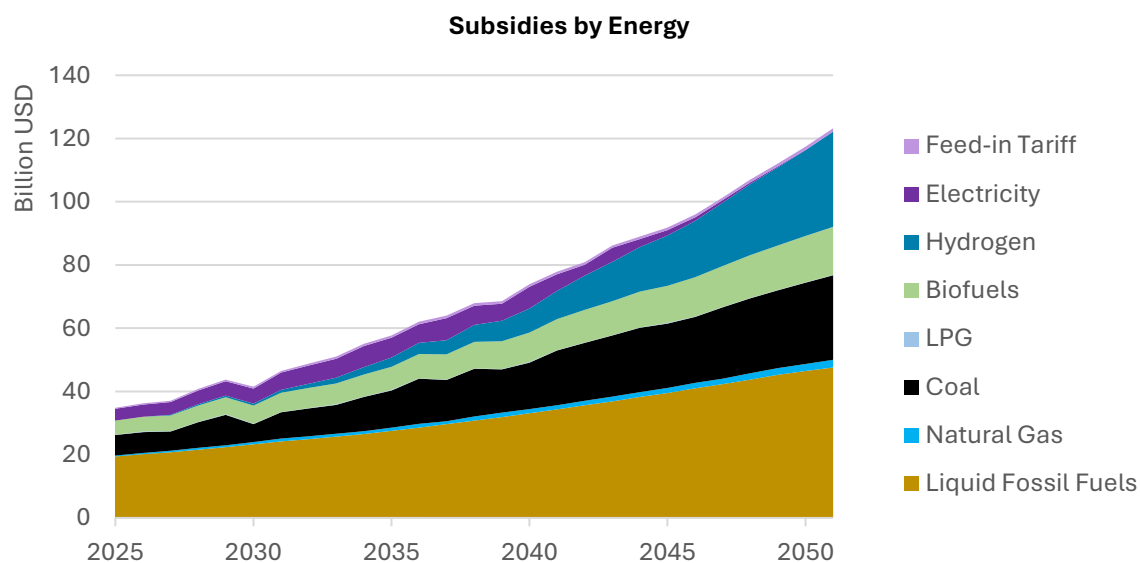


Figure 6.9. The burden of energy subsidies.

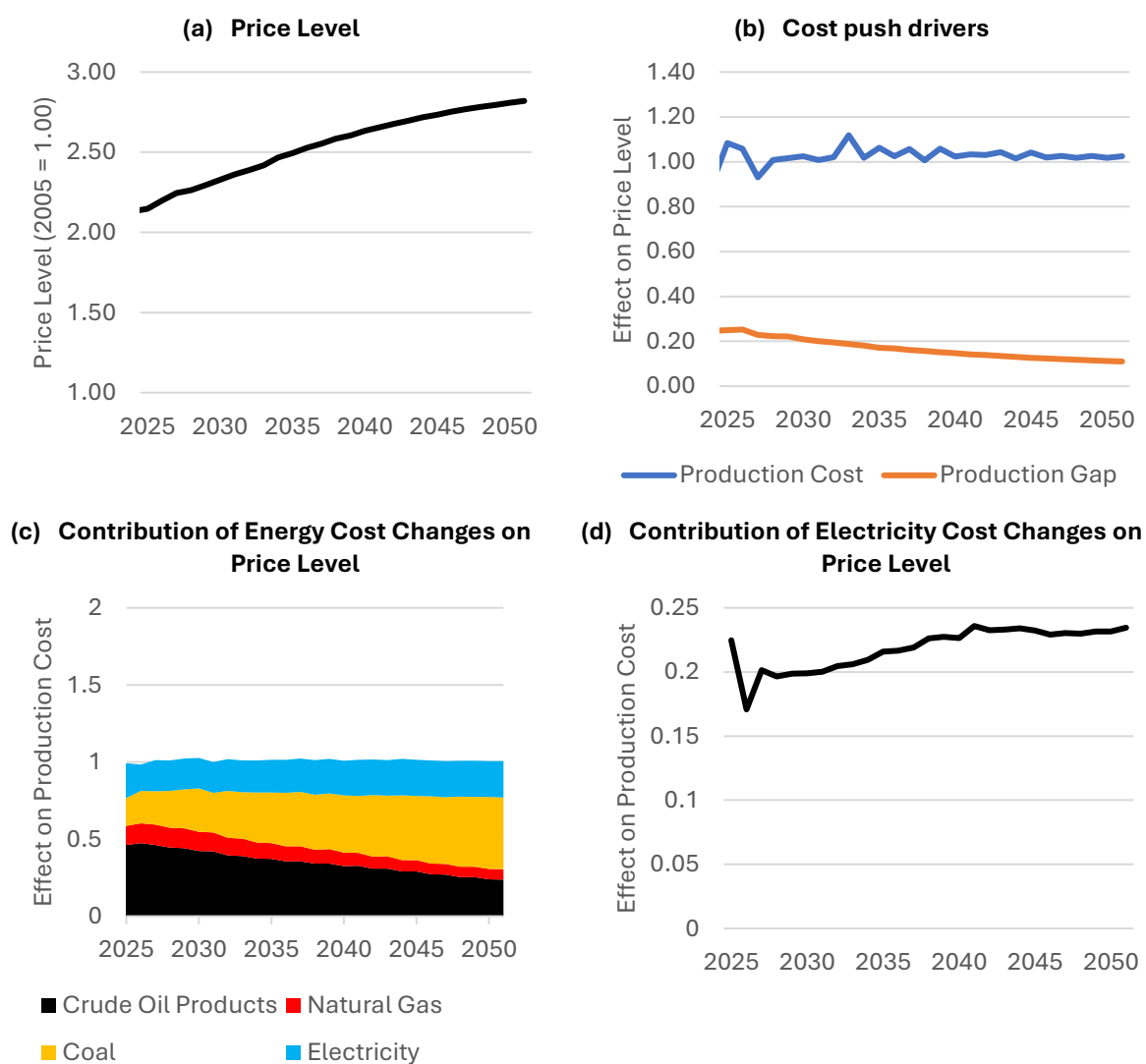


Figure 6.10. Price level and cost-push drivers

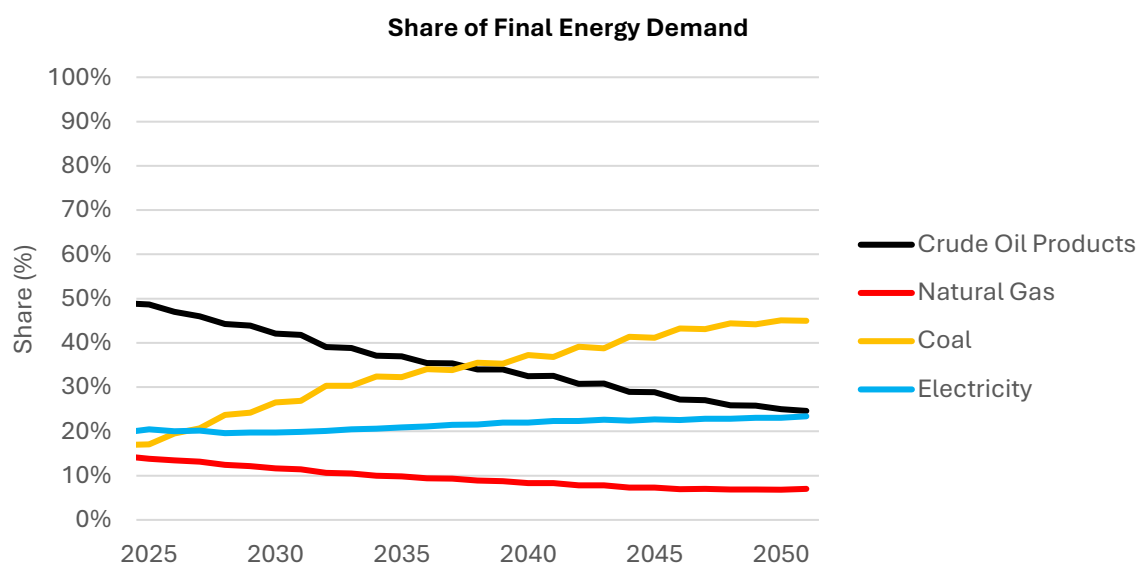


Figure 6.11. Share of final energy demand in the economy under the base run.

Figure 6.11 shows the price level and its cost-push drivers. Yamaguchi describes that price level is driven by supply-demand gap and production costs²⁹. The detailed explanation of the two drivers on price is presented in Appendix B. The effect energy costs on price level would depend on how the dependent the economy is to that energy³⁷⁹, thus final energy mix becomes an important factor to be observed. Figure 6.11 shows that the economy would shift its dependence from crude oil and its products to coal, primarily due to the use of it in the industrial sector. The increasing use of coal in the industrial sector, particularly the cement and non-ferrous metals industries as shown in Chapter 5, have made its share in the final energy demand almost tripled from 2025.

The detailed effect of electricity price on price level is presented in Figure 6.10(d). The share of electricity increases through the years in the baseline simulation, making the economy more sensitive to changes in price. Being a subsidized commodity, continuing to provide electricity subsidies may control inflation, but it could increase the state budget deficit which may affect tax rates and, in turn, consumption. Note that the effect only shows price level change contribution, and not the actual change in price level. That discussion is left for Section 6.4 and Section 6.5.

Changes in price level, i.e. inflation, would affect real GDP. The annual growth of the inflation adjusted GDP is shown in Figure 6.12. Between 2025 to 2050, the real economic growth could be 4.1% per year under the baseline simulation. The effect of electricity price changes on real GDP growth shall be explained in Section 6.4 and Section 6.5.

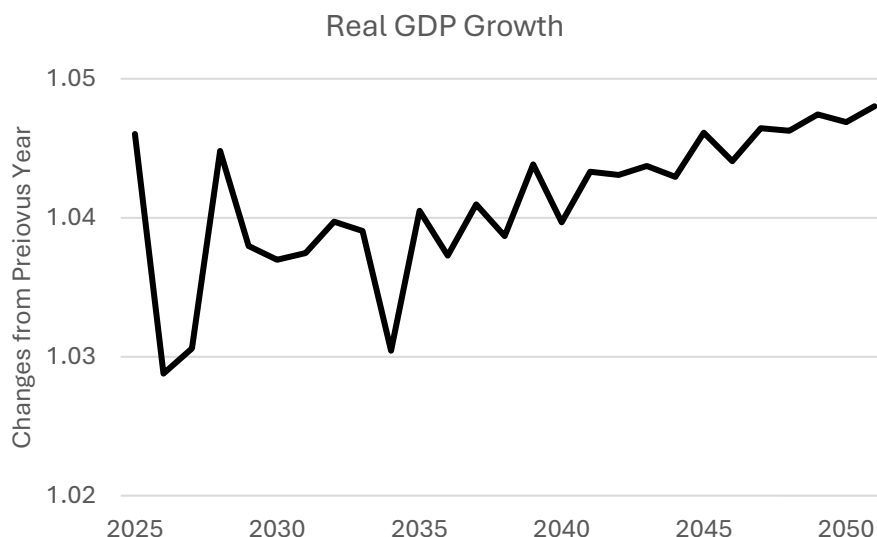


Figure 6.12. Real GDP growth under the base run.

6.3.3. Social Indicators

Although at the macro-level the effect of electricity price is not so significant, it directly affects households as mentioned in Chapter 4. Depending on their income level, electricity expenditures would affect households differently. Figure 6.13 shows that, while its proportion is generally increasing, aspiring-middle-income and middle-income households would be the most affected group should there be changes in electricity price.

The share of electricity expenditures in aspiring-middle-income households is around 5.4% in 2025 and increases to 9.2% in 2050 or increase 2.1% per year. In the middle-income households, the share is 7.6% in 2025 and becoming 11.1% in 2050, an increase of 1.5% per year. The increase of electricity expenditure share in aspiring-middle-income is higher than the increase of electricity price itself as discussed in the economic indicators (1.3% per year). The higher increase is due to the increased use of electronic appliances such as electric stoves and mobile devices, shown in Figure 6.13(b) and as explained in Chapter 4.

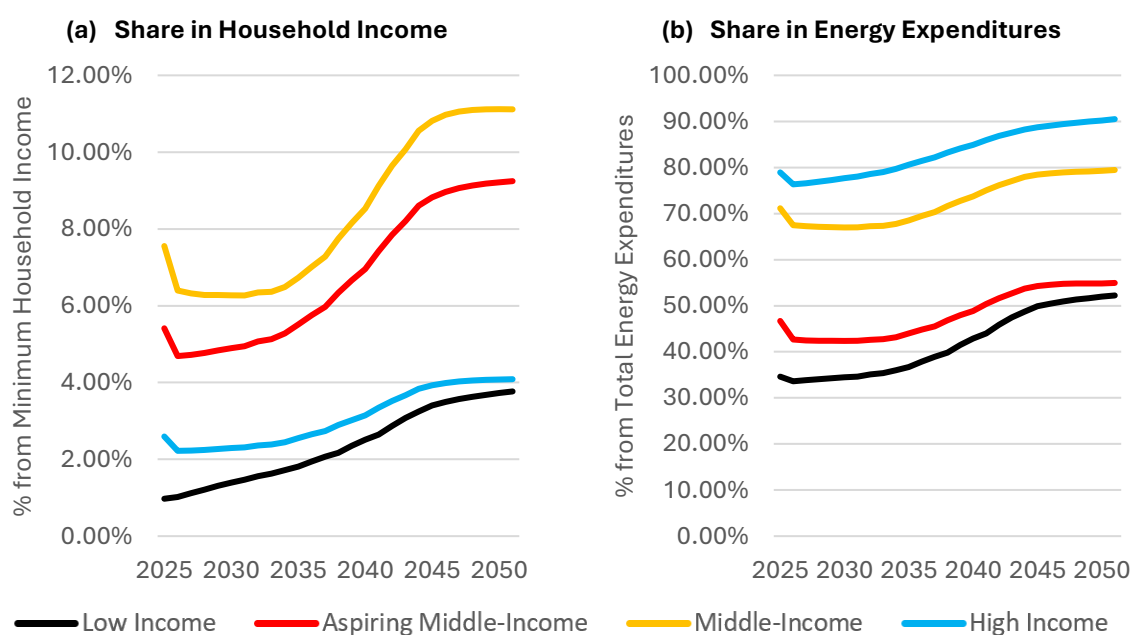


Figure 6.13. Share of Electricity Expenditures in Households Income and Energy Expenditures

The second and third social indicators are related the labour market and is driven by macroeconomic variables particularly GDP and Inflation^{29,380}. An increase in GDP is positively related to labour demand which could reduce unemployment, assuming the jobs created match with the labour capability. Figure 6.14(a) shows the gap between labour demand and the employed labour as the effect of overall economic growth, i.e. jobs created. The demand for labour increases with the increase in real GDP, although not as quickly – 4% increase labour demand compared to 4.1% annual increase in real GDP – since there is a delay in adjusting labour demand.

The third social indicator is unemployment, presented in Figure 6.14(b). Under the baseline, the unemployment rate increased from 5.94% in 2025 to 6.04% in 2040 but then stabilize around 6% until the end of simulation. The temporary increase in unemployment rate indicates that the rate of people exiting employment – due to lay-offs, quitting, or retirement – is faster that people obtaining jobs. One of the causes is the labour market delay where, as the economy improves, the proportion of population who progressed to higher education would also increase³⁸¹. While this may improve future productivity, it also requires a longer period of education - thus delaying them entering the labour market. On the other hand, the number of people exiting their jobs continues to increase for the three reasons stated above. Jo et al. warns the effect of inflation on unemployment rate since it may increase the chances of firms to lay off their employees³⁸⁰. Since the inflation rate is higher in the first half of the simulation, the fraction of the employed labour that could be laid-off is also higher. As the price level saturates (see Figure 6.10), the lay-off fraction decreases – just in time for the labour with higher-education entering the market.

Up to this point, the effect of renewables adoption in the power sector on the social indicators have not been discussed. Section 6.4 shall explore the adoption progression of renewables through changes in policies and Section 6.5 through changes in uncertainties.

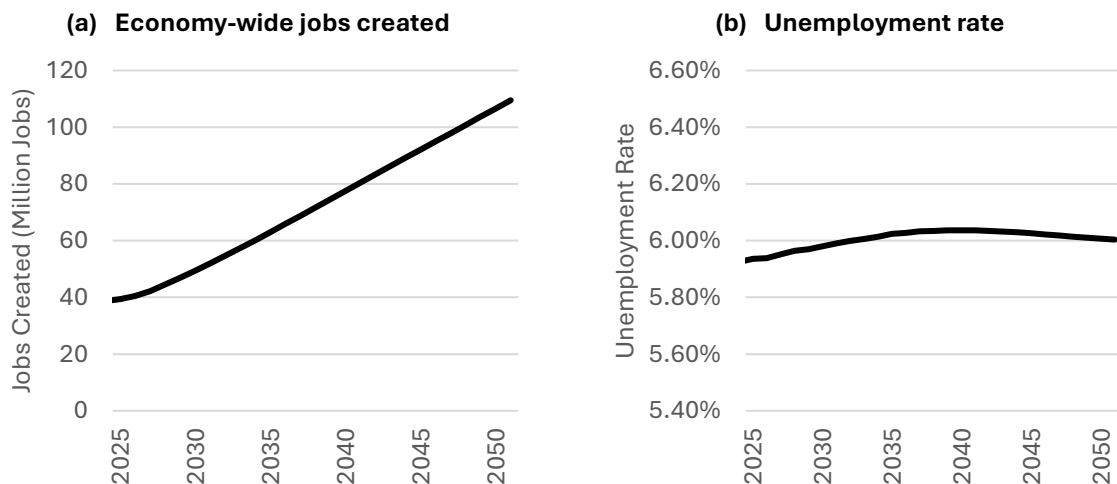


Figure 6.14. Labor demand in the whole economy and unemployment rate.

6.3.4. Environmental Indicators

The increasing proportion of coal in the power mix does not proportionately increase the grid emission factors due to the improvement of efficiencies in the thermal power plants. At the beginning of the simulation, most CFPP are sub-critical as found by Gu³⁵⁸. Under the baseline scenario, it is assumed that future CFPP will use advanced, higher-efficiency technologies. However, this assumption serves as an uncertainty as the efficiency would depend on what kind

of technology will be implemented. Sub-critical power plants have thermal efficiency 30-36%¹⁰, while the ultra-supercritical (USC) efficiency is 40-42%¹⁰ and the advanced ultra-supercritical (A-USC) power plants could surpass 47%²⁵⁹. This is also true for the efficiency of GFPP and DG which would both still hold a considerable share in the energy mix. GFPP efficiency could be improved to more than 60% using Combined-Cycle Gas Turbine (CCGT)³⁸². To date, the highest reported CCGT efficiency is in Japan at 64%, with a potential to be improved further to 70%³⁸³. The average DG efficiency is 20%-25%³⁸² but can be as high as 35%³⁸⁴ and can potentially reach 45% using dual-fuel Premixed Charge Compression Ignition technology (DF-PCCI)³⁸⁵.

Figure 6.16 shows the land-use for power plants and bioenergy. As can be seen, the required land for bioenergy provision dwarfs land-use for power plants which is attributed to the use of biofuel in the transportation sector. As a result of the biofuel demand in the that sector described in Chapter 3, the land availability could be depleted around 2046, limiting the land expansion for all purpose, including power generation. By the end of simulation, the total land required for power plants could be 1.3 million hectares. Despite renewables generation's intensive land use, particularly solar and wind⁷, their small proportion in the power mix led them to occupy a much lower land compared to coal, natural gas, and diesel power plants. By the end of the simulation, RE uses 0.15 million hectares of land or only 12% of all the land used for power plants.

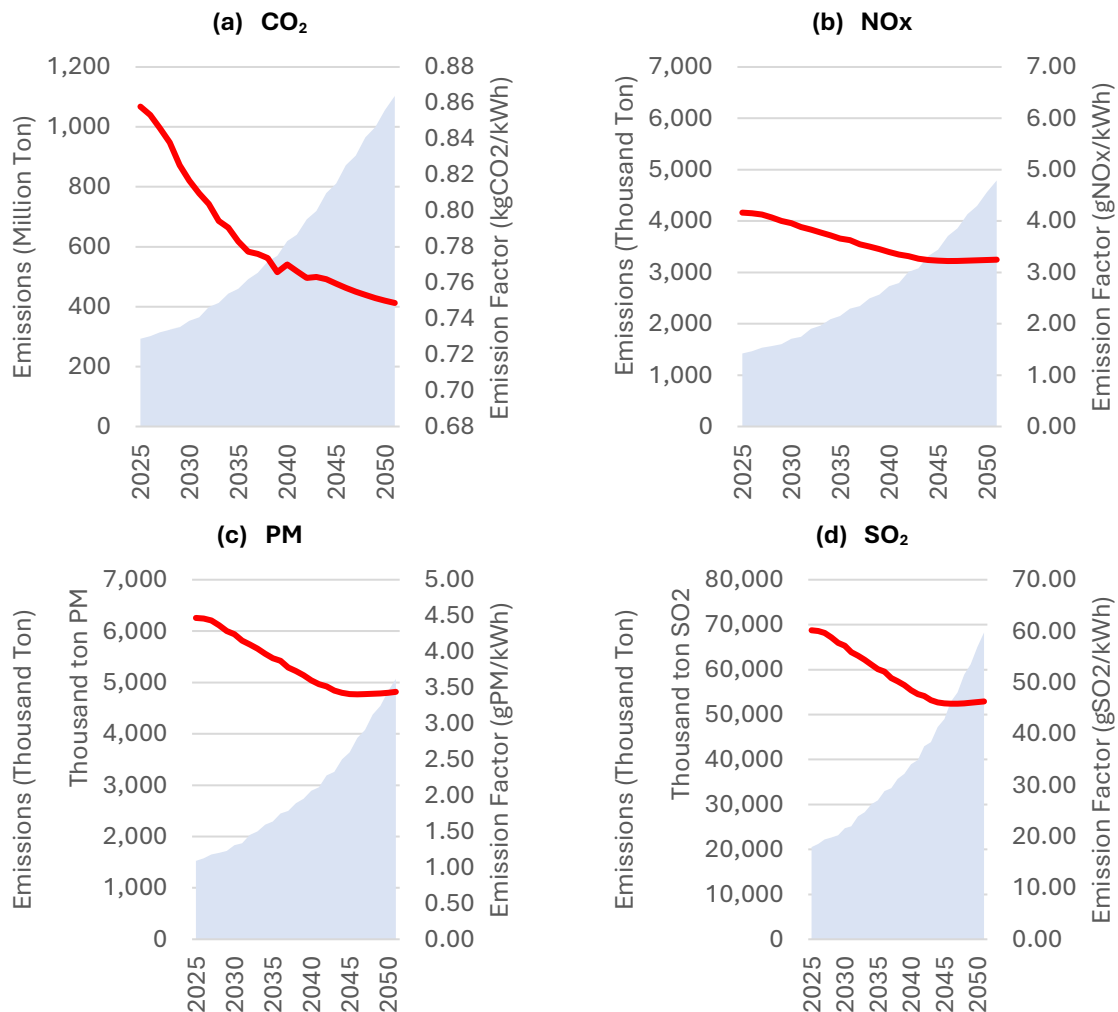


Figure 6.15. Emissions from the power sector.

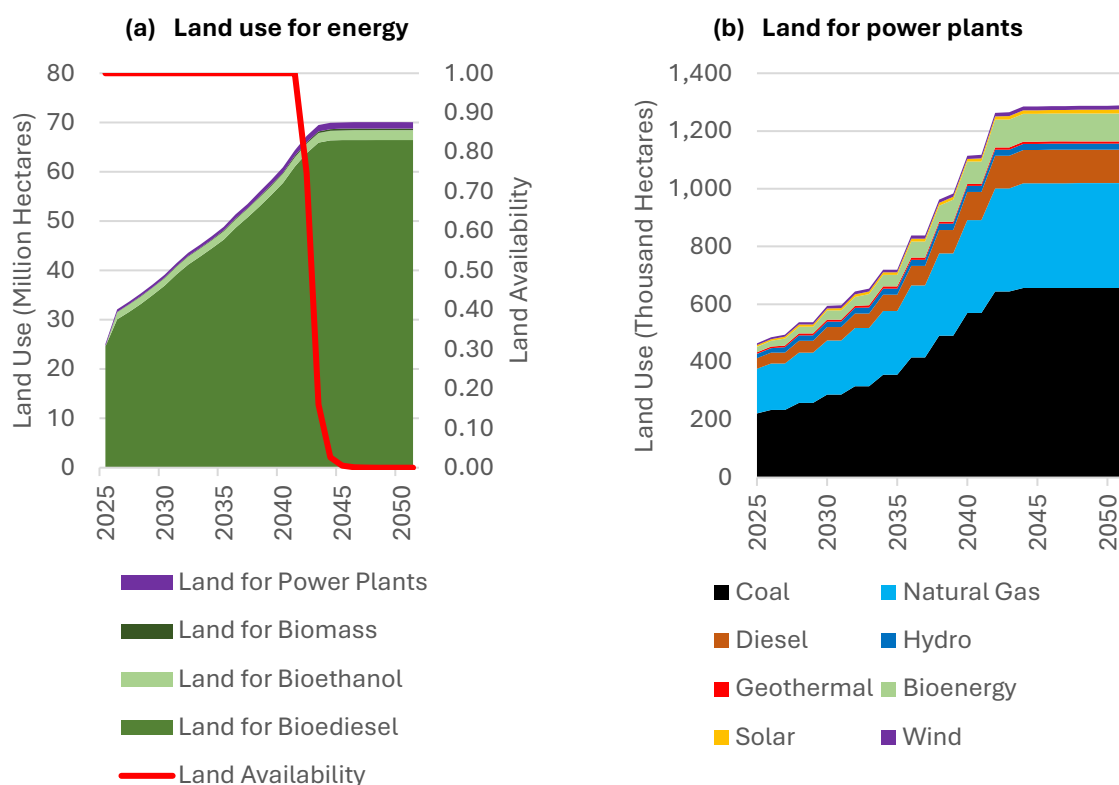


Figure 6.16. Land use for bioenergy and land availability.

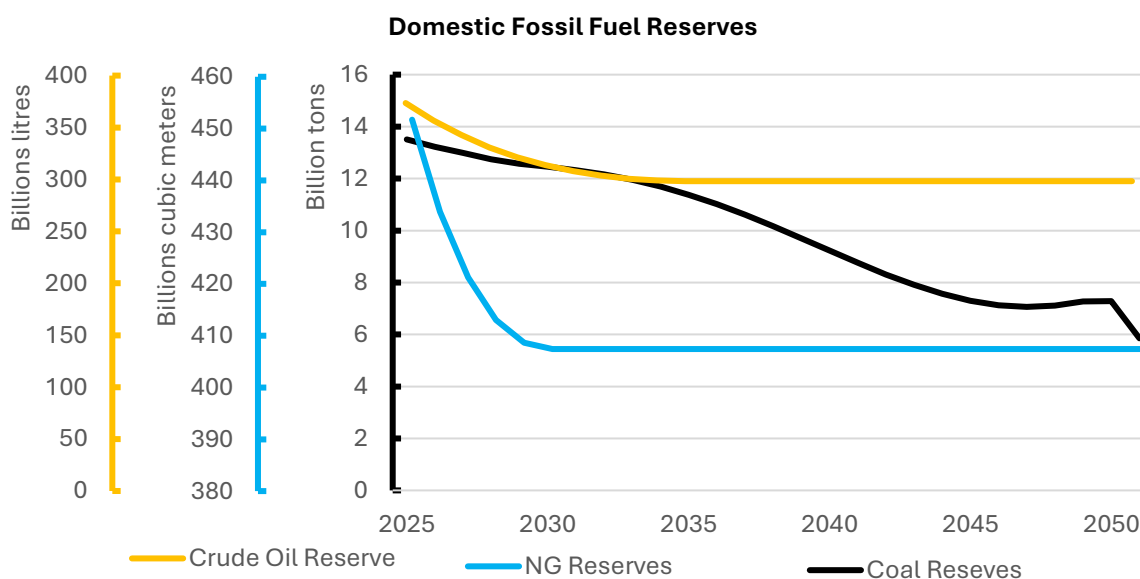


Figure 6.17. Domestic fossil fuel reserves under the base run.

The increasing use of coal in the nation's energy mix (see Figure 6.13) leads to the continued extraction of coal reserves which causes the reserves to decline to almost half of the 2025 level, as shown in Figure 6.17. On the other hand, natural gas and crude reserves could stagnate at a certain level when the extraction of oil is no longer economically viable. The most alarming resources availability could be the critical minerals, as can be seen in Figure 6.18. Both copper and nickel could be depleted in 2034, assuming the refining of both metals in the industrial sector as well as the production of electric vehicles and renewable energy uses domestic reserves. In addition, the possibility of using recycled metals to replace primary resources in

production is not included. Nonetheless, the concern of depleting mineral resources has been voiced, including from the government³⁸⁶. The reserves for nickel which is used for nickel pig iron (NPI) and ferronickel production may only be available for another 11 years, while the high-grade nickel which is used in batteries could still be sustained for more than 25 years³⁸⁶.

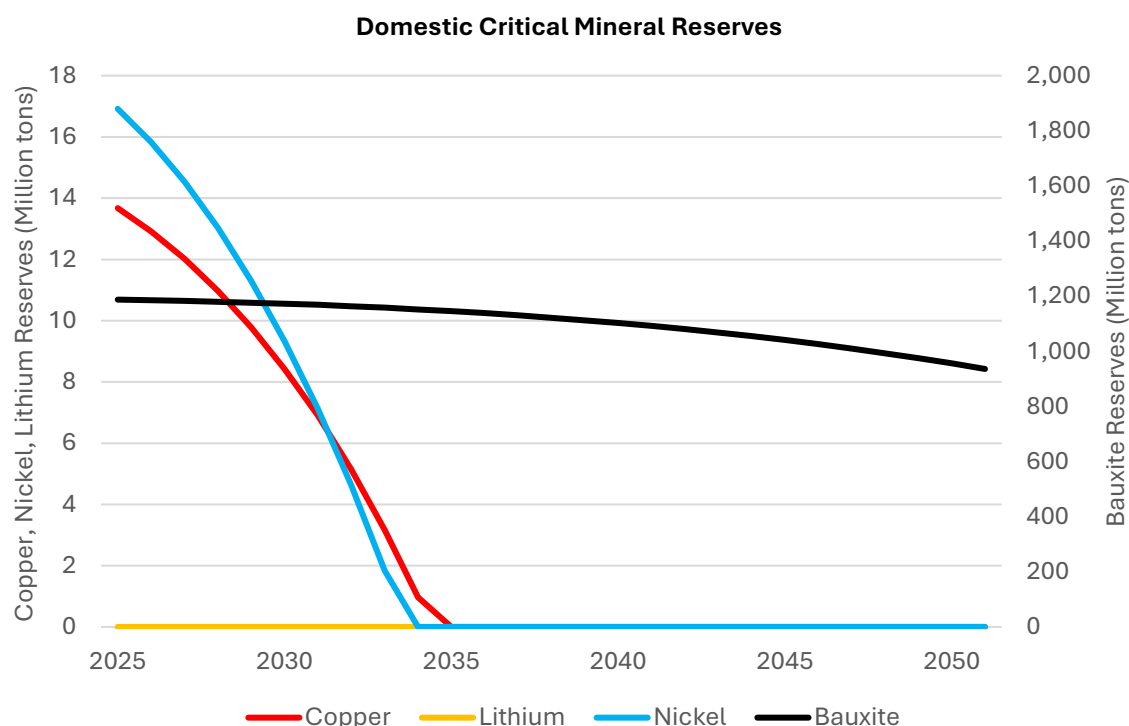


Figure 6.18. Domestic critical minerals reserve under the base run.

6.4. Policy Tests

Several policies have been proposed by the GOI in increasing the use of renewables in the power sector as have been elaborated in Table 2.1 of Chapter 2. From those identified policies and looking into the model developed in this chapter, the effectiveness of five policies in increasing RE shall be evaluated.

A Feed-in Tariff (FIT) – a market intervention policy³⁴⁸ – has often been proposed as an instrument to increase the adoption of renewables in the power sector. Indonesia has been implementing a FIT since 2011. Initially targeting geothermal power plant adoption, the FIT policy has now expanded to other renewables^{30,33}. The FIT policy aims to reduce investment risk by eliminating the gap between the actual generation cost and the electricity market price¹⁶. The rate ranges from 6.6 to 11.4 US cents per kWh, but the most common rate is 7.53 cents per kWh in case of geothermal³⁰. A newer regulation sets a higher rate, ranging from 11.8 to 29.6 cents per kWh, in line with the findings by Setiawan et al. who suggested a rate higher than 11.4 cents per kWh³⁰.

A more instant way to increase the share of RE is through the early retirement of CFPP. However, considering the relatively new assets of CFPP, prematurely ending their service could be costly. The Asian Development Bank (ADB) proposed the Energy Transition Mechanism to assist an early replacement of CFPP with renewable energy one of which through debt¹³¹. The potentially negative impact of increasing debt is the increase in tax rates and, in turn, reduce consumption and investment¹³⁴.

The third policy to be tested is a carbon tax which is not only a market-intervention policy³⁴⁸, but could also serve as a fiscal space expander. Carbon taxes are imposed on carbon dioxide emitting goods and services. This policy acts on the other side of the adoption, reducing the economic benefits of using fossil-based power plants. The GOI has planned the implementation of carbon tax and CFPP will be one of its subjects according to the regulation No.7/2021³⁸⁷.

While the first three policies may increase the adoption of renewables, this may come at the expense of electricity price if there are no changes in the end-price subsidy. However, Figure 6.9 shows most of the energy budget is allocated for fossil fuels, most notably oil products and coal. On the other hand, subsidies for 'cleaner' energy such as biofuels, hydrogen, and electricity are smaller. Thus, the fourth policy to be tested is the re-allocation of energy subsidies to accommodate the FIT tariff and other transition policy if it should be necessary.

The apparent fiscal limitation to support energy transition, or energy price in general, have led to the formulation of fiscal policies that aims to increase its space. One fiscal policy that was studied in previous research is the depletion premium on fossil fuels²¹. The depletion premium stems from the Hartwick Rule for weak sustainability which requires the scarcity rent from exhaustible resources to be invested in reproducible capitals, for example the development of alternative energies. Such approach has been implemented in Norway through their Norwegian Fund²¹. In line with this, the GOI has planned to develop an Energy Security Fund to support energy transition efforts, which one of its sources is the depletion premium of fossil fuels¹⁰. Considering the increasing use of coal in the power sector as depicted in Figure 6.6, this policy may be effective in providing fiscal space for energy transition not only in the power sector but the whole economy.

6.4.1. Feed-in Tariff (FIT)

A cost factor to the electricity market price is set to accommodate the changing FIT rate in each year as suggested by the Ministry of Energy and Minerals regulation No. 14/2014³⁰. The factor increases the maximum buying price by PLN, i.e. the electricity market price, so that the renewable power producers may sell their electricity at a higher price although it may not cover their actual generation cost. Thus, increasing the FIT price factor may improve the economic benefits of adopting the renewable energy. While a high FIT price factor may induce higher renewable adoption, it would directly translate to electricity price if the subsidy for the consumers is not increased. The results of the simulation are presented in Figure 6.19 until Figure 6.29.

Changes in the FIT is shown to have a relatively high impact on the power mix as shown in Figure 6.19, however the effect is not proportional between increasing and decreasing FIT. Increasing FIT have a clear negative impact on the share of fossil-based power generation – which is desirable. Increasing FIT 50% from the baseline led to a 0.4% decrease in fossil-based power generation, and a 50% decrease in FIT led to a 2.7% increase of share. The effect on FIT on renewables is not as clear. In both cases on increasing and decreasing FIT, the share of renewable energy in the power mix increased until 2035. The reason behind this is that, in the case of lower FIT, the increase in fossil-based generation reduces electricity price which caused a higher increase in demand (see Figure 6.20). In turn, the demand increase drives the construction of both technologies of power generation. Beyond 2035, however, the share of RE decreased significantly since the additional capacity is fulfilled by fossil-based generation. When FIT is increased, RE share also increased at the same period. However, higher FIT necessitates larger fiscal space, and the subsidy rate cannot be sustained as shown in Figure

6.19. Thus, RE share could decrease from the baseline beyond 2035. In addition, the with more RE due to FIT, the electricity price increased as shown in Figure 6.20. While the effect is momentary, it was enough to reduce electricity demand thus reducing the need for additional installed capacity, including from RE.

The change in electricity price due to changes in FIT have a direct consequence on state budget, price level, and real GDP growth. The increase in FIT rate increased state deficit 0.4-2.1% between 2025 to 2038 as shown in Figure 6.21. Afterwards, the deficit became shortly lower than the baseline because the energy subsidy budget has been exhausted earlier and thus modifying the subsidy rate for all energy after which the state budget deficit ratio to GDP stabilizes around the baseline. The effect of lowering FIT on the state budget is the opposite with increasing FIT between 2025 to 2038. However, in 2039 the deficit fell even lower than the baseline since at this point the share of renewables was at its lowest point compared to the baseline as shown in Figure 6.19 which resulted in the lowest expenditure for FIT. Later, the deficit would also stabilize around the baseline.

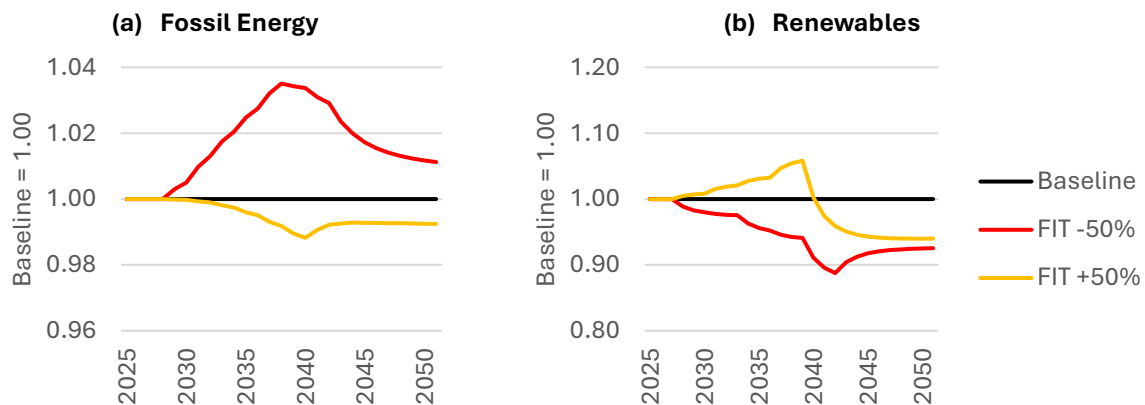


Figure 6.19. Effect of changes in FIT on the share of fossil energy and renewables in the power mix.

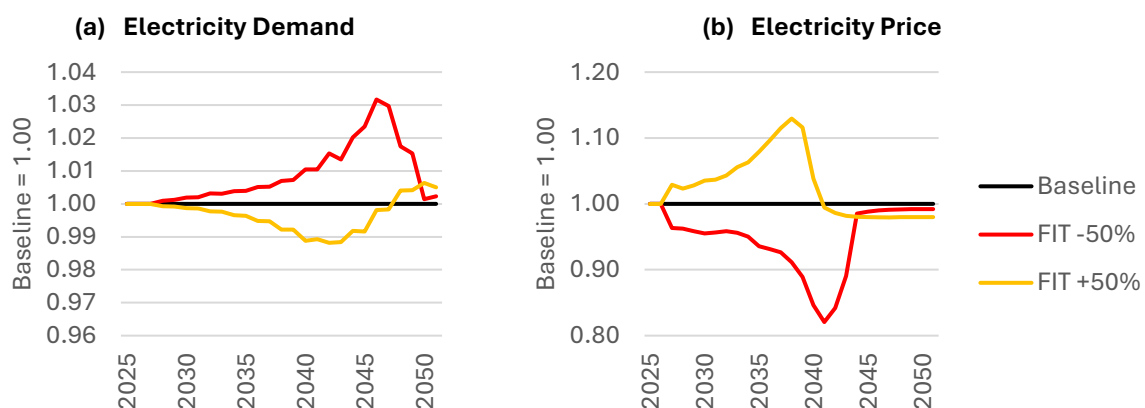


Figure 6.20. Electricity demand and price under different FIT.

The increased adoption of RE from FIT push affects price level negatively. Figure 6.22 shows that in general the changes in price level follows the changes in the effect of electricity on price level. Exceptions can be observed in 2027-2028, 2040-2041 and 2044-2045 where sharp changes in cost-push effects from electricity lead to an inverse change in price level. At these time points, the changes in price level are mostly driven by the cost passthrough from the industrial sector as the result of energy transition in the sector. The increase in RE capacity in

the power sector increased the adoption of electrified production pathways in industries that have high consideration on carbon emission, particularly cement. However, the higher electricity cost also meant a higher cost-push effect on price level. In addition, the decrease in electricity demands due to increase in price means a shift in energy mix towards fossil fuels, making the economy more sensitive to changes in fossil fuel price. The effect of FIT changes on price level immediately affects real GDP growth as shown in Figure 6.23.

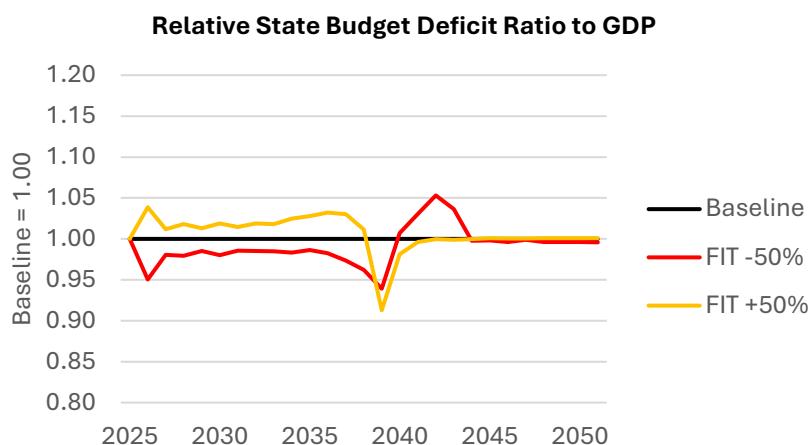


Figure 6.21. Effect of FIT on state budget deficit ratio to GDP

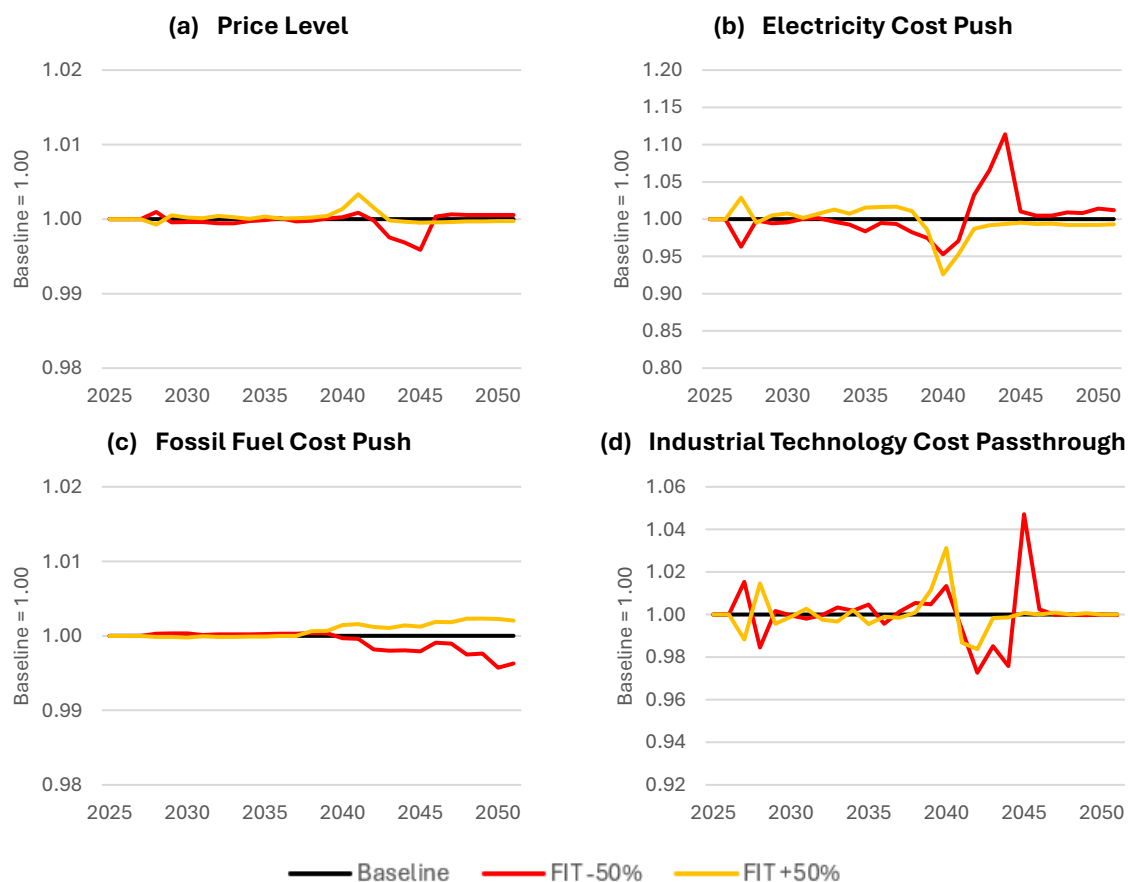


Figure 6.22. Effect of FIT on price level

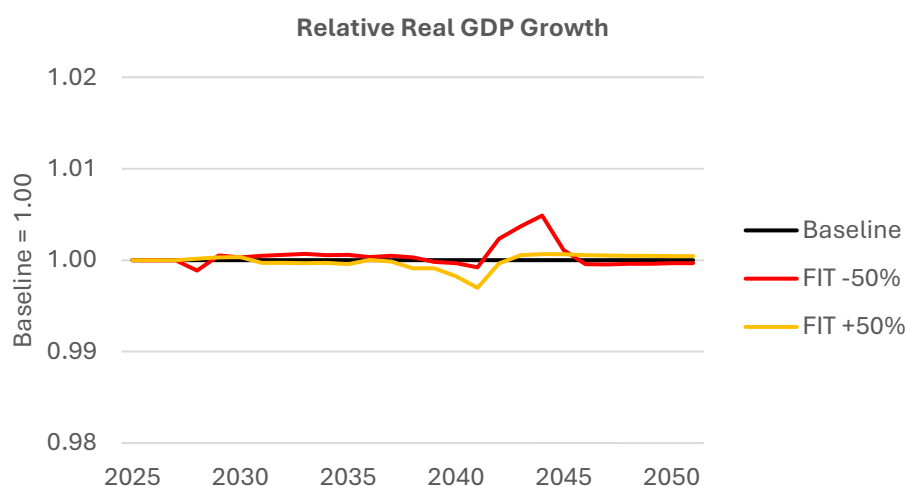


Figure 6.23. Effect of FIT on Real GDP Growth.

Figure 6.24 shows the effect of FIT on household electricity expenditure where it is shown to be relatively similar in all income groups. As in the baseline, aspiring-middle-income and middle-income households are the most impacted by the change in electricity price. FIT also impacted economy-wide jobs creation and unemployment rate as demonstrated in Figure 6.25. In general, a lower FIT – which led to a lower inflation rate – can open more jobs. The effect of changing FIT on the unemployment rate mimics its effect on price level, where higher inflation may lead to higher layoff rates and, in turn, higher unemployment.

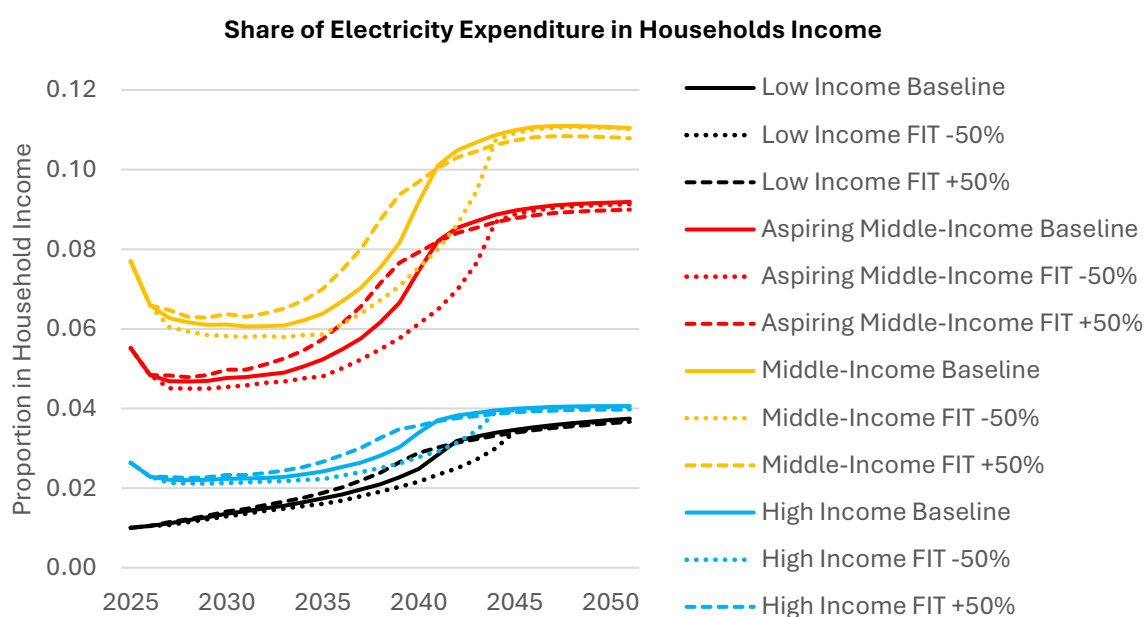


Figure 6.24. Share of Electricity Expenditures under different FIT.

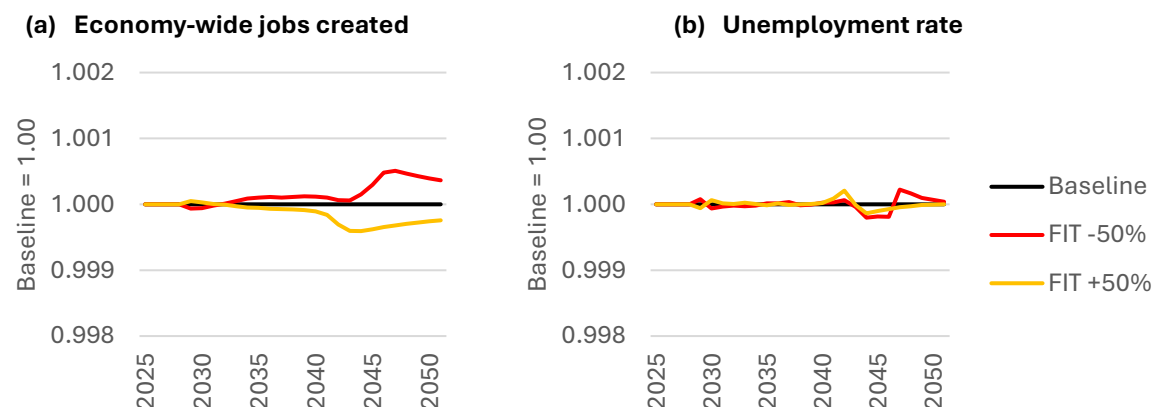


Figure 6.25. Effect of changes in FIT on Labor demand in the whole economy and unemployment rate.

The result of changes in the power mix is reflected in the emissions from the grid, as can be seen in Figure 6.26. With higher adoption of renewables under the higher FIT than the baseline, emissions of all pollutants are reduced. However, since higher FIT exhausts the energy budget earlier than the baseline, the share of RE is again reduced as explained in Figure 6.19 and the emission factor increase again and may even become higher than the baseline.

In the case of land-use, both increasing and decreasing FIT yields a similar effect although at a different magnitude and for different reasons (see Figure 6.27). When the FIT is decreased, electricity price goes down and results in higher electricity demand which necessitates the addition of new power plants. In contrast, the increase in land use when FIT is increased is due to the increase land-use for RE, particularly biomass power generation. The effect of FIT on land use indicates that among the renewable energy, biomass has the highest potential to be adopted based on the adoption characteristics set according to Table 6.2.

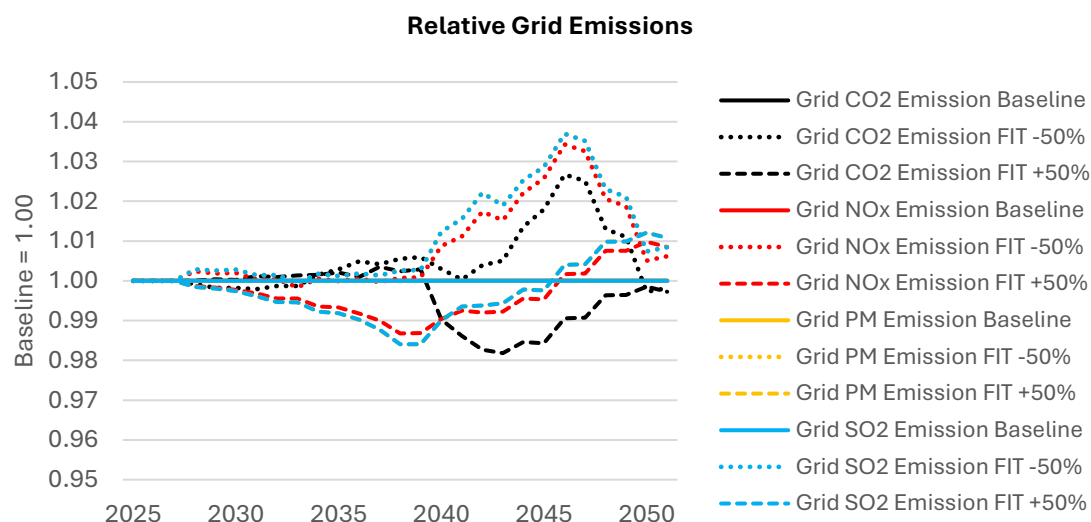


Figure 6.26. Emissions from the power sector under different FIT.

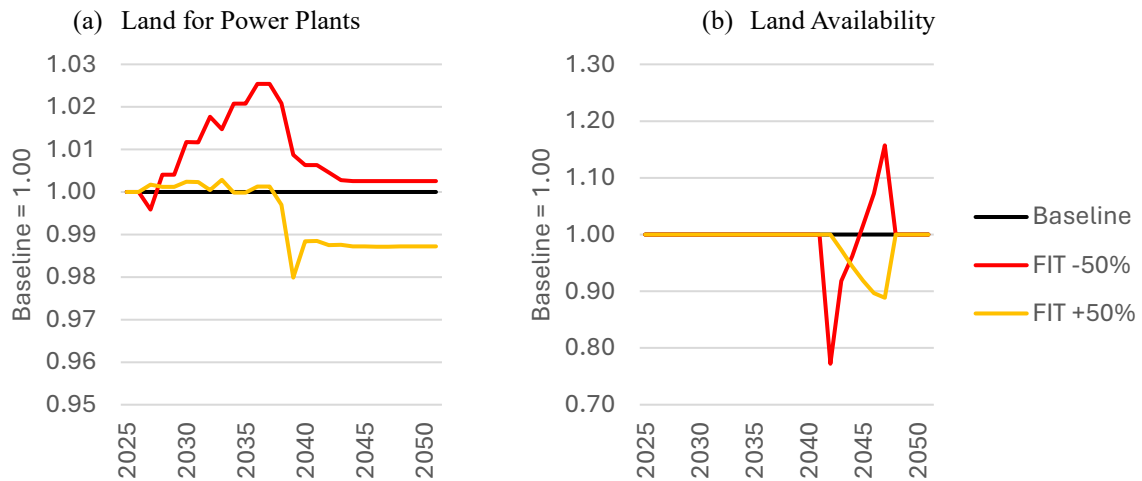


Figure 6.27. Effect of FIT changes on land use for power plants and land availability.

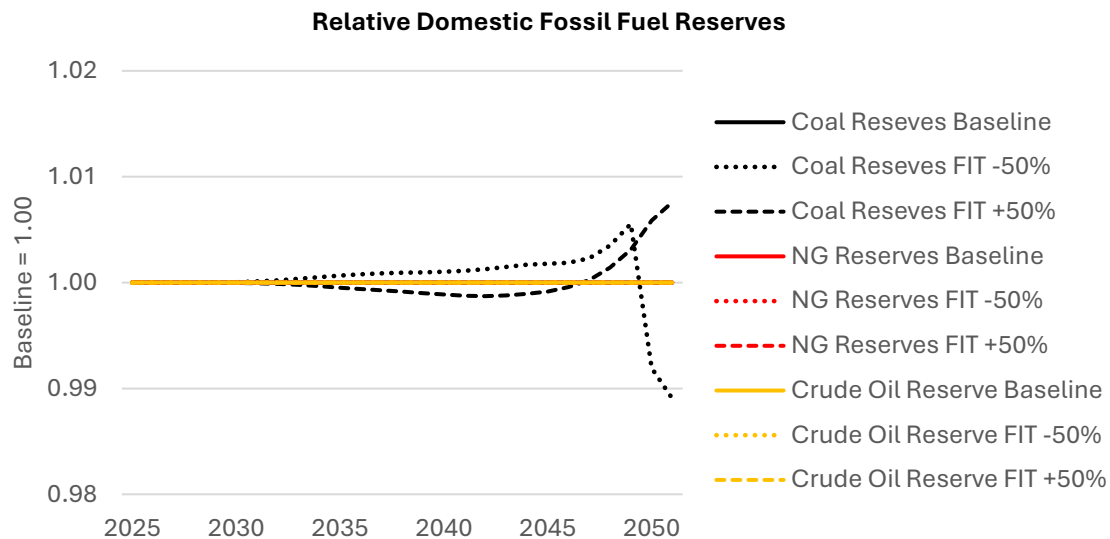


Figure 6.28. Fossil fuel domestic reserves under different FIT.

The effect of changing FIT rate on resources is shown in Figure 6.28. The increasing share of CFPP due to the lower FIT rate led to a higher exploration rate for coal hence increasing coal reserves. However, reserves quickly turned to be lower than the baseline as the extraction cost become higher, leaving the remaining resources to be uneconomically viable to extracted. In contrast, coal reserve is lower than the baseline when FIT rate is higher causing more RE to be adopted. But the reserve soon increase as the FIT rate cannot be sustained and more CFPP is installed and used. Natural gas and crude oil reserves is unaffected by changes in FIT because its extraction cost has already become too high even in the baseline. Mineral resources are also affected by changes in FIT. With more RE due to higher FIT led to more minerals to be extracted, and conversely for lower FIT. Copper and nickel are the two most affected minerals since they are both intensively used in RE technology.

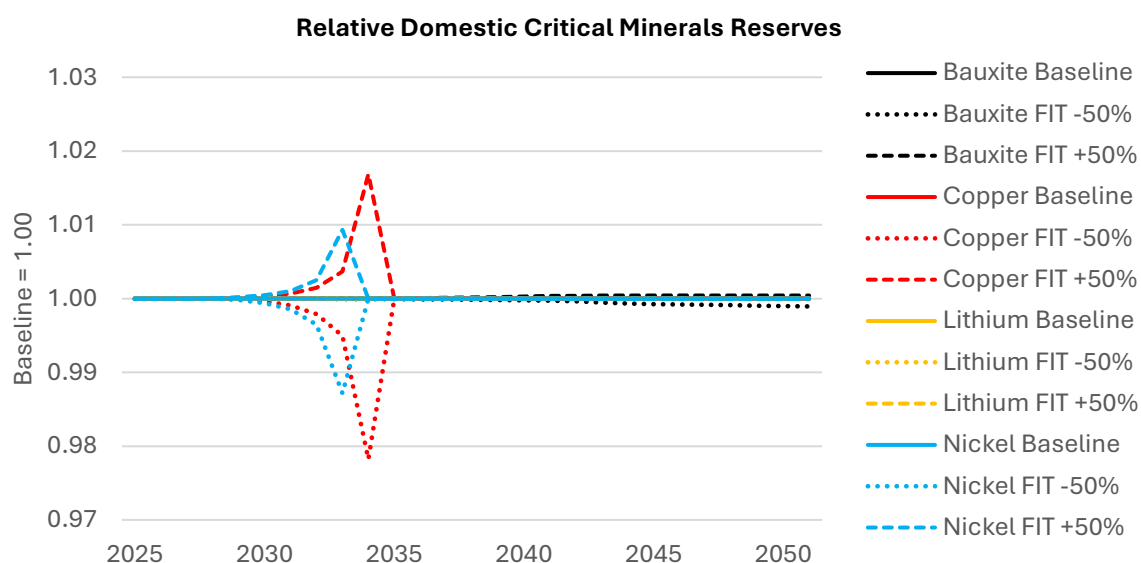


Figure 6.29. Critical minerals domestic reserves under different FIT.

6.4.2. The early retirement and future ban of CFPP

Two parameters are changed to emulate the early retirement and future ban of CFPP. First is the lifetime of the CFPP itself which was changed to become 5 years and 10 years. To avoid future CFPP investments, its relative benefit is zeroed. The results of the policy are shown in Figure 6.30 until Figure 6.40.

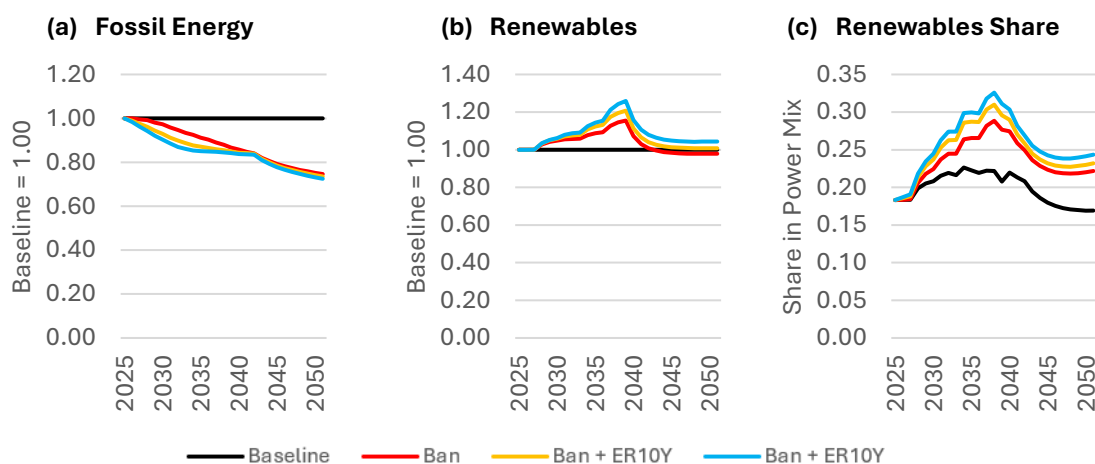


Figure 6.30. Effect of CFPP early retirement and ban on the power mix.

The early retirement and future ban of CFPP is effective to increase renewables share in the power mix as illustrated in Figure 6.30. However, it also leads to higher electricity prices as shown in Figure 6.31. The higher electricity price leads to higher subsidy expenditure which causes the energy subsidy budget to be exhausted. In turn, the fiscal incentives for renewables cannot be sustained and the adoption rate decreases rapidly. Another consequence of the higher electricity price is lower demand (see Figure 6.31) which caused the installed capacity of fossil-energy declined rapidly below the baseline. Overall, the share of renewable energy in the power mix can be improved 31% to 44% using this policy where hydropower and wind enjoyed the highest increase compared to other renewables due to its ample resource availability and power generation availability factor.

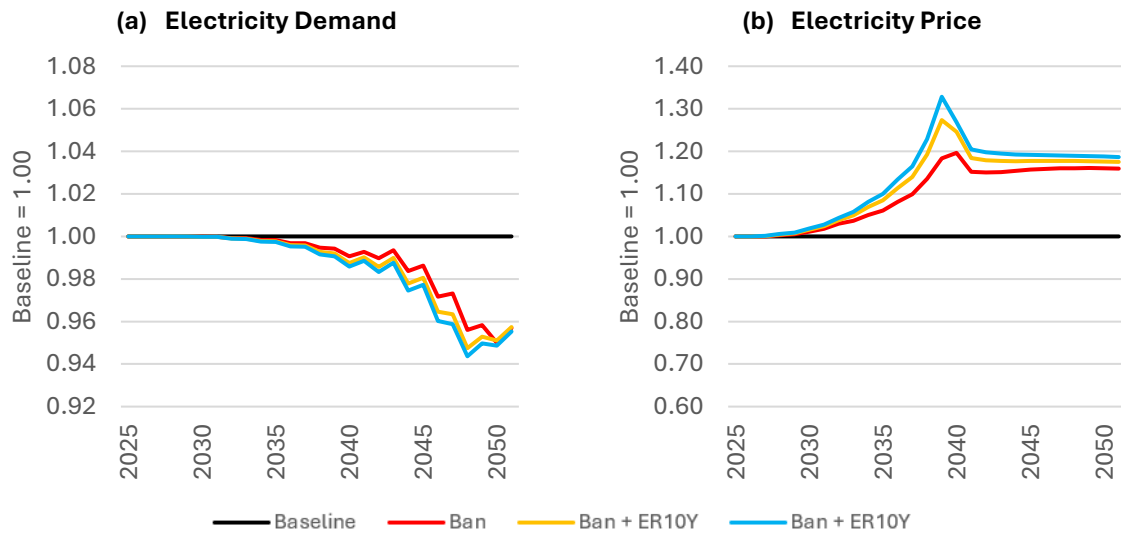


Figure 6.31. Electricity demand and price under different FIT.

The increasing subsidy for electricity due to CFPP early retirement and ban is shown in Figure 6.32. At its maximum point, the deficit could be 8% higher than the baseline when the ban is paired with early retirement in 5 years. The deficit increase can be minimized when no early retirement is implemented, where the deficit could be reduced to 3.5% around the same point in time. In addition, the deficit could stabilize around the baseline after the subsidy is exhausted under this policy. On the other hand, the deficit increasingly become higher than the baseline again when early retirement is applied since the subsidy for electricity substitutes kept increasing.

The increasing electricity price also pushed the price level of goods to increase higher than the baseline as depicted in Figure 6.33 which immediately affects real GDP growth (see Figure 6.34). The shifting away from coal have made the economy to be less susceptible to fossil fuel price but increasingly more on electricity. In addition, the cleaner power mix invites industrial sector to electrify their production pathway as in the effects of increased FIT. But it also came with the same consequences of higher production cost and hence price level.

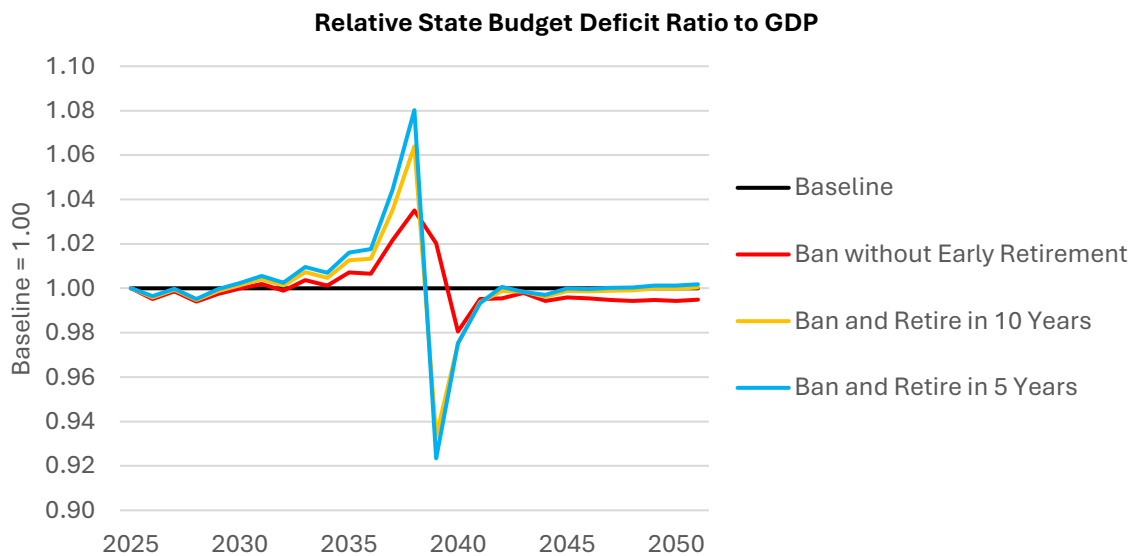


Figure 6.32. Effect of CFPP early retirement and ban on state budget deficit ratio to GDP.

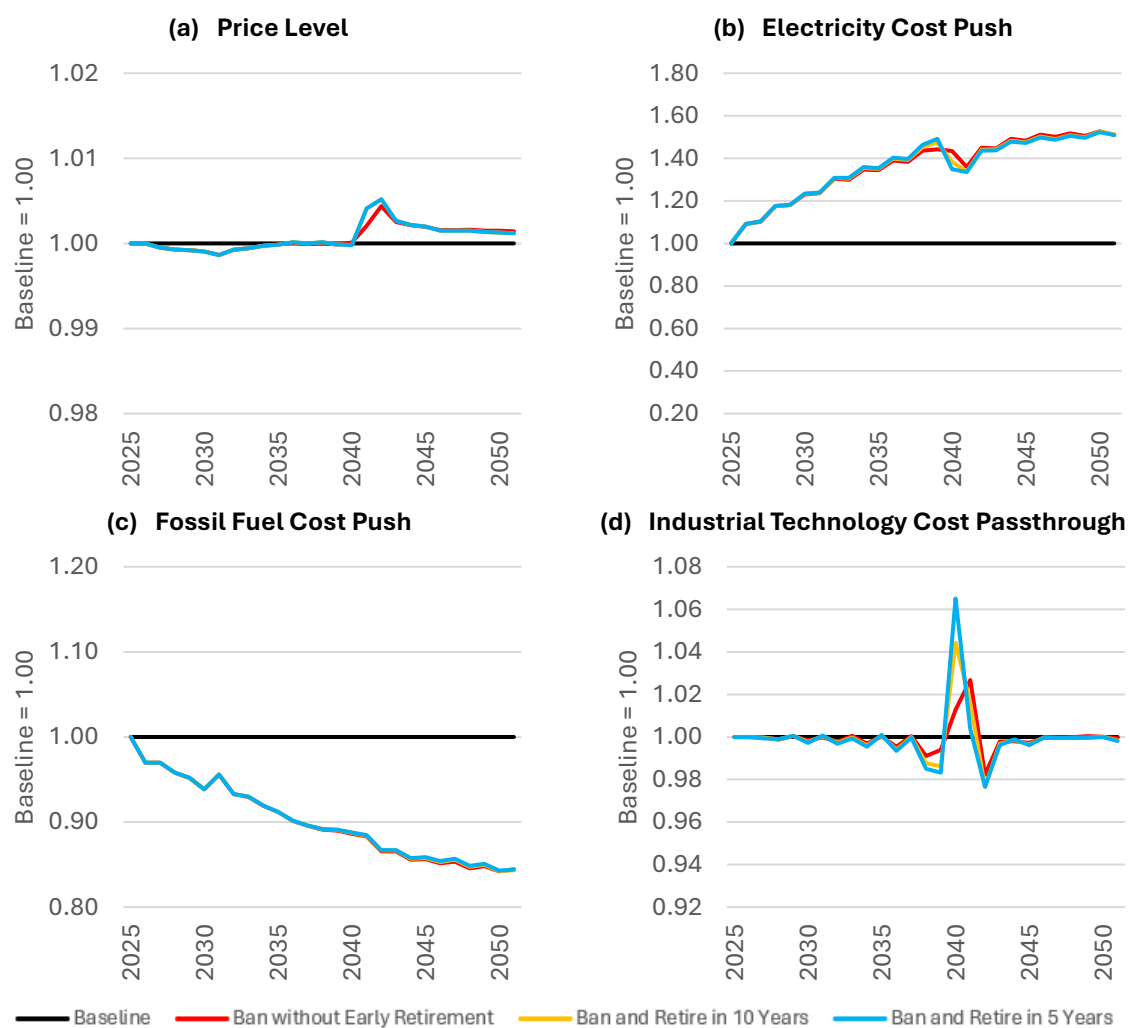


Figure 6.33. Effect of CFPP early retirement and ban on price level.

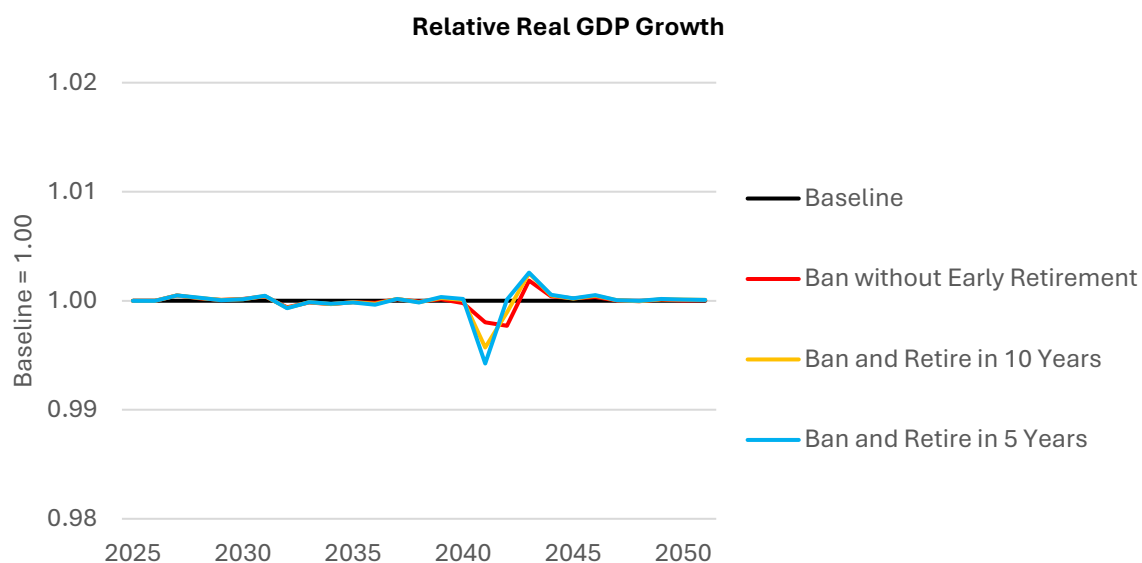
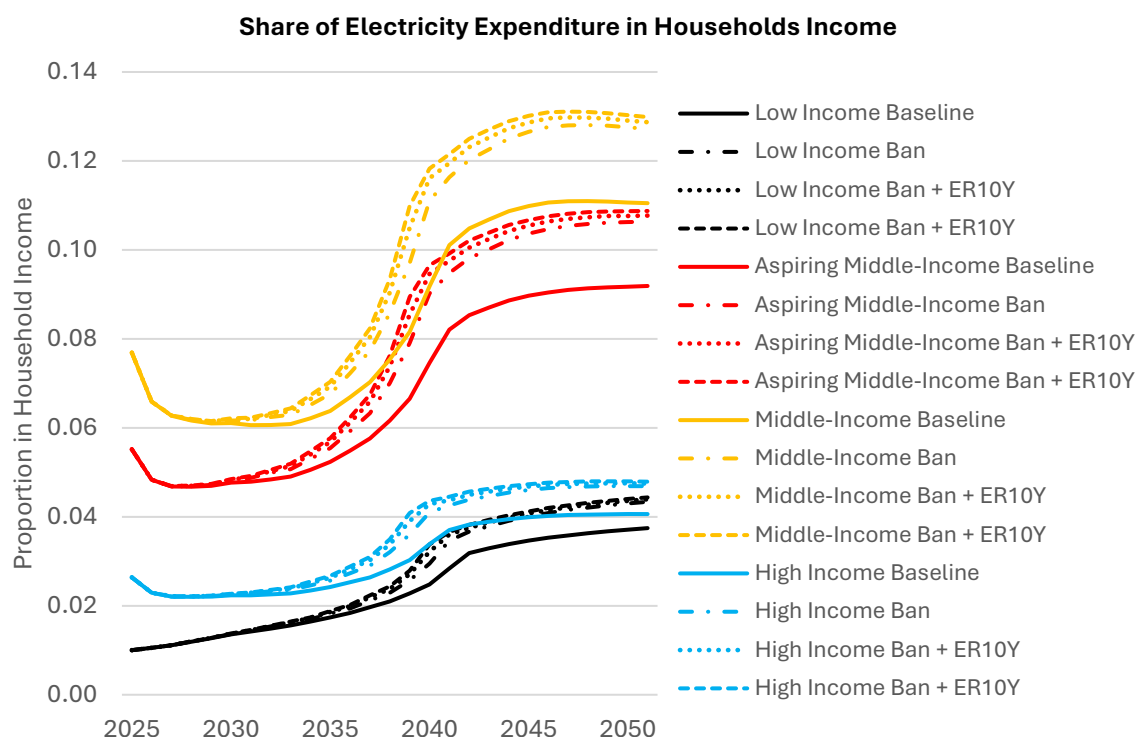


Figure 6.34. Effect of CFPP early retirement and ban on Real GDP Growth.

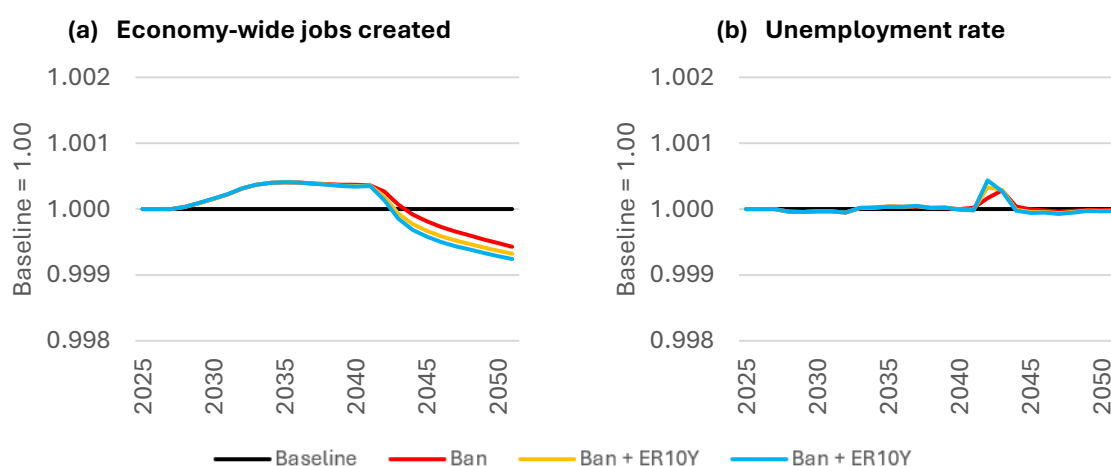
In addition to increasing the burden on the state budget, Figure 6.35 shows that the increase in electricity price also increases the share of electricity expenditure in households. The increase

in electricity expenditure is equally felt across income groups, ranging between 16-17% following the increase in electricity price. However, like the effect of FIT rate increase, aspiring middle-income and middle-income households are also the ones who are affected the most by early retirement and banning CFPP. The effect of the early retirement and ban of CFPP policy on economy-wide job creation and unemployment can be seen in Figure 6.36. A faster early retirement and ban of CFPP results in the highest inflation and could lead to an increase in jobs creation which obeys the Phillips curve³⁸⁰, but in the long run it resulted in less job creation. In addition, higher inflation also led to higher unemployment.



Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

Figure 6.35. Electricity expenditures in households with CFPP early retirement and ban.

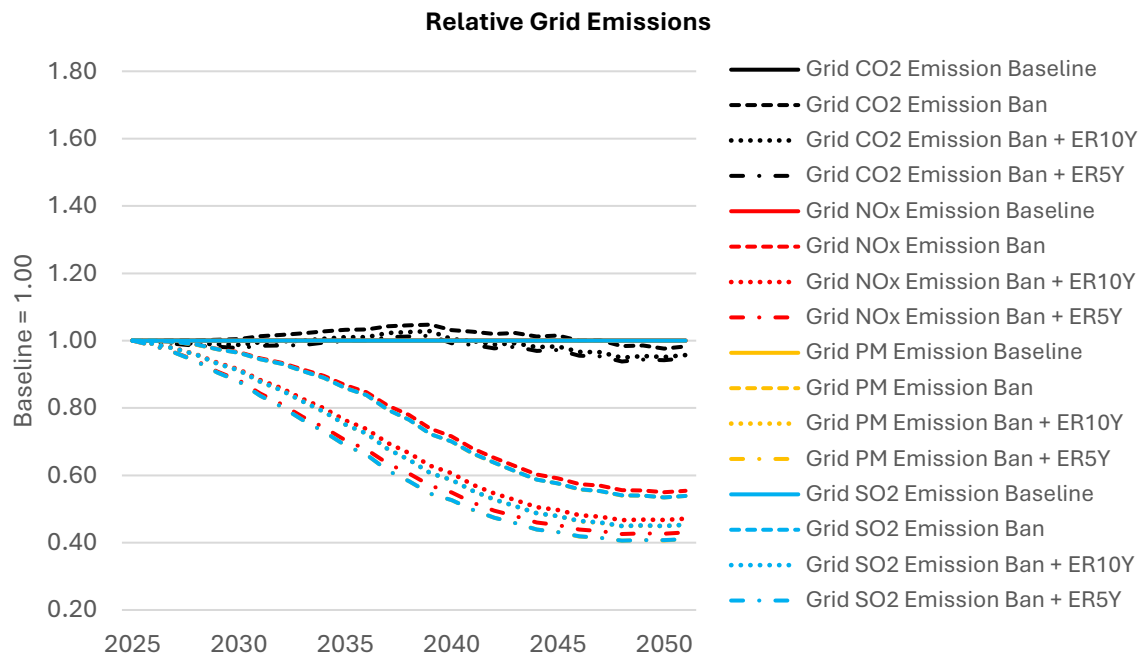


Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

Figure 6.36. Effect of CFPP early retirement and ban on Labor demand and unemployment rate.

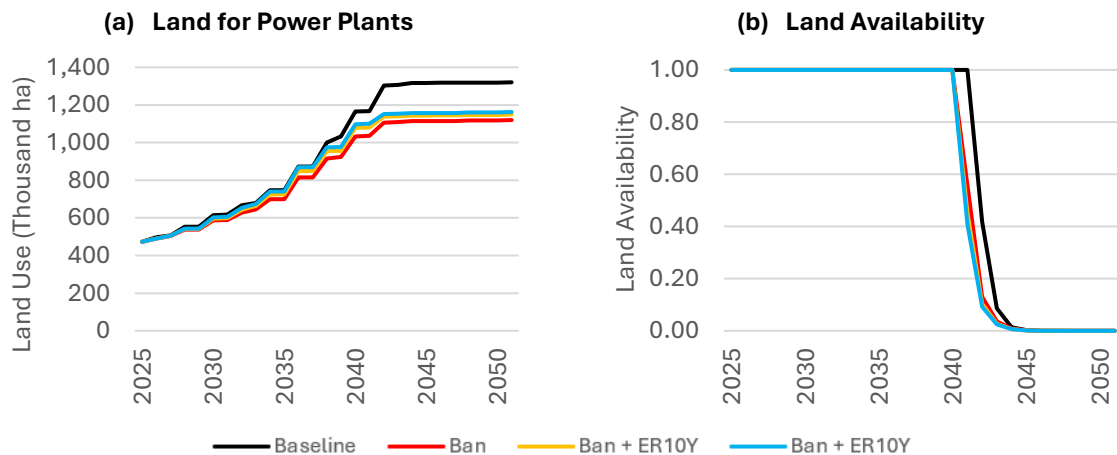
Enforcing a ban and an early retirement on CFPP showed a mix effects on the environmental indicators. Figure 6.37 shows that, while NO_x, PM, and SO₂ can immediately be reduced with this policy, CO₂ emission increased momentarily but then decreased overtime. The increase was due to the increase in biomass power generation which has a higher emission factor even compared to coal because of its lower heat rate but relatively equal emission intensity per weight of fuel³⁸⁸. The grid CO₂ emissions then decrease due to the lower electricity demand as illustrated in Figure 6.31.

The lower electricity demand also decreases the land use for power plants (see Figure 6.38). In terms of overall land use, however, the policy led to a higher use for biofuel. The banning of CFPP requires an equally reliable power generation in which case the diesel power generation – which fuel is blended with biodiesel – can provide. In addition, the resulting higher electricity price due to the policy also led to less EV adoption in the transportation sector which increased the biofuel consumption.



Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

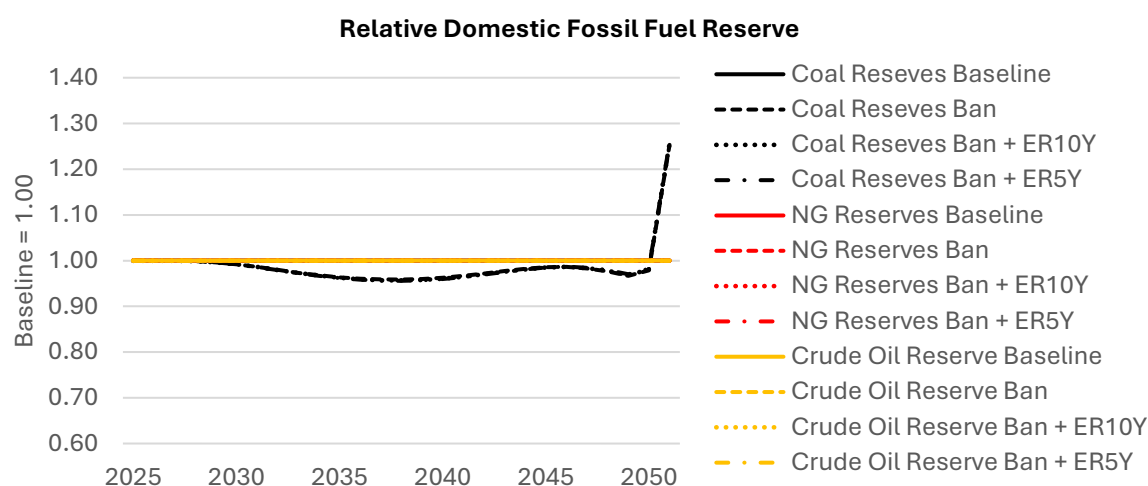
Figure 6.37. Emissions from the power sector with CFPP early retirement and ban.



Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

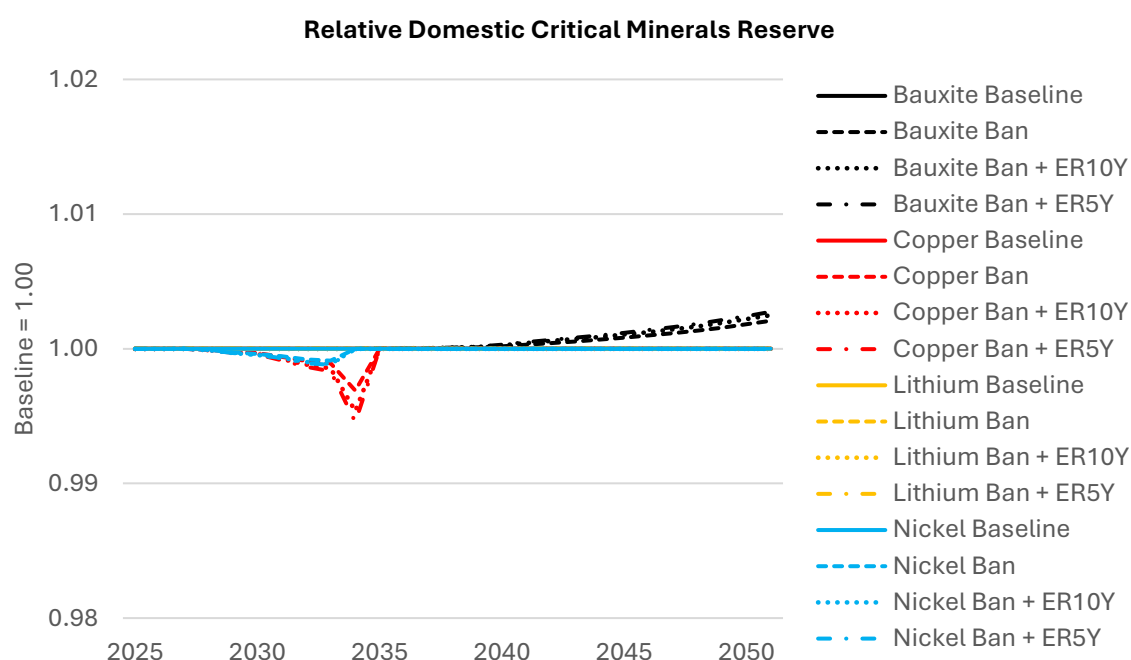
Figure 6.38. Effect of CFPP early retirement and ban on land use for power plants and land availability.

The significant decrease in coal consumption for CFPP led to a lower reserve due to lower demand for exploration as shown in Figure 6.39. However, the long-term effect of the policy is positive, in that it led to a higher reserve due to less extraction compared to the baseline. The banning of CFPP also led temporary increase in critical minerals to be supplied for the surging additional RE capacity. In the long term, the demand for minerals is lower than the baseline which is demonstrated clearly by the increased reserves of aluminium in Figure 6.40. The continuous decrease in demand is mostly due to systemic impact of rising electricity price on industrial production costs, including the non-ferrous metals industry.



Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

Figure 6.39. Effect of CFPP early retirement and ban on Fossil fuel domestic reserves.



Note: ER10Y = with early retirement in 10 years, ER5Y = with early retirement in 5 years

Figure 6.40. Effect of CFPP early retirement and ban on critical minerals domestic reserves.

6.4.3. Carbon tax

The GOI have formulated carbon tax implementation under the Decree No. 7/2021, in which the tax rate shall be at least equal to the domestic carbon price³⁸⁷. However, the price set by the government at 2.1 USD per ton of CO₂ is very small compared to the suggested price of minimum 30 USD per ton of CO₂³⁸⁹. Following the policy and recommended price, the model is then tested with carbon tax of 2.1, 8.4, and 33.6 USD per ton of CO₂. Although the decree only mentioned CFPP as the subject of the tax³⁸⁷, other gas-fired power plants and diesel generators are also included in this research. The revenue generated from the carbon tax is then added to the overall state revenue. The result of the policy is shown in Figure 6.41 to Figure 6.51.

Applying a carbon tax on fossil-based power generation is shown in Figure 6.41 to have a temporarily positive impact on RE share, particularly at higher carbon prices. However, the higher share compared to the baseline is only until a certain point in time when the energy subsidy budget can no longer withstand the subsidy for RE. Nonetheless, the carbon tax did support the budget so that it can provide a longer lasting subsidy as shown in Figure 6.43 which could resulted in a lower electricity price (see Figure 6.42) assuming the energy budget allocation is kept.

After the energy subsidy budget is exhausted, the implementation of carbon tax affects the RE share negatively except at low carbon price. The increase in electricity demand due to the lower electricity price led to more power generation capacity to be installed, leading to more installed capacity in the future. However, when carbon price is high, the benefit of diesel generator turned out to be the most reduced which is already have an economic disadvantage even among fossil-based generation. The reduced relative benefit of DPP increased the benefit of CFPP which is still cheaper despite with the carbon tax. Despite its environmental impacts, CFPP has a higher power generation availability factor which reduced the need for large install capacity and hence the lower total installed capacity under the high carbon price setting.

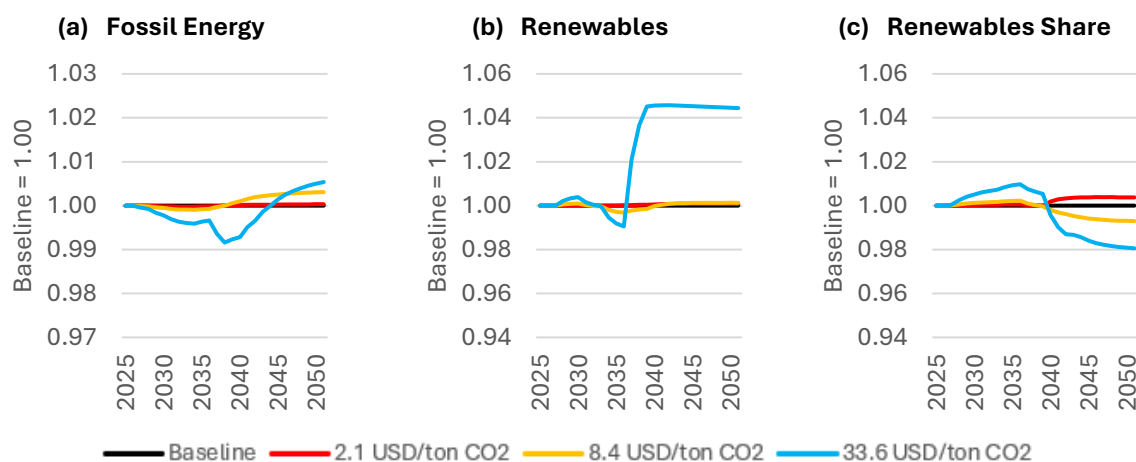


Figure 6.41. Effect of carbon tax on the power mix.

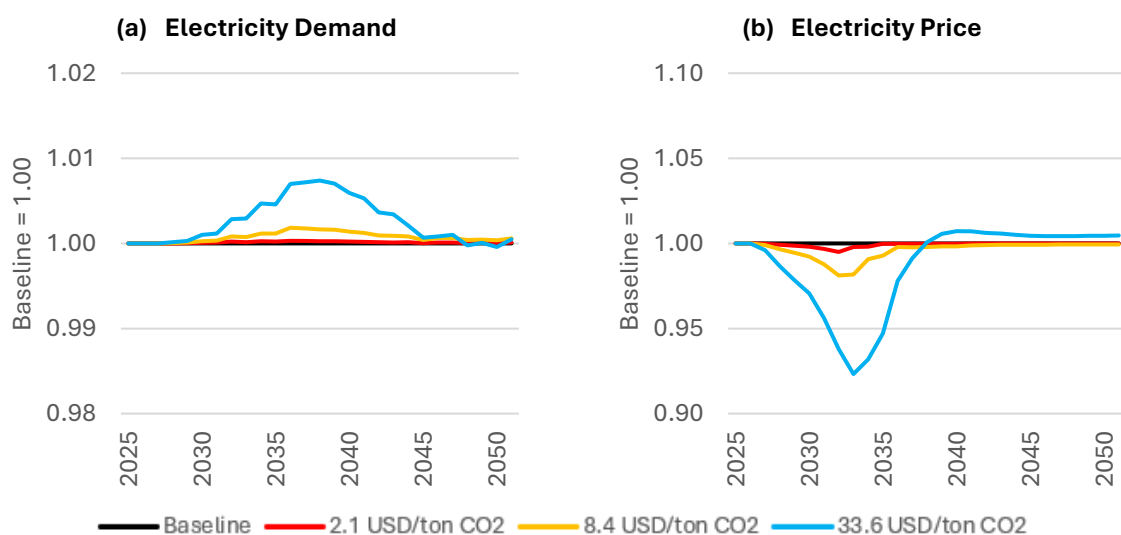


Figure 6.42. Electricity demand and price under different carbon tax.

The effect of a carbon tax under the low carbon price is not as clear, since it leads to a higher RE share in the power sector. The explanation lies in the intersection between the power sector and the industrial sector for the provision of clean hydrogen. With the profit-maximizing assumption in the power sector, the resource will be prioritized for hydrogen production which has a higher market price compared to electricity. Under the low carbon price, the relative benefit of BePP is lower than the baseline in general, with its allocation for hydrogen production also lower, so and more can be built for power generation purposes. Thus, the RE share increase in the power sector is due to this increase in BePP.

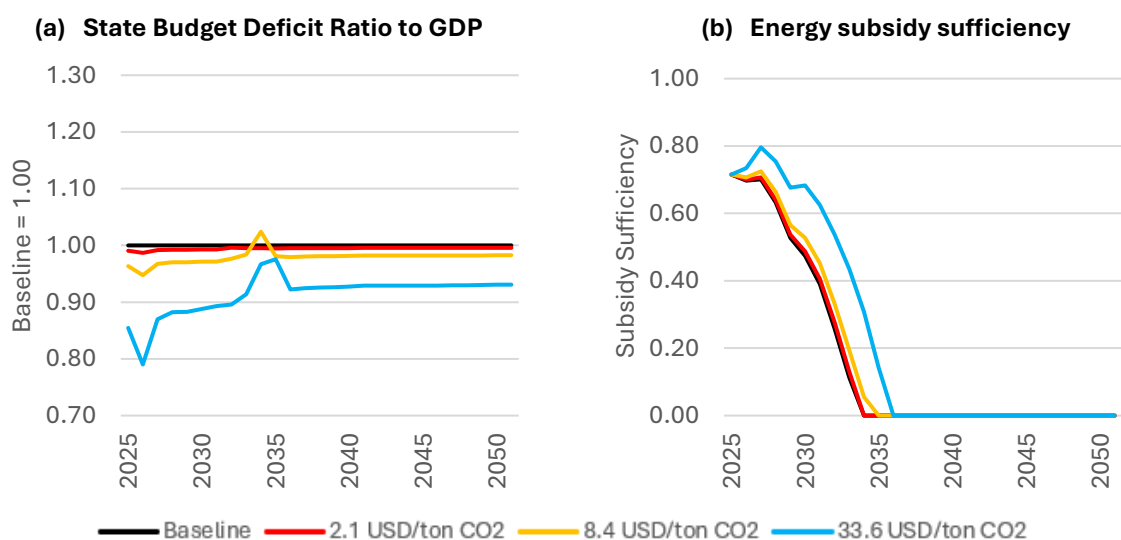


Figure 6.43. Effect of carbon tax on state budget deficit ratio to GDP and energy subsidy sufficiency.

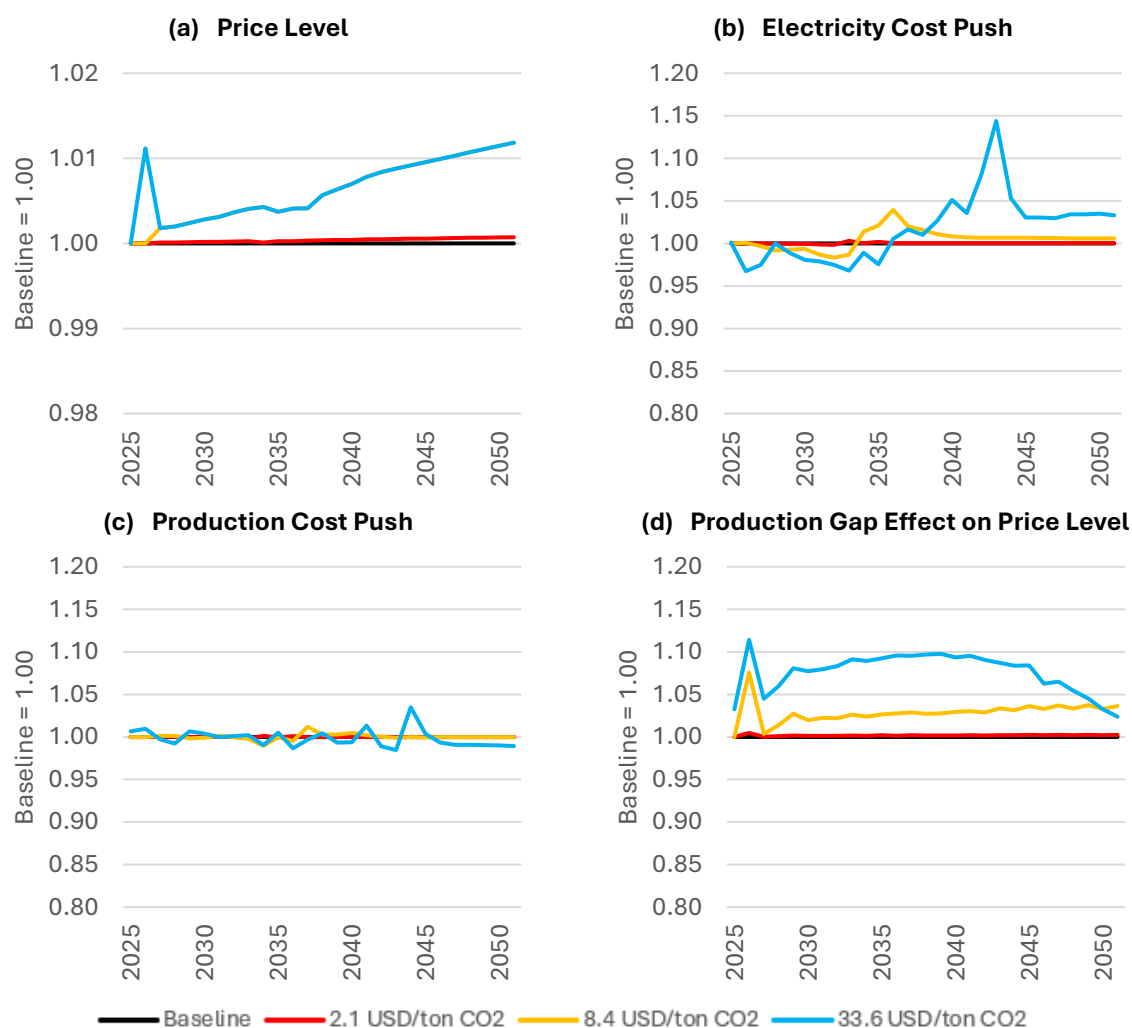


Figure 6.44. Effect of carbon tax on price level.

Implementing a carbon tax is shown to have a positive impact on the state budget as shown in Figure 6.43. The carbon tax could add fiscal space for energy budget, delaying the time it gets exhausted. While applying the current 2.1USD/ton of CO₂ carbon price could not extend the state budget, it could increase the energy subsidy budget by 18% in 2039 after which it is depleted just like the baseline. With 8.4 and 33.6 USD per ton CO₂, the budget depleted could be postponed by one and three years, respectively. The additional revenue from carbon tax could be used to further fuel FIT to increase the RE adoption in the power sector as shown in Figure 6.41. In terms of price level however, increasing the carbon tax rate led to higher price levels despite the relative decrease in electricity prices. Looking at Figure 6.44, it can be explained that the driver of the price level increase is not from the production cost-push but the production gap effect. The increase in tax revenue could increase the government's revenue-dependent spending, which increases aggregate consumption and thus increasing price level²⁹. The price level increase is then exacerbated by the sudden increase in electricity price due to the exhausted subsidy budget as shown in Figure 6.42. As the result of the changes in price level, Figure 6.45 shows the real GDP growth under a higher carbon tax is lower than the baseline which concurs to the findings by Hasudungan¹⁵.

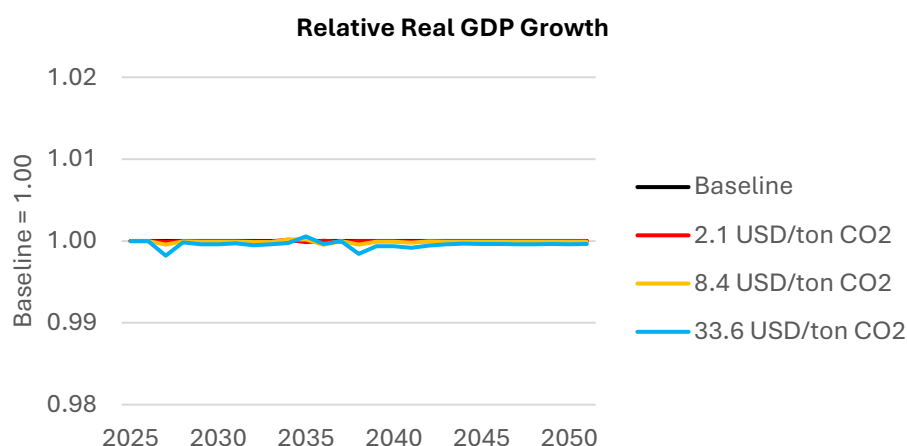
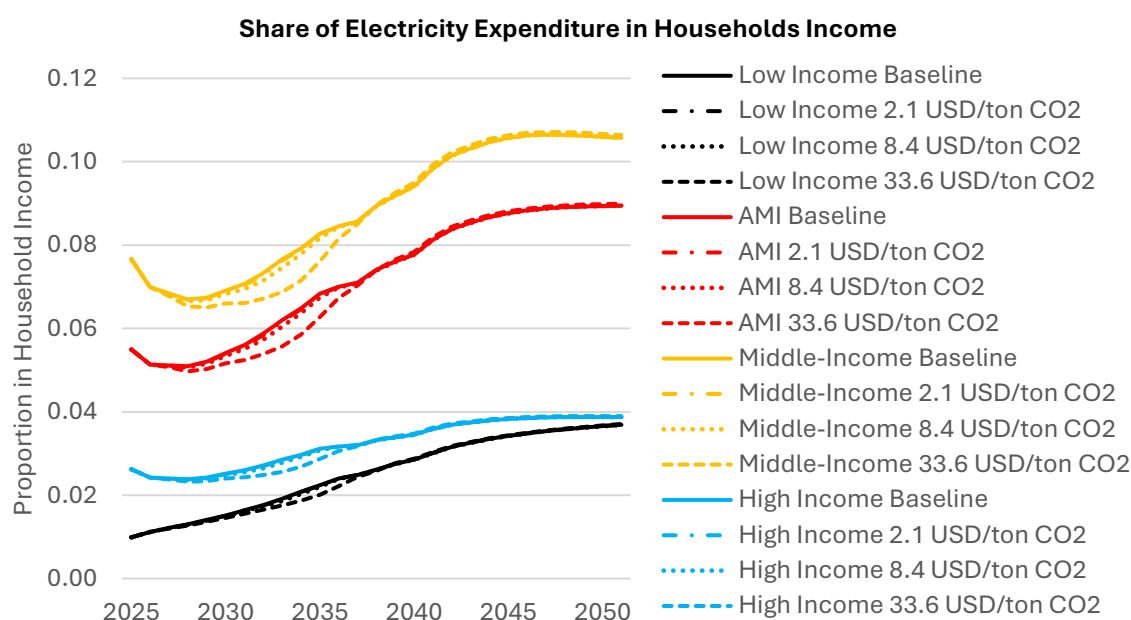


Figure 6.45. Effect of carbon tax on real GDP growth.



Note: AMI = Aspiring-Middle-Income

Figure 6.46. Effect of carbon tax on household expenditure for electricity.

The lower price of electricity due to the larger fiscal space for subsidies eases the household expenditure burden for electricity as shown in Figure 6.46, although only temporarily until the subsidy budget eventually gets exhausted, after which electricity price increases from the baseline due to a higher share of RE and making its expenditure share in households also higher. When the budget is available, household expenditure on electricity could be reduced by 1% to 10% but then increases around 1% from the baseline when the budget is no longer sufficient. In terms of jobs creation, the higher inflation rate under the carbon tax policy implementation led to slightly more jobs, but at the same time higher unemployment due to the higher layoff rate. The simulation result shows that the increase in economy-wide jobs creation could compensate the effect of lay off rate. causing a higher increase in unemployment rate. At the highest carbon price simulated, the jobs created in 2050 could be 0.7% higher while unemployment rate is 0.1% higher than the baseline.

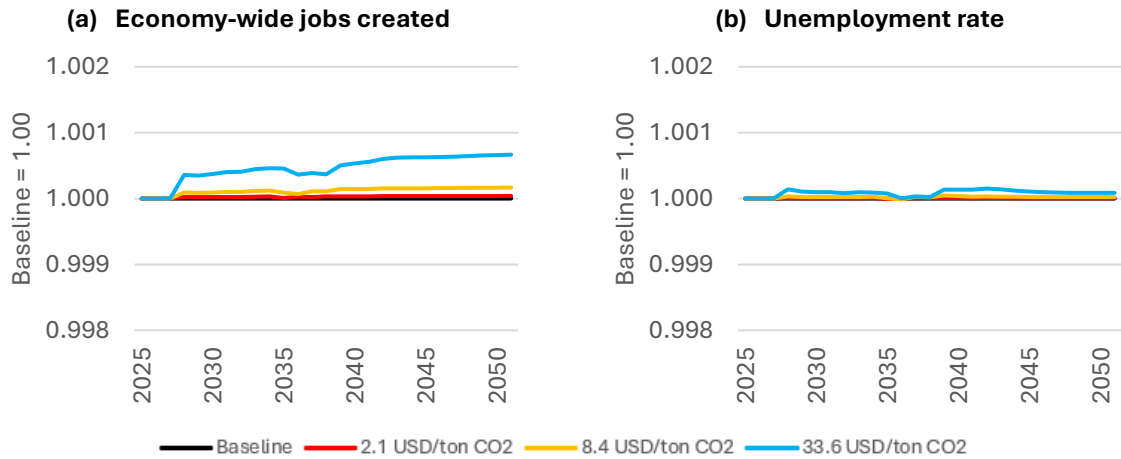


Figure 6.47. Effect of carbon tax on labour demand and unemployment rate.

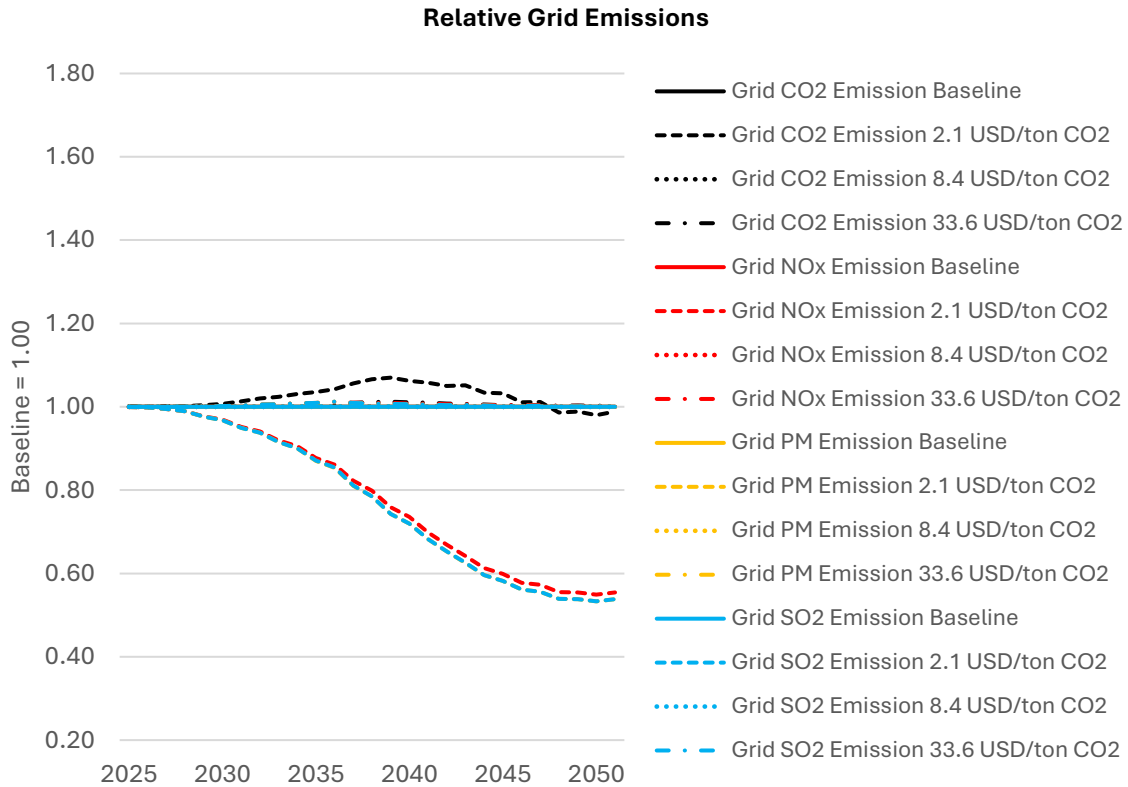


Figure 6.48. Changes in Emissions from the power sector with carbon tax.

Figure 6.48 shows that with more RE in the power mix under the carbon tax policy, the emissions of NO_x, PM, and SO₂ could be reduced significantly. However, the use of BePP also meant a higher CO₂ emission. Implementing carbon tax which led to a higher RE means a higher land use for power plants following the higher installed capacity due to the momentary increased in electricity demand as shown in Figure 6.42. However, the higher land-use for power plants did not translate to lower land availability. Quite the opposite, the land availability could be higher than the baseline when carbon tax is imposed since the land for biodiesel production which is to be used in DPP decreased more significantly than the increase in land for biomass for BePP.

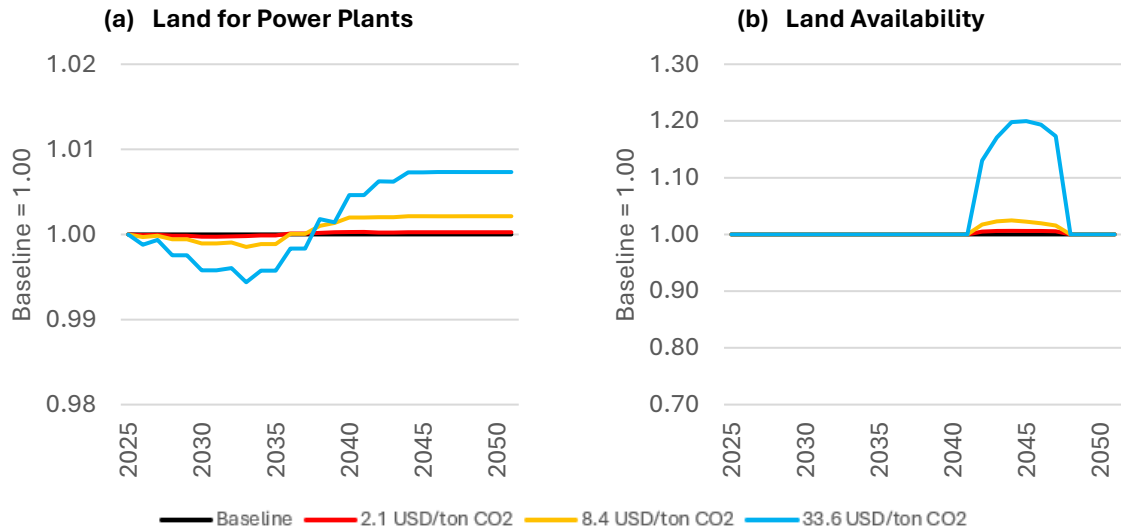


Figure 6.49. Effect of carbon tax on land use for power plants and land availability

Regarding fossil resources, implementing carbon tax only affects coal reserves as it could be the only one left that has economic viability to be extracted as shown in Figure 6.50. The state of the coal reserve follows an almost sinusoidal behaviour. The initial decreasing from the baseline is due to the lower overall demand for coal, primarily because of the decreased demand from the industrial sector as the price of electricity decreased. The reserves then increased with the increasing demand in both industrial sector and power sector until then rapidly decreased again due to the increasing extraction cost. However, with lower extraction rate at the later stages of the simulation the ending reserves become higher, hence another increase in reserve compared to the baseline. As for minerals resources, Figure 6.51 shows the reserves of copper and minerals are significantly reduced when there is a sudden increase in RE.

Figure 6.50. Effect of carbon tax on fossil fuel domestic reserves

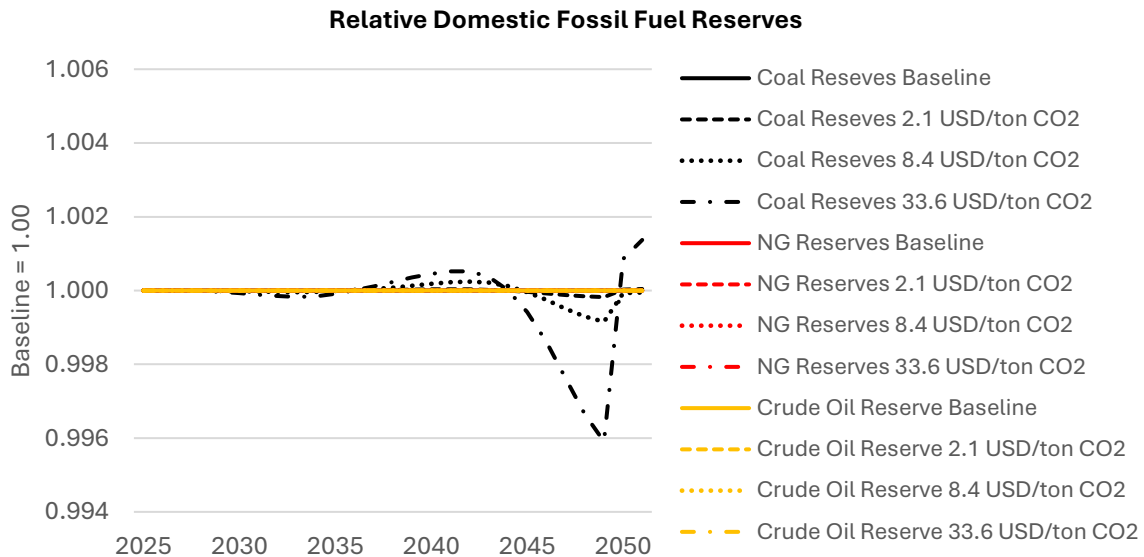
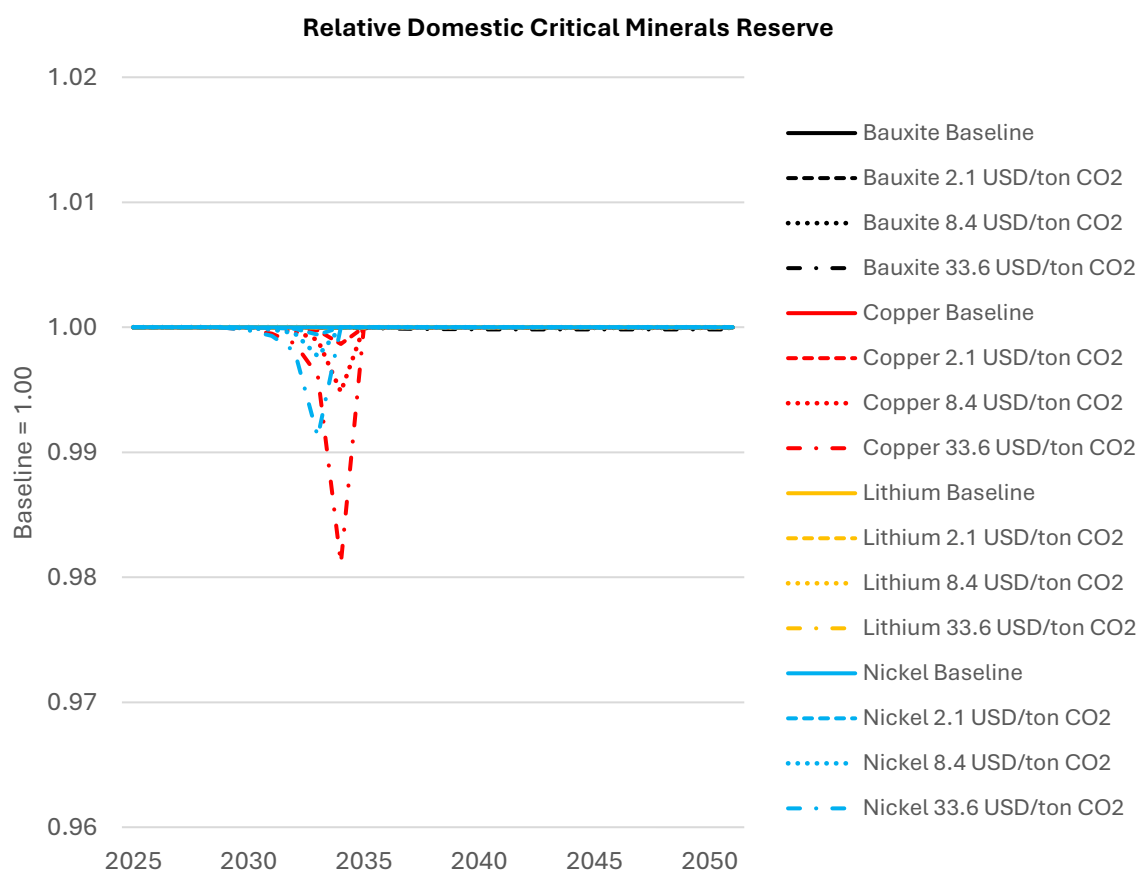


Figure 6.51. Effect of carbon tax on critical minerals domestic reserves.



6.4.4. Fossil fuel subsidy

As shown in Figure 6.9, the current policy provides a large sum of subsidy for fossil fuels especially liquid fuels used in the transportation sector. Chapter 3 have discussed in detail how the energy demand in the transportation sector would continue to increase, and that its dependence on fossil fuel could continue. This relentlessly increasing burden of fossil fuel subsidies left only small room in the fiscal space to be allocated elsewhere, including to support RE adoption in the power sector. Previous sections have illustrated the subsidy for electricity and RE is not sufficient. Thus, this section shall explore the effect of reducing fossil fuel subsidies on the adoption of renewable power generation and the observed indicators by reducing the subsidy rate by 12.5%, 25%, and 50% from the baseline.

Figure 6.52 shows that changing only subsidy rates for fossil fuel by reducing it may lead to a decrease in RE share. The reason being that the reallocated subsidy to electricity reduces its price and significantly increases its demand, thus requiring more power generation capacity to be installed. Under the adoption characteristics in Table 6.2, the power sector would favour fossil-based generation more. In addition, the renewables exploitation rate also hinders the process of adding RE installed capacity – an uncertainty which effect will be explored in Section 6.5.

Reducing fossil fuel subsidies is shown to relieve state budget deficit and improve energy subsidy budget sufficiency significantly in Figure 6.54. However, the budget deficit steadily returns to the baseline as the subsidies allocated increase demand for electricity (see Figure 6.53). In terms of price levels, however, Figure 6.55 shows that a sudden increase in price due to lower subsidy rate could cause a sharp increase in price levels since the economy is heavily

reliant on fossil fuel. After the increase, price levels could slightly decrease as the economy shifts its dependence to electricity, but then levels increase again slightly with the increase in electricity price. As a result of inflation, the real GDP growth is also negatively affected by decreasing fossil fuel subsidy rate for most of the time as shown in Figure 6.56, and the real GDP itself could be 0.5% lower than the baseline by 2050.

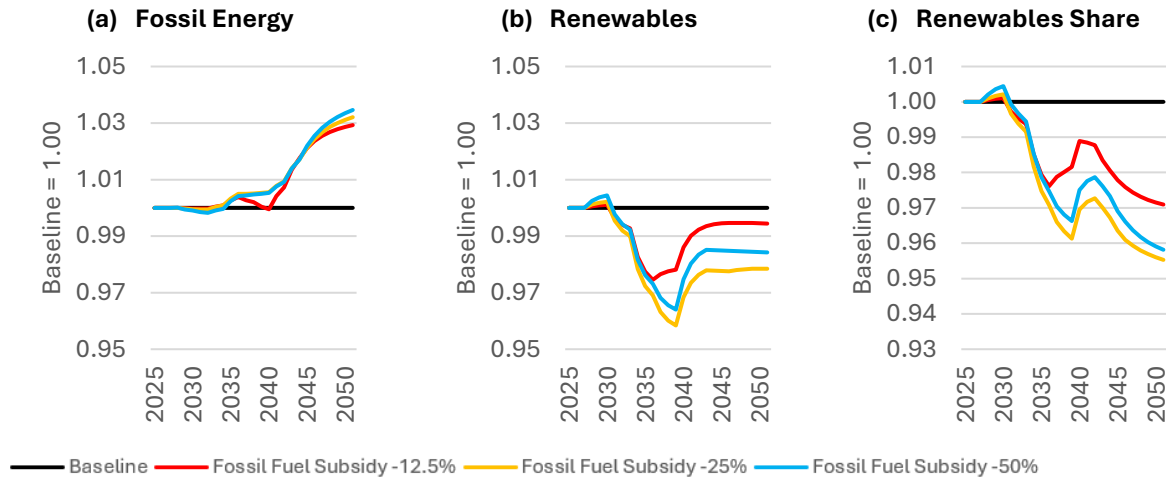


Figure 6.52. Effect of reducing fossil fuel subsidy on the power mix.

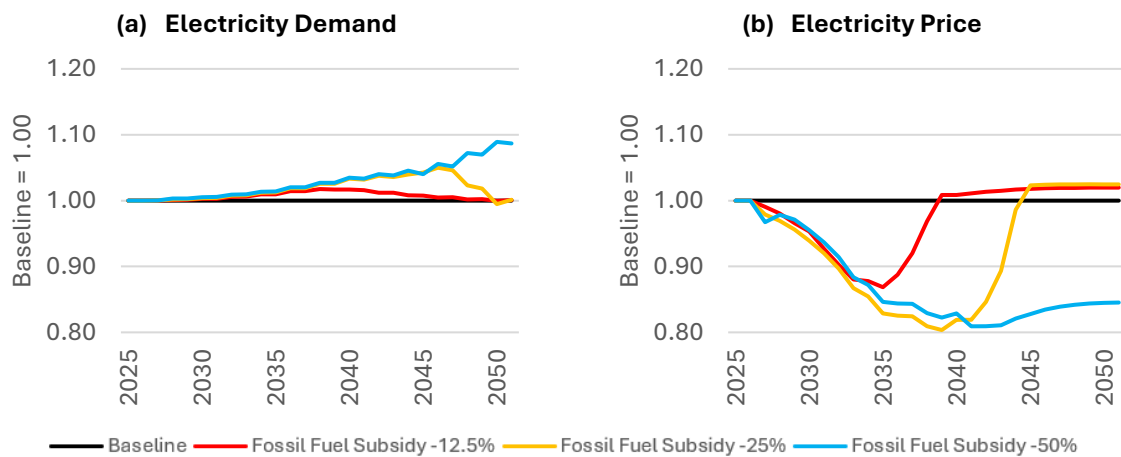


Figure 6.53. Electricity demand and price under different fossil fuel subsidy reduction

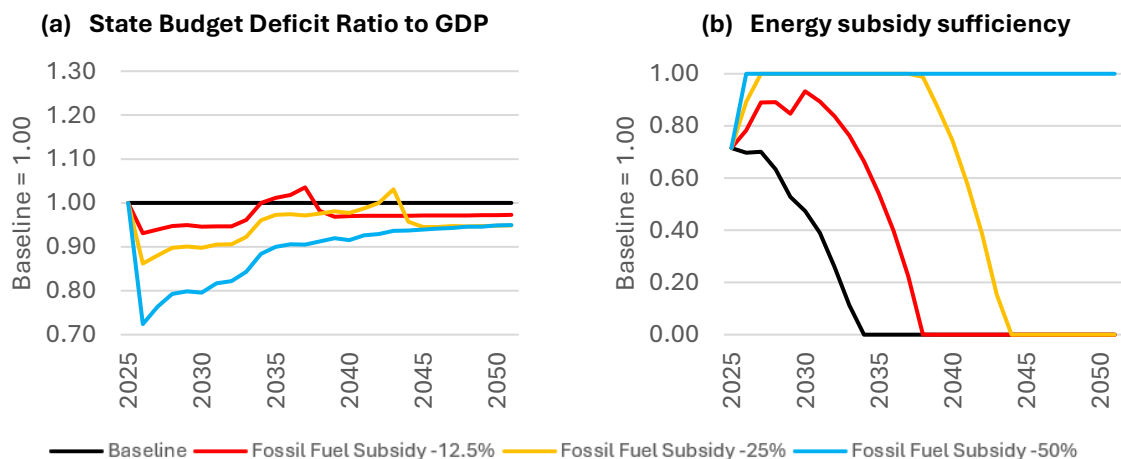


Figure 6.54. Effect of fossil fuel subsidy reduction on state budget deficit and energy subsidy sufficiency

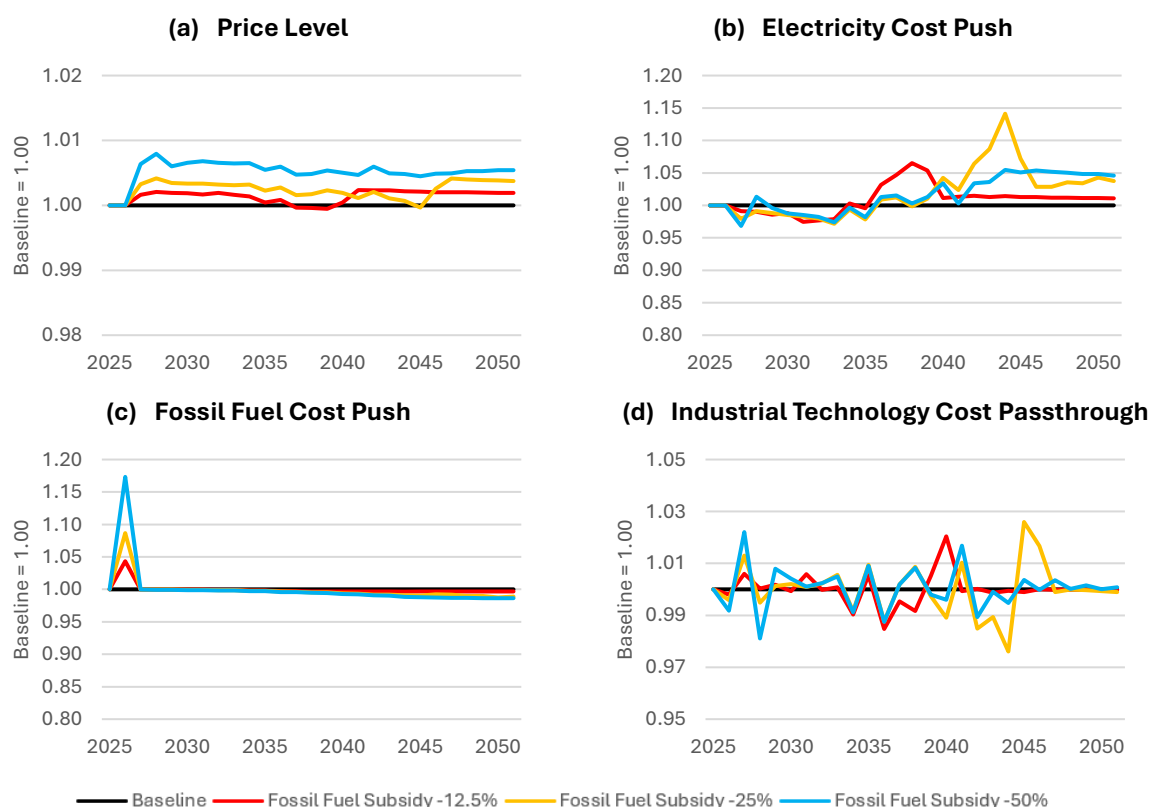


Figure 6.55. Effect of fossil fuel subsidy reduction on price level

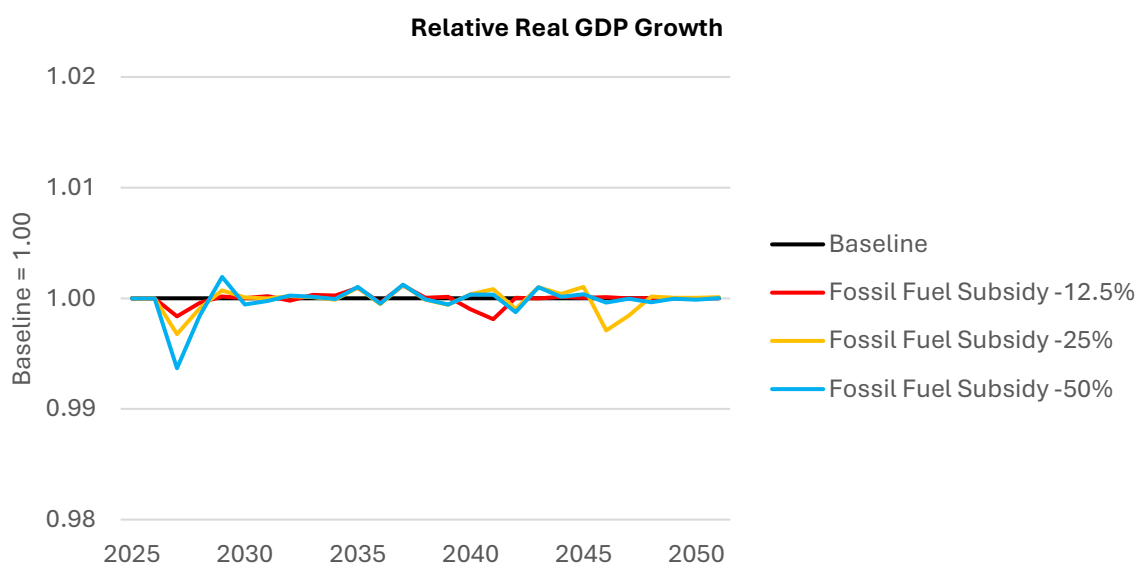
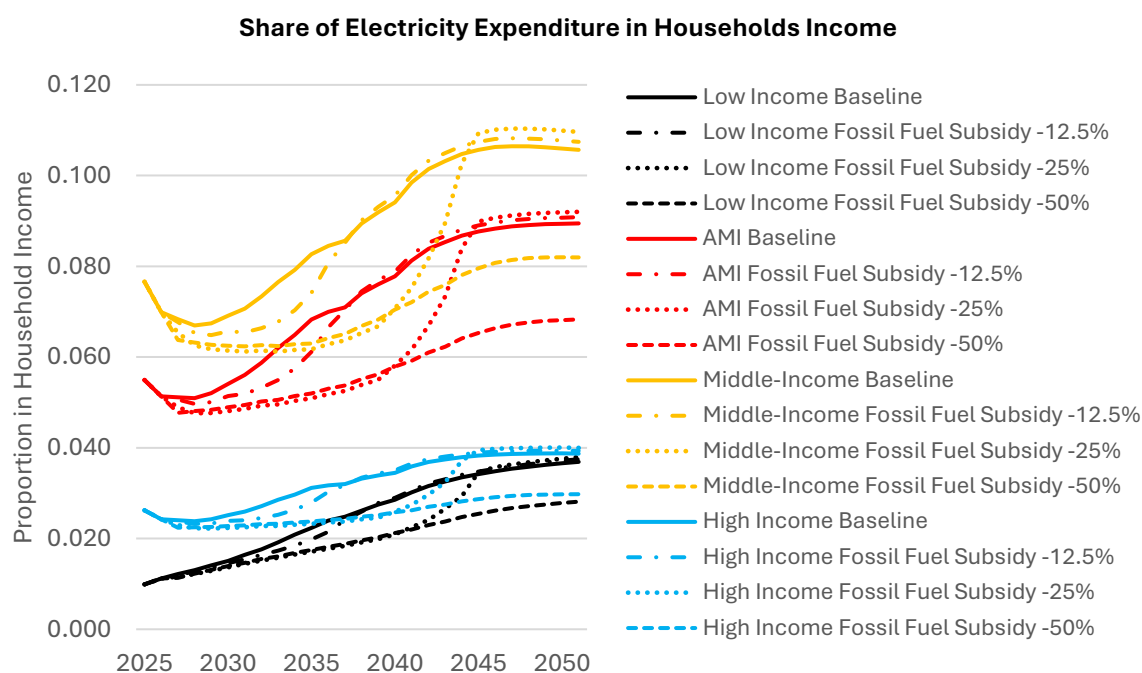


Figure 6.56. Effect of fossil fuel subsidy reduction on real GDP growth

As with the case of applying a carbon tax which could increase fiscal space for electricity subsidy, reducing fossil fuel subsidy rate can also have a positive impact on the burden of electricity expenditure on household income as presented in Figure 6.57. On economy-wide jobs creation and unemployment rate, although the inflation caused by the fossil fuel subsidy reduction led to higher unemployment in some years, it is outweighed by the jobs created (see Figure 6.58). Although it can still be argued who enjoyed the jobs created and who gets unemployed.



Note: AMI = Aspiring Middle-Income

Figure 6.57. Effect of fossil fuel subsidy reduction on household expenditure for electricity.

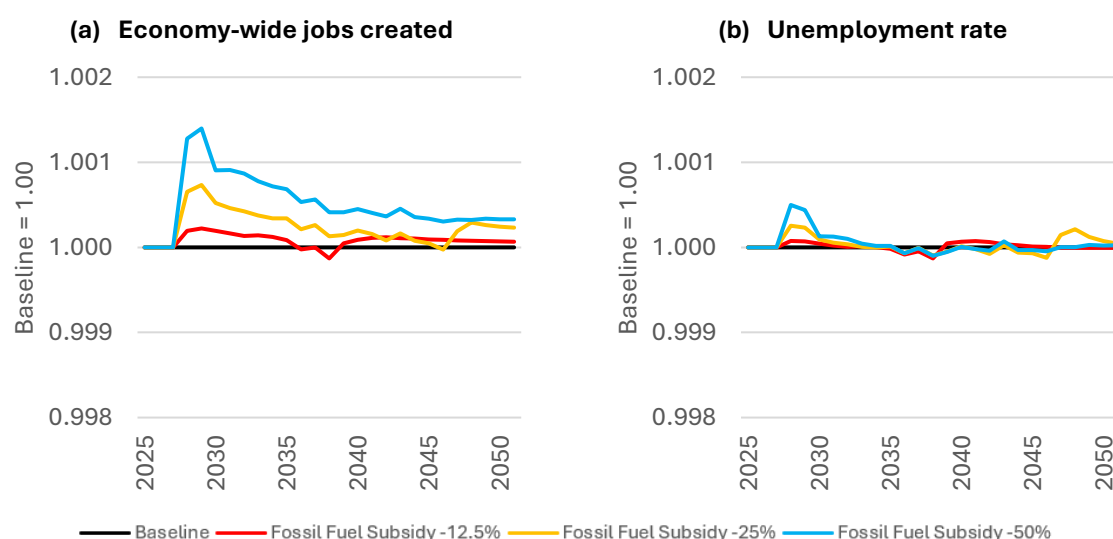


Figure 6.58. Effect of fossil fuel subsidy reduction on labour demand and unemployment rate.

Figure 6.59 shows that the reduction of fossil-fuel subsidy led to a higher emission on all of the pollutants following the increase in fossil-based power generation, especially with the increase in CFPP in the power mix. While the increase in CFPP in the power mix affects emissions negatively, its effect on land-use and availability is relatively positive as presented in Figure 6.60 where the land availability under the highest fossil fuel subsidy reduction led to the highest land availability among the other subsidy reductions. The increasing use of CFPP also led to a higher demand for coal exploration, hence the higher reserves as depicted in Figure 6.61. Regarding mineral resources, however, the sudden increase in fossil fuel price when it is first implemented would spike the RE adoption hence leading to a large consumption of mineral resources (see Figure 6.62).

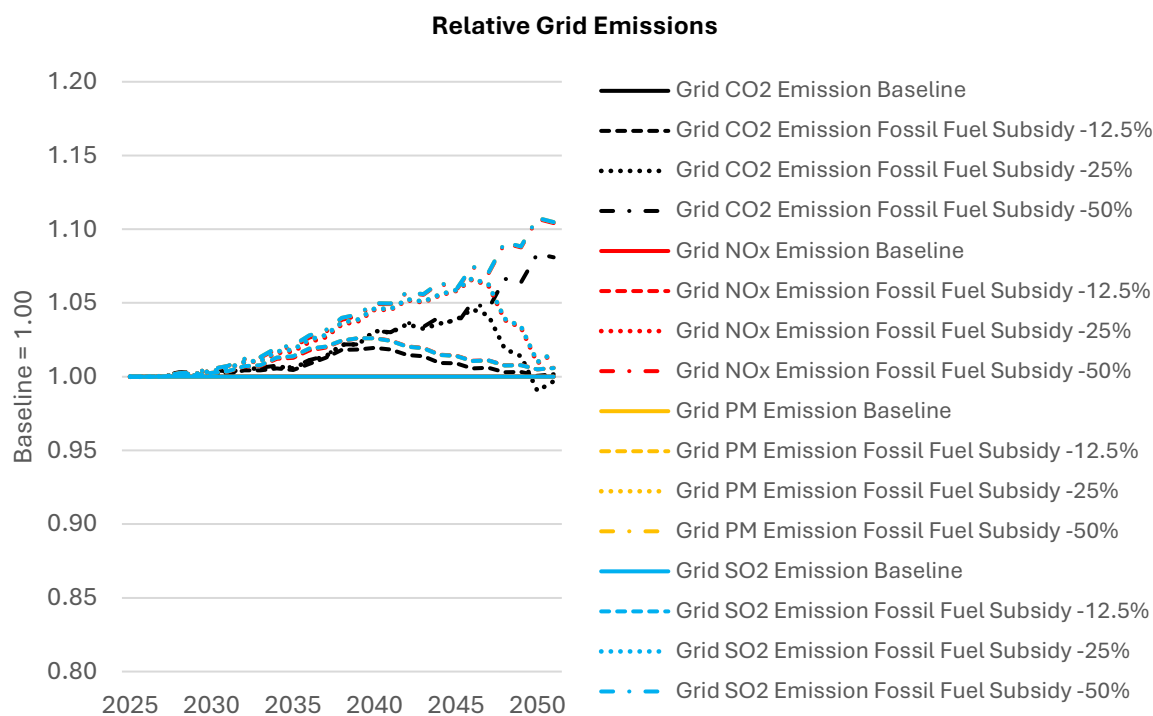


Figure 6.59. Effect of fossil fuel subsidy reduction on emissions from the power sector.

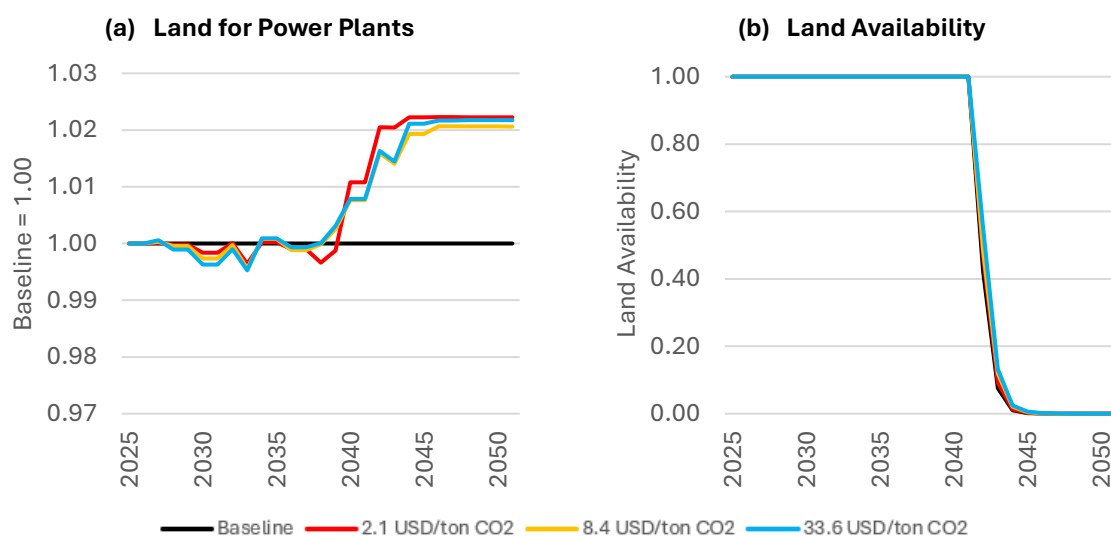


Figure 6.60. Effect of fossil fuel subsidy reduction on land use for power plants and land availability.

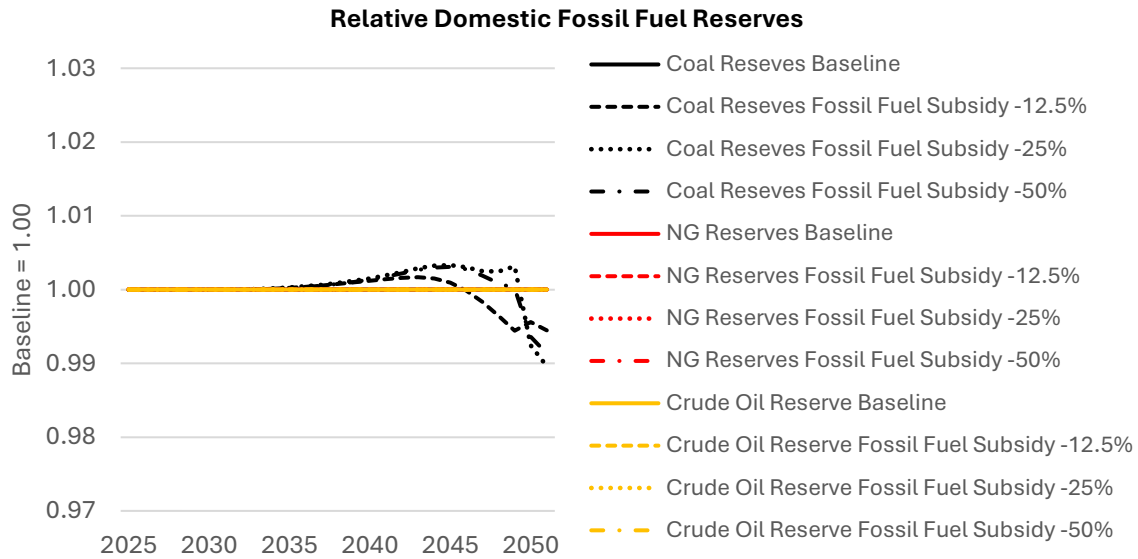


Figure 6.61. Effect of fossil fuel subsidy reduction on fossil fuel domestic reserves.

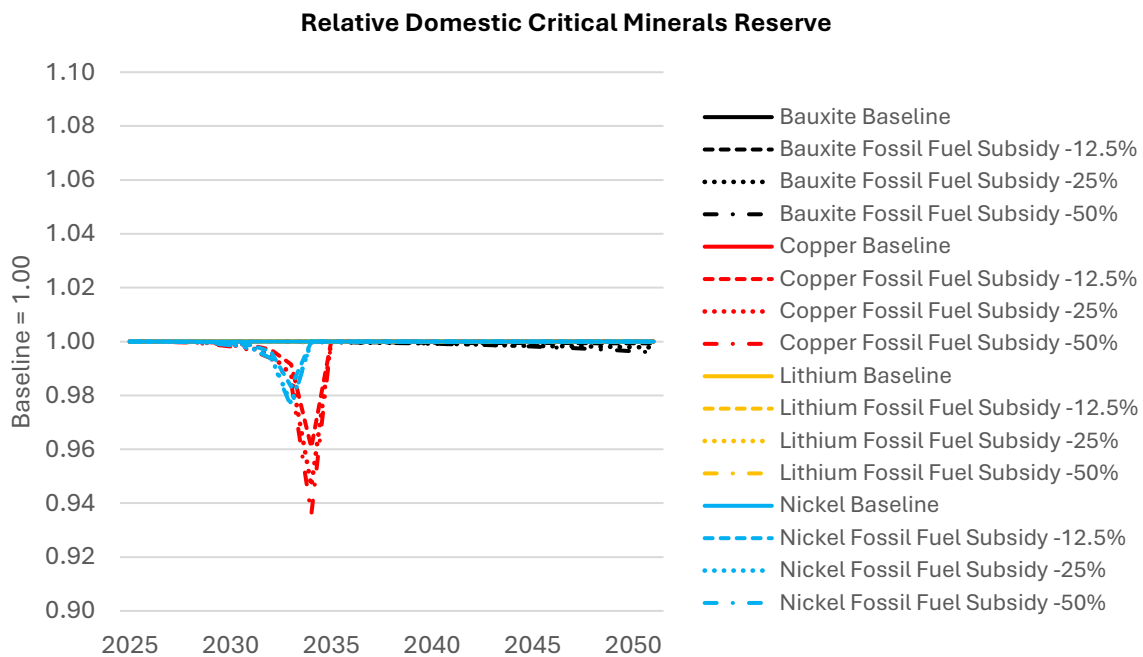


Figure 6.62. Effect of fossil fuel subsidy reduction critical minerals domestic reserves.

6.4.5. Depletion Premium

With the persistently intensive use of coal demonstrated under most of the policy discussed above (except for CFPP early retirement and ban), applying a depletion premium on coal could be beneficial both in reducing the use of CFPP and increasing the fiscal space. El Serafy formulated the depletion premium by incorporating the time to depletion – formulated as the time for the reserves to be depleted under the production rate of a resource in a given year, market price, and a discounting factor where lower values would result in higher premium³⁹⁰. Using that formulation, this section applies a depletion premium on coal using different three discounting factors: 25%, 5%, and 1%.

Implementing depletion premium on coal have a similar effect to implementing carbon tax, where it can be used to increase the fiscal space for electricity subsidy hence lowering its price as shown in Figure 6.64. This decrease in price leads to an increase in electricity demand, which then increases the total installed capacity in the power sector. Figure 6.63 shows that, without any restrictions on which technology to be adopted, both fossil-based and renewables power generation increase in size. However, RE increased slightly higher since CFPP now have an additional burden of paying the coal premium, hence lowering their economic benefit.

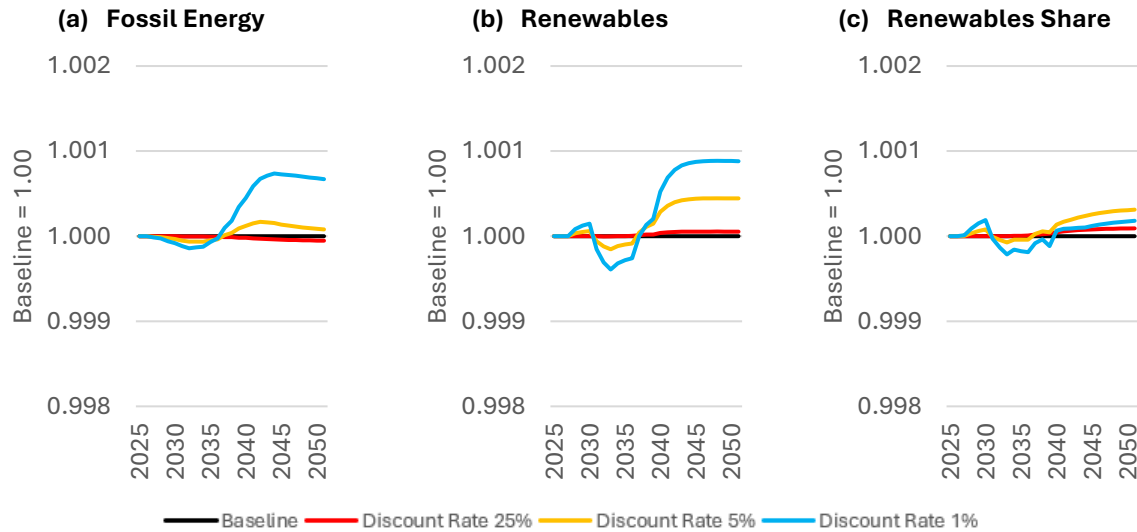


Figure 6.63. Effect of coal depletion premium on the power mix.

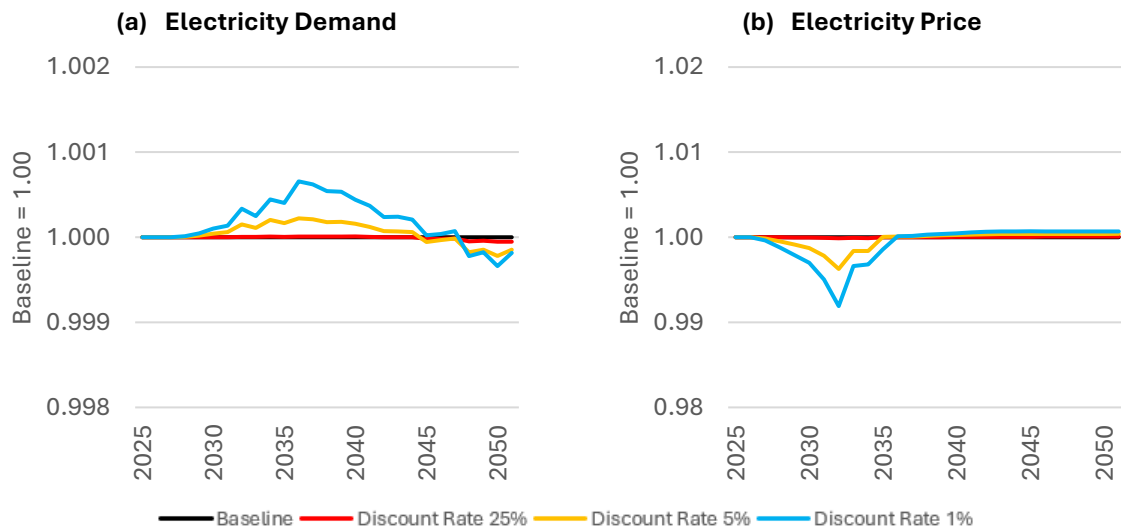


Figure 6.64. Electricity demand and price under different coal depletion premium.

From the economic perspective, the additional state revenue from the coal depletion premium could alleviate the state budget deficit. Unlike a carbon tax or fossil fuel subsidy reduction, the deficit does not approach the baseline when comparing Figure 6.65 with Figure 6.43 (for carbon tax) and Figure 6.54 (for fossil fuel subsidy reduction). This constant decrease in deficit from the baseline shows the advantage of the depletion premium over the two fiscal-expansion policies since the premium rate would increase following the increasing extraction of the resource. However, since the depletion premium is subject to the market price of the resources, imposing it on coal could only add smaller revenue because of coal's low price. The small

increase in state revenue has its benefit reflected on its effect on price level (see Figure 6.66). Although the price level still increases compared to the baseline, it is much lower than the effect of carbon tax or reducing fossil fuel subsidy because the government spending related to the increase in revenue would be less. As a result, the impact of coal depletion premium on real GDP growth is very small that it is negligible.

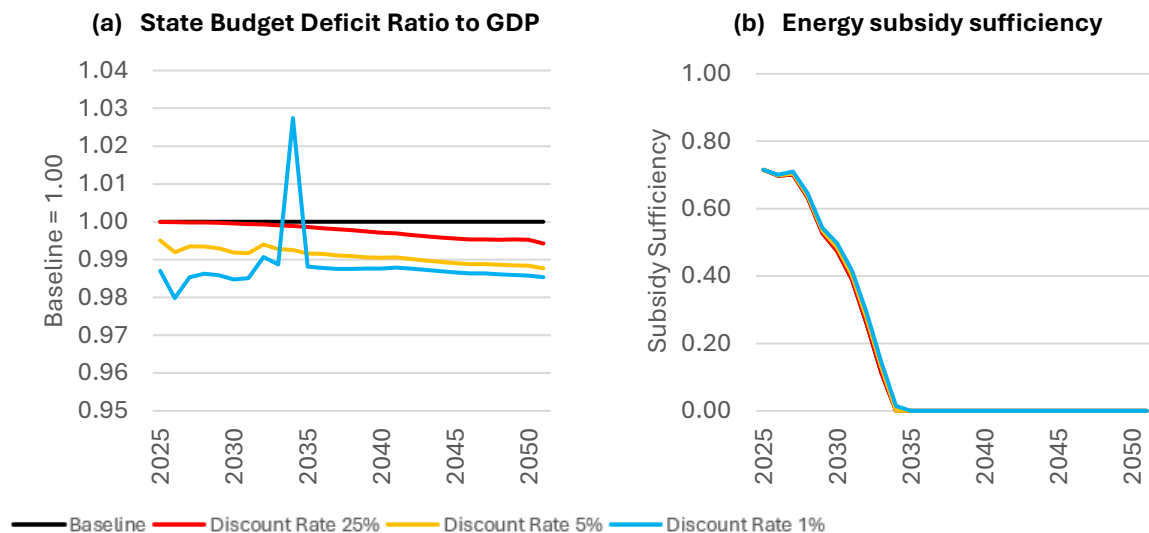


Figure 6.65. Effect of fossil fuel subsidy reduction on state budget deficit and energy subsidy sufficiency.

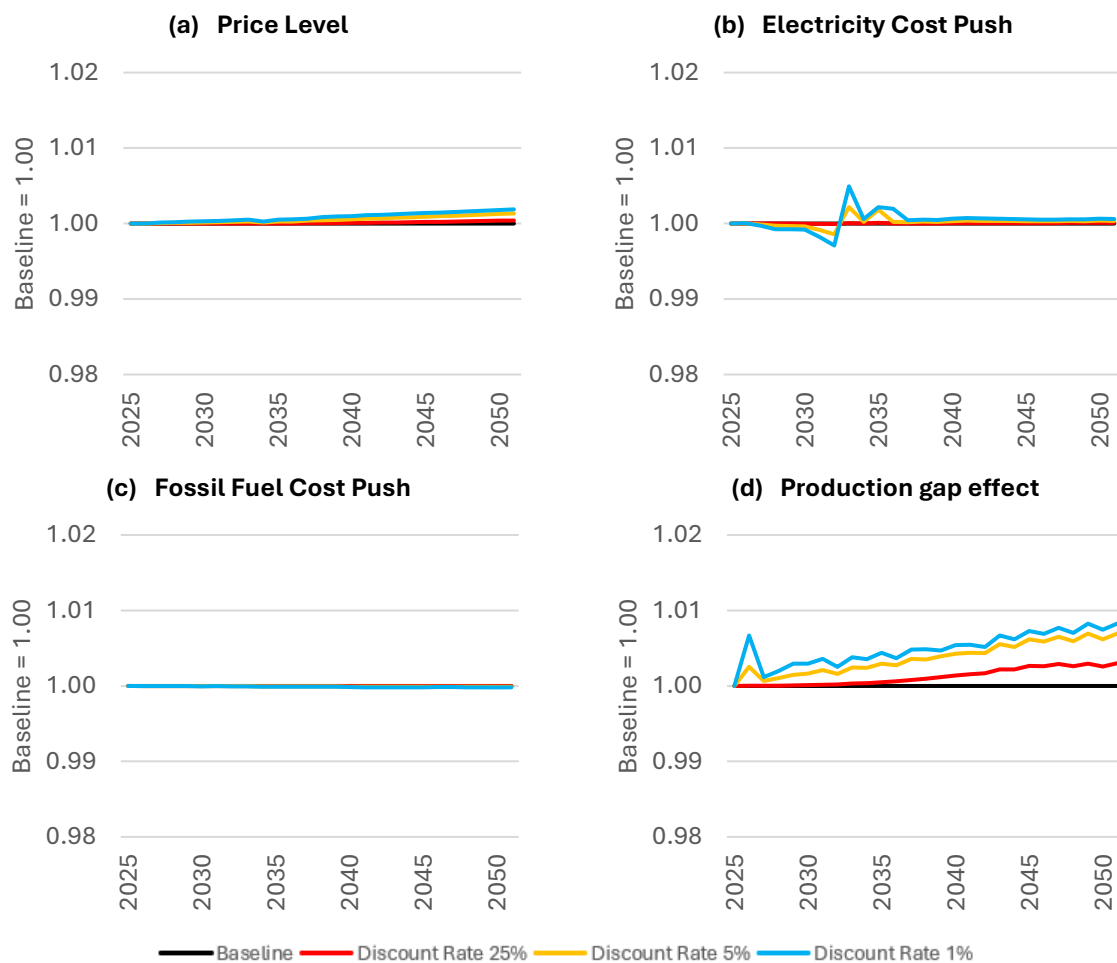


Figure 6.66. Effect of carbon tax on price level.

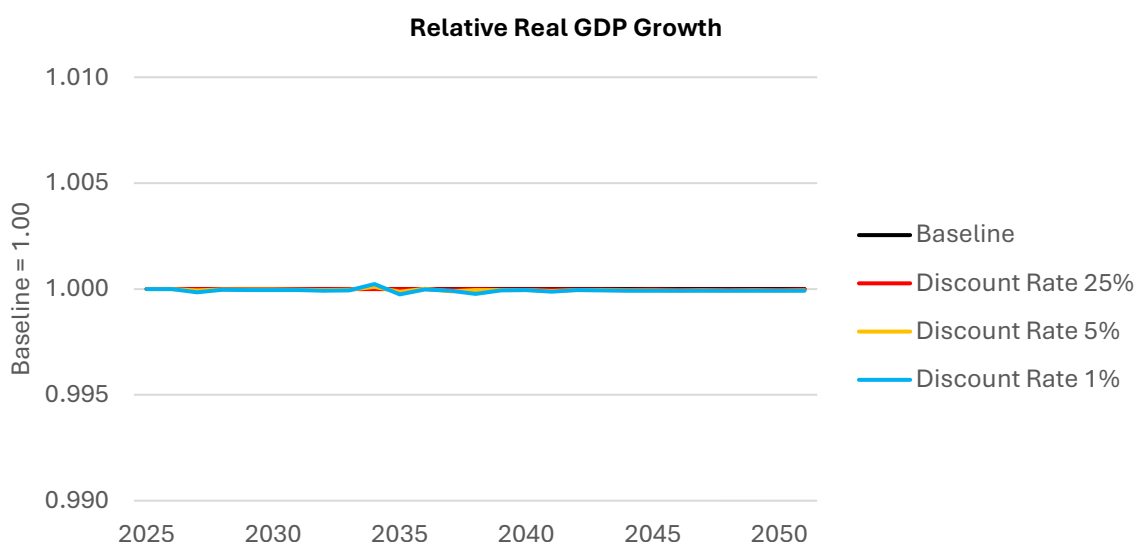
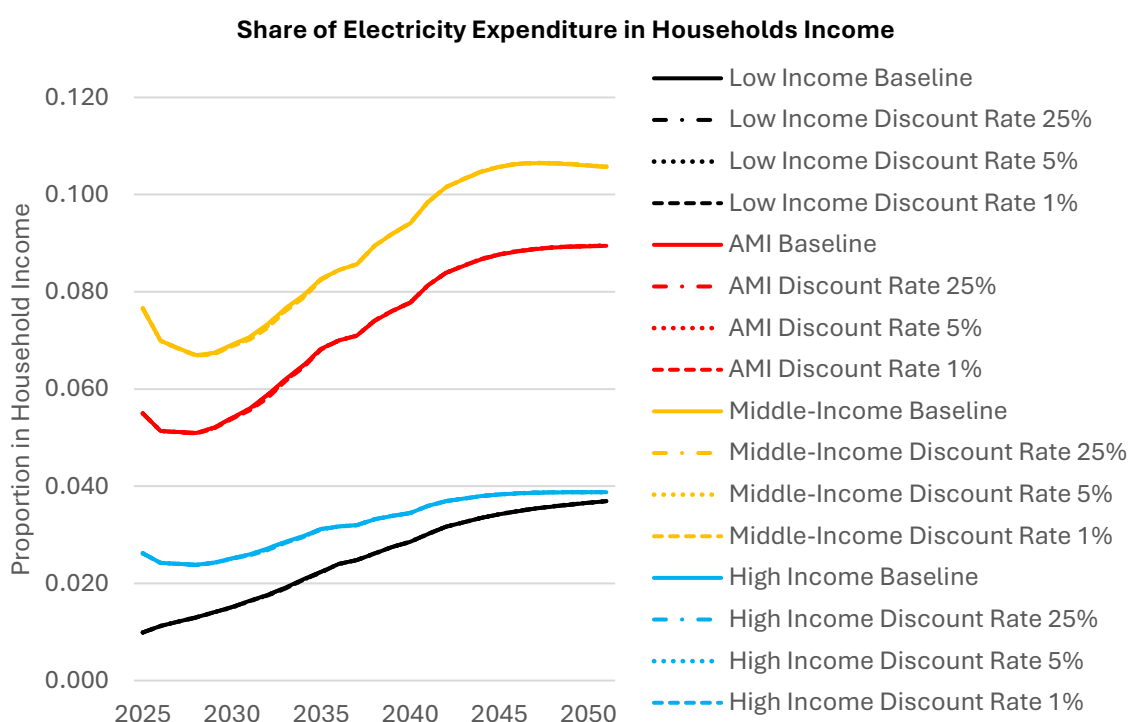


Figure 6.67. Effect of fossil fuel subsidy reduction on real GDP growth.

The effect of the coal depletion premium on social indicators is shown in Figure 6.68 and Figure 6.69. Since the decrease in electricity price is relatively small compared to the other policies, the effect on household expenditures is not significant (see Figure 6.68). Similarly, the effect on economy-wise jobs creation and unemployment is negligible (see Figure 6.69).



Note: AMI = Aspiring Middle-Income

Figure 6.68. Effect of fossil fuel subsidy reduction on household expenditure for electricity.

Figure 6.70 shows the effect of coal depletion premium on land use. The increase installed capacity due to increase in demand as explained earlier led to more land to be used for power plants and less land availability. As for resources consumption, implementing coal depletion premium was not shown to have a noticeable effect on coal reserves as presented in Figure

6.71, because it only led to a small change in the power mix. The impact on coal reserves is similar to the implementation of carbon tax, where the reserves showed a sinusoidal behaviour over time and for the same reason too. Similarly, the sudden increase in RE also led to the sharp extraction rate of minerals (see Figure 6.72).

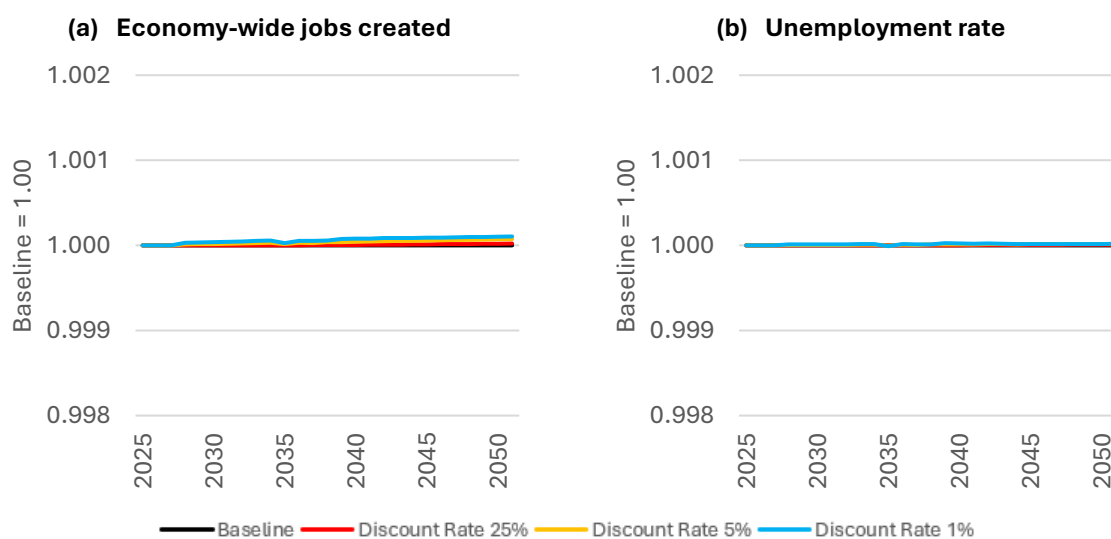


Figure 6.69. Effect of fossil fuel subsidy reduction on labour demand and unemployment rate.

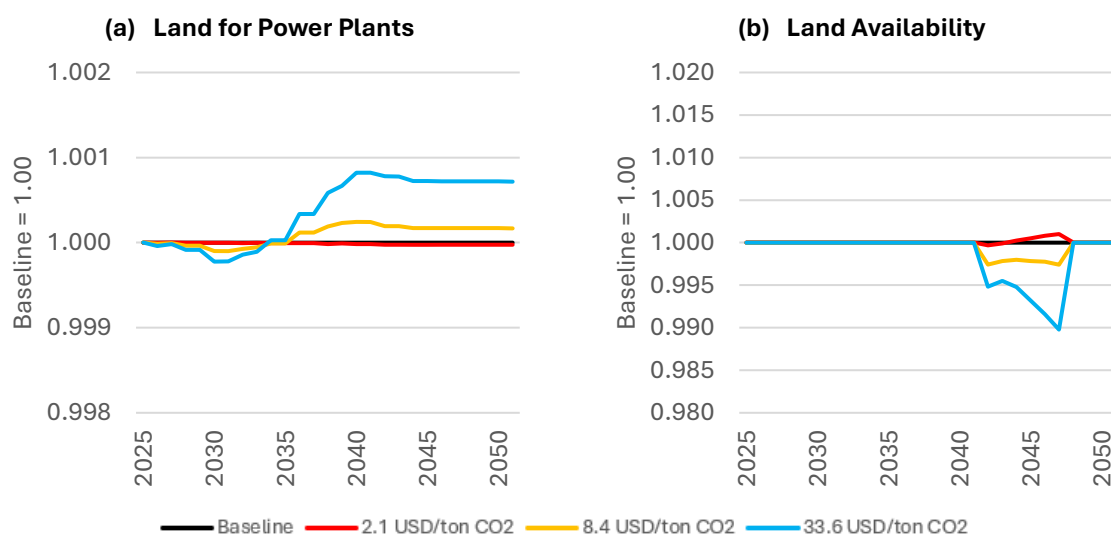


Figure 6.70. Effect of coal depletion premium on land use for power plants and land availability.

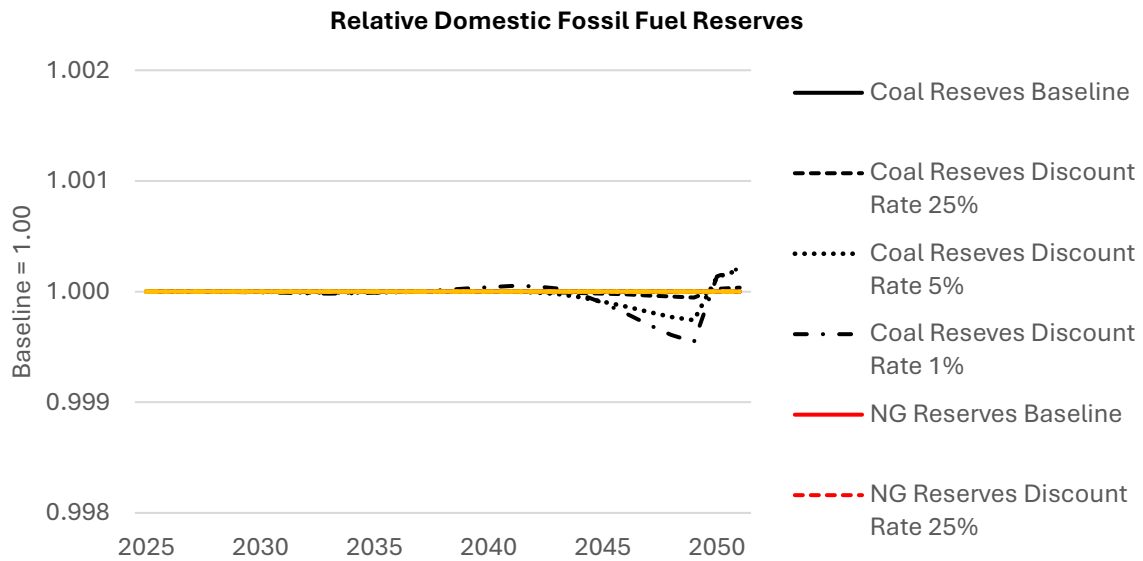


Figure 6.71. Effect of depletion premium on fossil fuel domestic reserves.

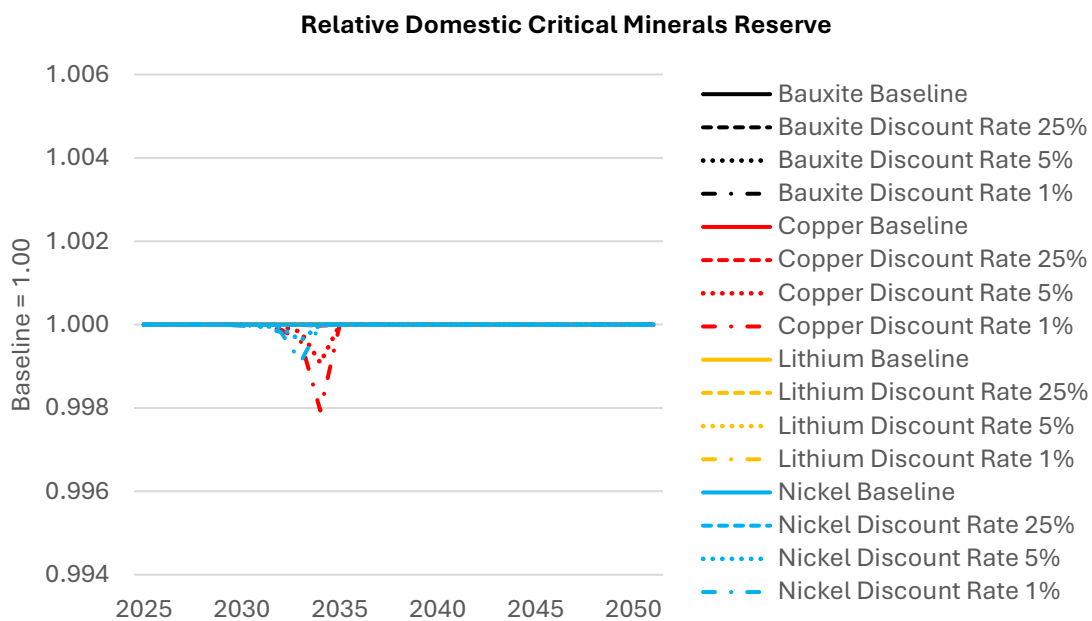


Figure 6.72. Effect of carbon tax on critical minerals domestic reserves.

6.5. Uncertainty Tests

From the policy tests, three uncertainties directly related to power sector were identified. First were the technology adoption weights which illustrate the characteristics of the power sector. Under the current weights, the power sector would have a higher tendency to continue its reliance on coal as exemplified in all the policy tests. Secondly, Section 6.4.4 specifically pointed out the role of renewables development which hinders the adoption of RE in the power sector. Lastly, the base run result in Section 6.3 mentioned the role of thermal efficiency in improving emissions in the power sector, which would also be affecting mean resource consumption and thus the other variables such as the adoption of fossil-based power generation.

Considering the instrumental role of power mix, the resulting electricity price and demand in the observed indicators, the uncertainty test will focus on its effect on the power mix. The full extent of its effect shall be explored in the Scenario Analysis (Section 6.6).

6.5.1. Risk tolerance

Under the baseline, the power sector can be described as having a relatively low tolerance for operational risk, putting high weights on economic and technological criteria. Even in the environmental criteria, they emphasized on resource availability which can also be considered operational risks. These characteristics have fuelled their adoption for CFPP which are the cheapest way to produce electricity and with relatively high reliability. In addition, coal is abundant in Indonesia making it less prone to resource unavailability. To explore the adoption pathway under a different risk tolerance, the weights are modified to describe a different like what have been done in previous chapters – particularly Chapter 3 and Chapter 4. The variation of the adoption criteria weights is presented in Table 6.3.

Table 6.3. Adoption drivers weights emulating risk-tolerance in the power sector

Adoption Criteria	Baseline (Low)	Balanced	High
Economic	0.384	0.250	0.192
Environmental	0.097	0.250	0.548
Resource availability	0.75	0.50	0.25
Emissions to air	0.25	0.50	0.75
Technological	0.228	0.250	0.114
Organizational	0.291	0.250	0.146

Figure 6.73 shows the effect of changing the risk tolerance in adopting power generation technologies in the power sector on the power mix. By emphasizing more on the external benefits of the technology, particularly emission to air, the share of fossil-based power generation would reduce quite significantly and giving room for RE to be adopted. Figure 6.74 showed that a higher risk tolerance resulted in lower electricity price. However, this could not disprove the initial understanding that the price of electricity would increase with the increase in RE. The decrease in price was the result of the increase in CFPP and GFPP replacing diesel power generation which are more costly to run. The share of CFPP could increase even higher under the high risk-tolerance, replacing GFPP which has a much lower resource availability. The lower GFPP in the high risk-tolerance setting led to higher RE adoption, which under its highest share around 2039 resulted in a higher electricity price. The subsequent decrease in electricity price was in fact due to the decrease in RE share and resulted in a continued increase in electricity demand. In addition, it must be noted that even under the highest risk tolerance, the RE share could only reach 22% in 2038 and decreased afterwards which indicates the insufficiency in relying on higher awareness of the environmental impact to achieve the 31% RE share by 2050.

Reflecting on the policy test results, the decreasing electricity price could lead to lower inflation and less stress on the state budget. It could also reduce burden on household expenditure and lead to less unemployment. But lower price level could also lead to less jobs created. In addition, the higher share of CFPP could lead to a higher emission. The effect of this uncertainty on the indicators will be discussed further in the scenario analysis.

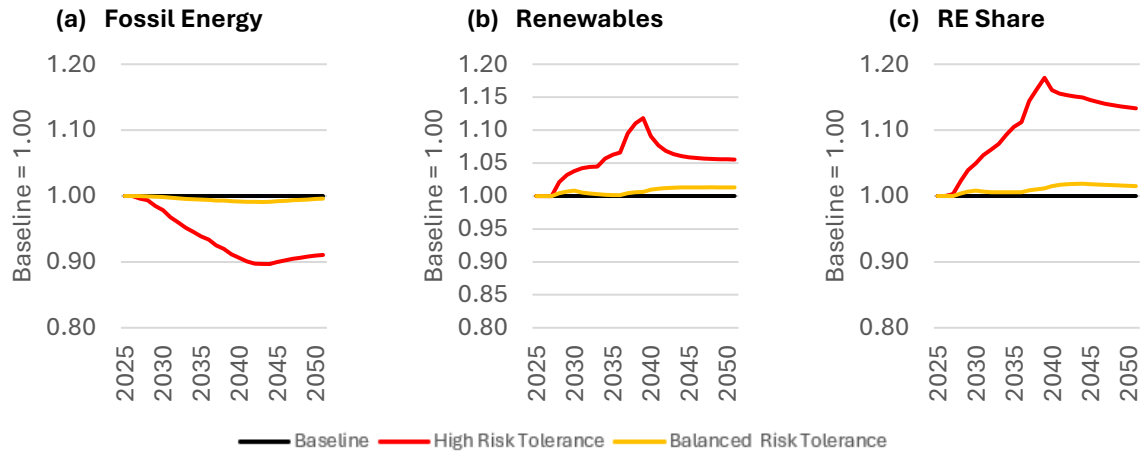


Figure 6.73. Effect of risk tolerance changes on the fossil energy and renewables share in the power mix.

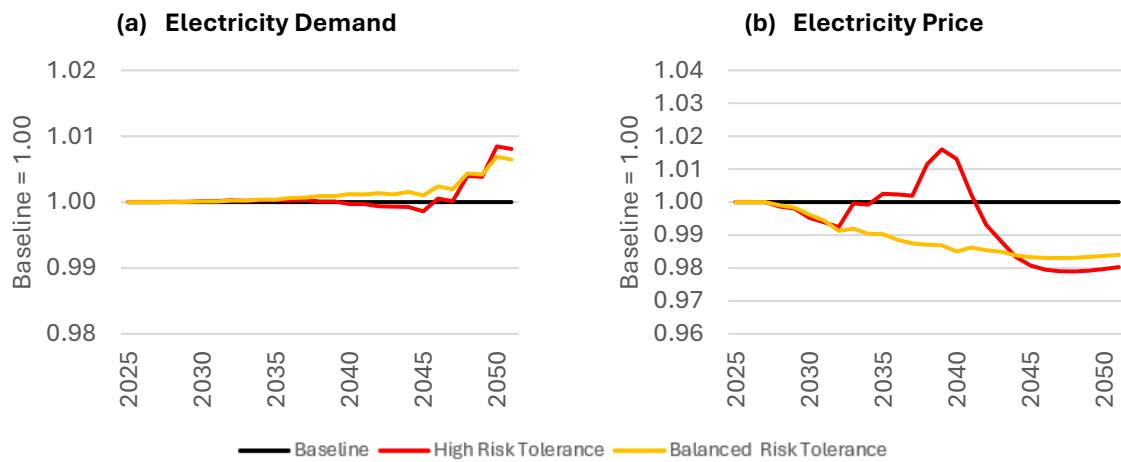


Figure 6.74. Electricity demand and price under different risk tolerance.

6.5.2. Renewable development rate

Adapting the resource exploitation model developed in Setiawan et al. for geothermal³⁰, uncertainties of renewable site evaluation lead time and success rates which control the exploitation success rate of these resources is used. These include economic factors for exploration, where if there is not enough assumed economic benefit, exploration will not be undertaken. The total success rate used in their work was 40%, which was derived from the success rate of exploration (50%) and exploitation (80%), and the total lead time is 4 years (2 years for exploration and 2 years for exploitation). For this study, a lower resource development success rate than the reference is used to account for the resources exploration profitability factor since it is not included the calculation. Table 6.4 shows the parameters value variation.

Table 6.4. Renewables and carbon storage potential development rate parameters

Parameters	Resources	Baseline	Fast development	Slow development
Success Rate (%)	Hydro	7.25	14.5	3.75
	Geothermal	5	10	2.5
	Bioenergy	20	40	10
	Solar	0.04	0.08	0.02
	Wind	0.08	0.16	0.04
	Carbon Storage	5	10	2.5
Lead Time (years)		4	2	8

Like the result in Chapter 5, Figure 6.75 shows that a faster renewable resources development resulted in a significant increase in RE share compared to the baseline. In addition, it led to continuous increase which answers the reason why in all the previous tests its share decreased despite an increase in electricity demand. With a slow development rate, the additional capacity requirement that could have gone to RE went to fossil-based power generation instead. However, with a higher share of RE, electricity price increases overtime leading to a lower electricity demand as presented in Figure 6.76.

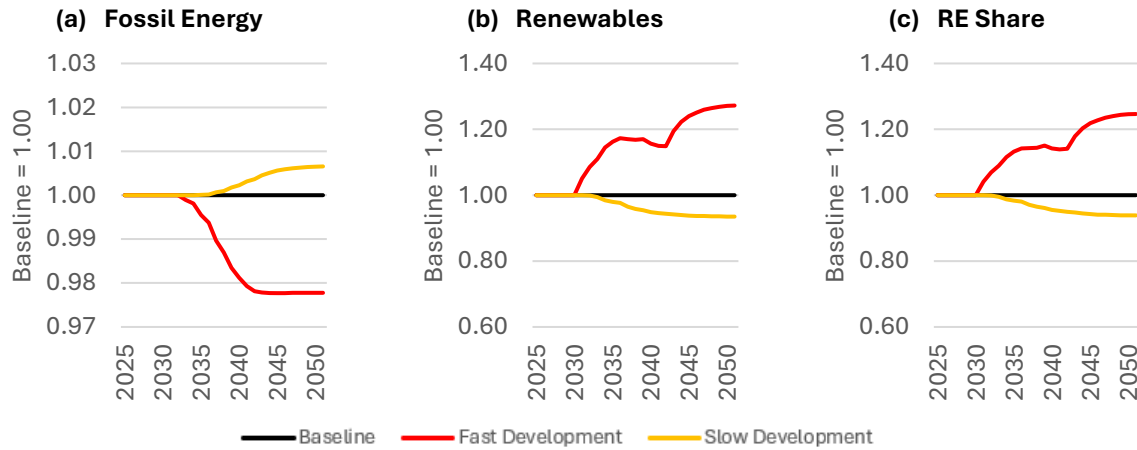


Figure 6.75. Effect of renewables development rate share in the power mix.

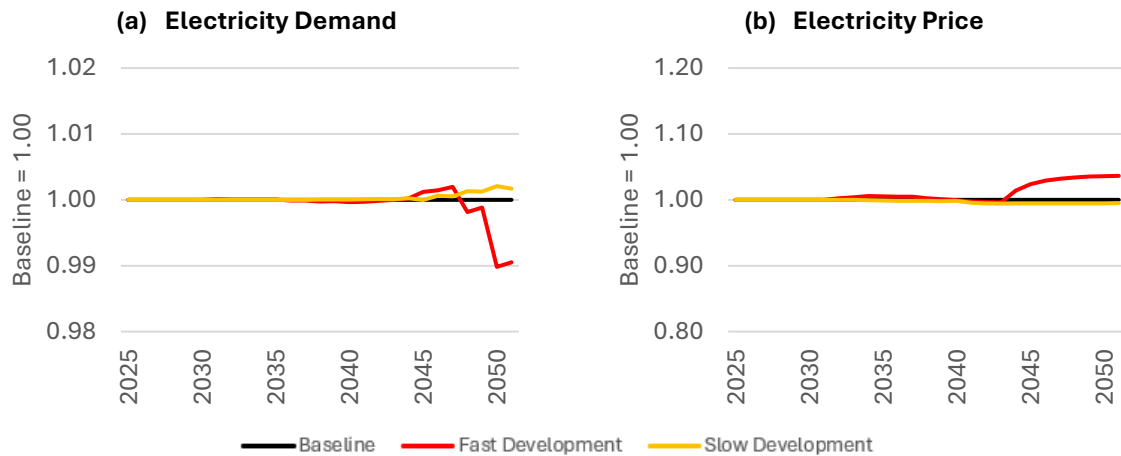


Figure 6.76. Electricity demand and price under different risk tolerance.

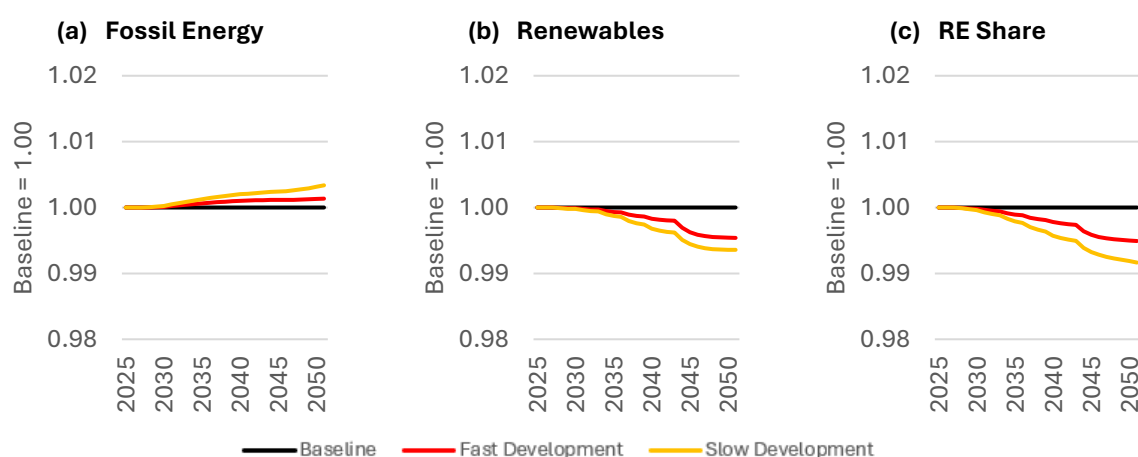
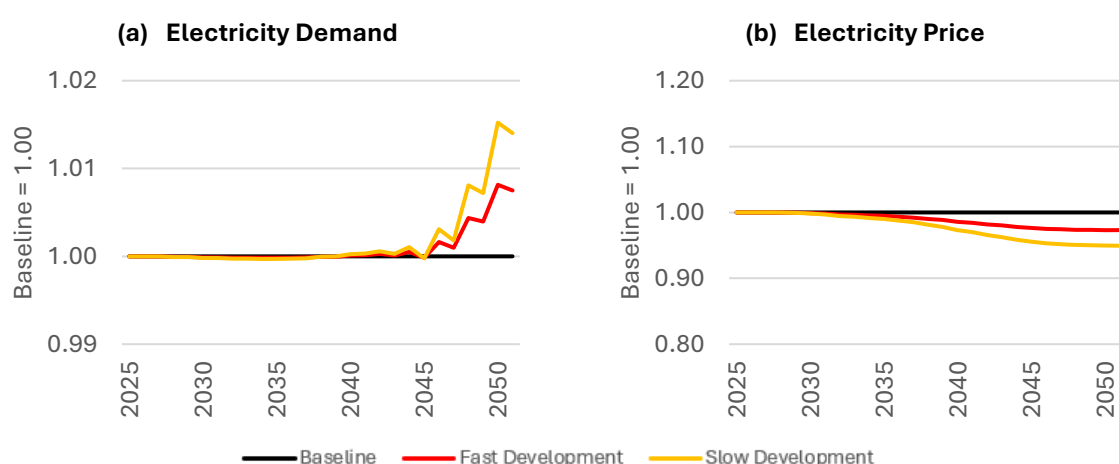
6.5.3. Thermal efficiency

Referring to Section 6.3.4, the thermal efficiency of fossil-based power generation is improving overtime. However, the limit to which it could improve to may also be higher than the baseline. In the baseline, the potential thermal efficiency for CFPP is assumed to be 40% which corresponds to the lower end of the USC power plant efficiency¹⁰. Since the highest reported efficiency for CFPP mentioned an efficiency higher than 47% using the A-USC power plants²⁵⁹, this research assumes a potential 50% efficiency for the highest case. As for GFPP, the efficiency can be improved to more than 60% using Combined-Cycle Gas Turbine (CCGT)³⁸² and with a potential to be improved further to 70%³⁸³. The average DPP efficiency is 20%-25%³⁸² but can be as high as 35%³⁸⁴ and can potentially reach 45% using Dual-Fuel Premixed Charge Compression Ignition technology (DF-PCCI)³⁸⁵.

Table 6.5. Values of potential thermal efficiency in the power sector under different uncertainty settings

Power Plants	Baseline	Moderate	Advanced
Coal-fired Power Plants	40%	45%	50%
Gas-fired Power Plants	45%	52.5%	70%
Diesel Power Plants	25%	35%	45%

Improving thermal efficiency of fossil-based power plants is shown to have a positive impact on electricity price (see Figure 6.78) at the expense of lower RE share as shown in Figure 6.77. Despite the setback on RE adoption, improving thermal efficiency could be more effective in reducing emissions compared to promoting RE through the market-based policies tested in Section 6.4. In addition, the lower electricity price would be beneficial economically and socially in terms of less burden on state budget and household expenditures. However, it would mean higher consumption of fossil resources which also should be avoided – although at a smaller rate due to the efficiency improvement. These assessments of the economic, social, and environmental indicators will be explored in detail in Section 6.6.

**Figure 6.77. Effect of renewables development rate share in the power mix.****Figure 6.78. Electricity demand and price under different risk tolerance.**

6.6. Scenario Analysis

The two previous sections explore the effects of implementing a policy one at a time on the power mix, electricity demand, and electricity price as well as specified economic, social, and environmental indicators. However, multiple policies are implemented at the same time, including on the demand-side. Thus, this section shall explore the effects of such combination occur simultaneously on the observed indicators.

Against the policy set in each scenario, two sets of uncertainties are applied. The first set is to emulate a disadvantageous situation and the other set an advantageous situation. In addition to the uncertainties in the power sector, the uncertainties in the demand-side are also incorporated in the same fashion reflecting on the results in the previous chapters. The value of each uncertainty is presented in Table 6.6.

Table 6.6. The values of the uncertainty parameters under different settings

Parameters	Advantageous	Disadvantageous
<u>Power Sector</u>		
Technology adoption risk tolerance	High	Low
Renewables development rate	Fast	Slow
Thermal efficiency		
CFPP	50%	40%
GFPP	70%	45%
DPP	45%	25%
<u>Residential Sector</u>		
Home appliances potential power rate improvement	-20%	+20%
<u>Transportation Sector</u>		
Battery potential energy density	350 Wh/kg	144 Wh/kg
Technology adoption characteristics	Economic < Environmental	Economic > Environmental
Public transportation development delay	0%	74%
Fossil energy price	Low oil & gas supply	High oil & gas supply
ICE tank-to-wheel potential efficiency	+50%	+25%
<u>Industrial Sector</u>		
Technology adoption risk tolerance	High	Low
Maximum hydrogen injection rate	100%	10%

6.6.1. National Energy Plan Scenario (NEP)

This first scenario is built upon the general directives in the National Energy Plan (NEP) and its subsequent regulations. The NEP mentions the implementation of FIT as part of the GOI effort to increase RE adoption¹⁰, although the FIT rate was not defined under this plan and is ultimately not provided under the Presidential Regulation No. 112/2022. The NEP also adds carbon tax implementation which is then realized under the Decree No. 7/2021. While depletion premium was mentioned in NEP, but to date it has not been regulated. On the other hand, there is no mention of the ban or early retirement of CFPP in NEP, but the roadmap for the policy is under review³⁹¹.

On the demand-side, the NEP includes the plan to increase the adoption of rooftop solar in the residential sectors but only through building permit not incentives. In addition, incentives for electric stoves are provided for the low-income and aspiring-middle-income to reduce LPG subsidy burden on the state budget. For the transportation sector, the NEP includes the plan for both BEV adoption and shift to public transport. However, the support for BEV is more accentuated with a clear regulation addressed for its adoption, for example to Minister of Finance Regulation No. 38/2023 regarding VAT incentive and Government Regulation No. 74 of 2021 regarding Luxury Tax incentive. On the other hand, public transportation expansion is relatively overlooked without a clear pathway for its development. While the electrification policy in the residential and transportation sector has been addressed, the NEP did not include

such policy for the industrial sector. Instead, the energy policy for that sector is more towards the resources allocation particularly fossil fuels which is like the baseline assumption. The policy parameter values are presented in Table 6.7.

Table 6.7. The values of the uncertainty parameters in the NEP scenario

Parameters	Scenario Value
Supply-side policy	
FIT	Baseline
Carbon tax	2.1 USD/ton
CFPP early retirement and ban	Ban and early retirement in 25 years
Fossil fuel subsidy	No reduction
Depletion premium	Not applied
Demand-side policy	
<u>Residential Sector</u>	
Rooftop solar incentives	0%
Electric stoves	Low Income = 100%
	Aspiring Middle-Income = 50%
	Middle-Income = 0%
	High-Income = 0%
Support for access to 2200VA power	No
LPG incentives reduction	No changes
<u>Transportation Sector</u>	
BEV incentives	100%
ICEV Sales Ban	Not Applied
Biofuel Land Availability Restriction	0%
Public transportation Expansion factor	2.5%
Public transportation expansion frequency	Every 8 years

The NEP scenario power mix simulation result is presented in Figure 6.79. The early retirement and ban for additional CFPP increases the share of RE significantly. The share of RE is further amplified when the renewables development is faster than the baseline, showing again its significance. However, the high RE share led to a higher electricity price as shown in Figure 6.80. The increase in electricity price was shown to be lowered when under the disadvantageous situation which corresponds to the lowest share of RE. However, the higher share of RE does not automatically increase the grid electricity price as exemplified by the comparison between the base uncertainty (red line) and the advantageous uncertainty (blue line) results. While the share of RE in the advantageous case is higher than the base case, the electricity price can be maintained at the same level because of the improvement in the fossil-based generations thermal efficiency. The RE share in the NEP policy could range between 20-29% at its highest point but could eventually decrease, constrained by economic capacity and resource availability.

The rising electricity price under the NEP policy decreases electricity demand. The higher electricity price led to the decrease in electricity demand in the transportation sector due to the 2% lower share of BEV. In the residential sector, the higher electricity price also decreased grid electricity demand due to lower adoption of electric stove – despite the incentives given – and the higher rooftop solar adoption. However, the most structurally affected by the increase in electricity price is the industrial sector. For example, the cement industry’s grid electricity demand decreased the most – almost halved – under the NEP policy which is the result of lower adoption of electrified production pathway, lower grid electricity sourcing, and lower overall

demand due to increase in price level and production cost. In 2050, the cement industry's demand was reduced by around 30% as the result of the NEP policy.

In addition to price, the uncertainty parameters also affect the electricity demand significantly. Despite the electricity price under the advantageous case being almost the same as the base case, the electricity demand is around 20% lower. The electricity demand in the residential and transportation sectors could be reduced due to the improvement in efficiency. More importantly in the transportation sector, the zero delay in public transportation development intensifies the shift to public transport which reduces the share of BEV significantly to 18% in 2050. In the industrial sector, while previously cement industry was the one affected the most, in this case the non-ferrous metals industry is the one that reduces their grid electricity demand the most since they can also access a higher efficiency thermal power plant like the power sector.

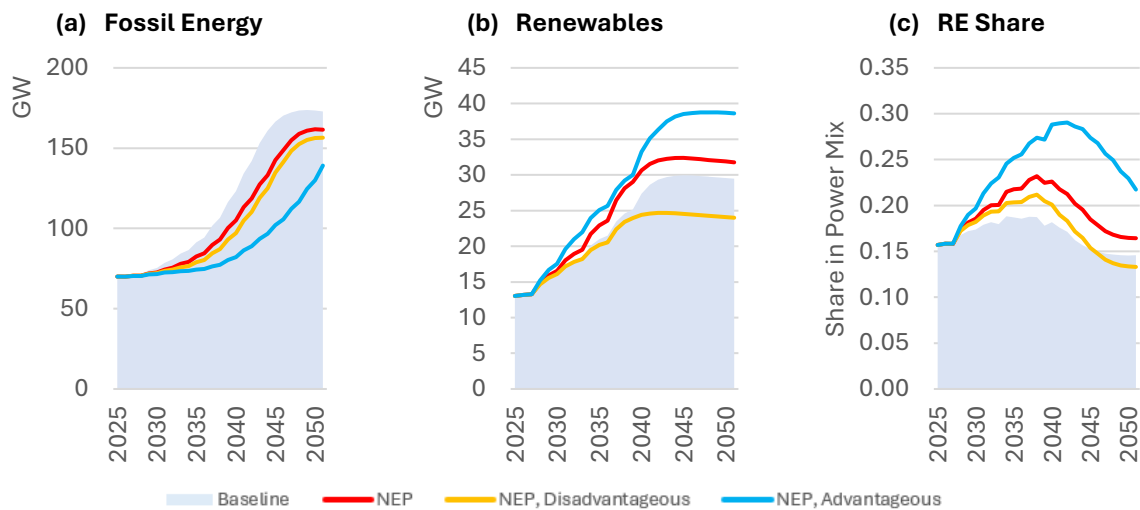


Figure 6.79. Fossil energy and renewables share in the power mix under the NEP scenario.

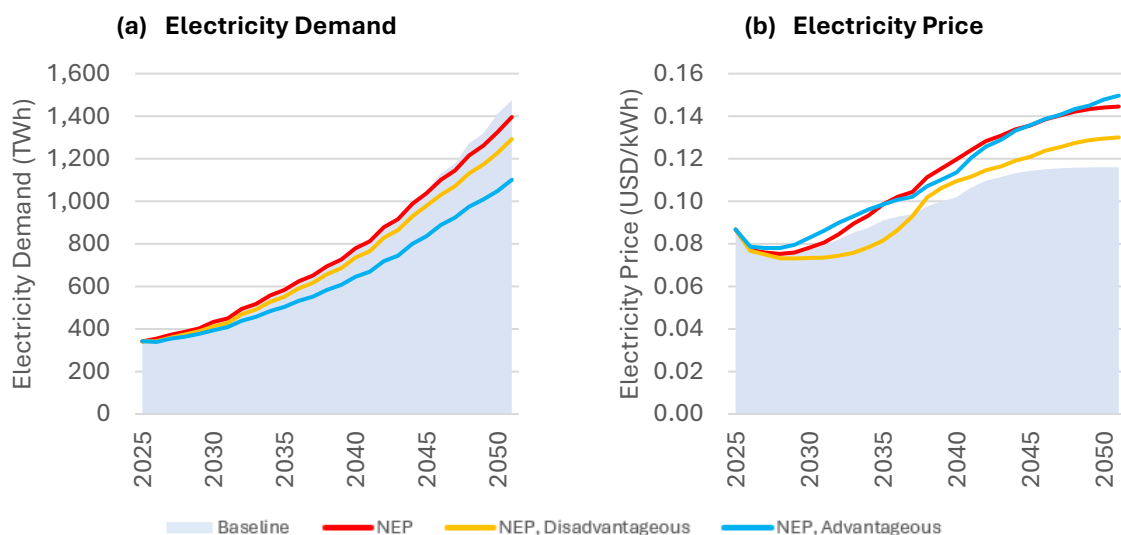


Figure 6.80. Electricity demand and price under the NEP scenario.

The results of the electricity price increase in the NEP policy on the economic indicators are presented in Figure 6.81 through Figure 6.83. The rising electricity price from the NEP policy led to a higher price level as shown in Figure 6.82. Looking into each driver, it is clear that the effect of electricity price increases overtime. However, the price level could be lower than the

baseline despite the increasing electricity price under the disadvantage case where the cost of fossil fuel is lower – indicating the continued dominance of fossil fuel in the economy. This situation is also favourable for the state budget since the subsidy for the fossil fuel would also be lower (see Figure 6.81). The larger fiscal space for energy subsidy can then be used to aid electricity price which was sufficient to lower it from the baseline between 2025 to 2037 as shown in Figure 6.80. In general, the disadvantageous situation could also lead to higher real GDP growth than the baseline, while the NEP policy without the low fossil fuel price could result in slightly lower real GDP growth.

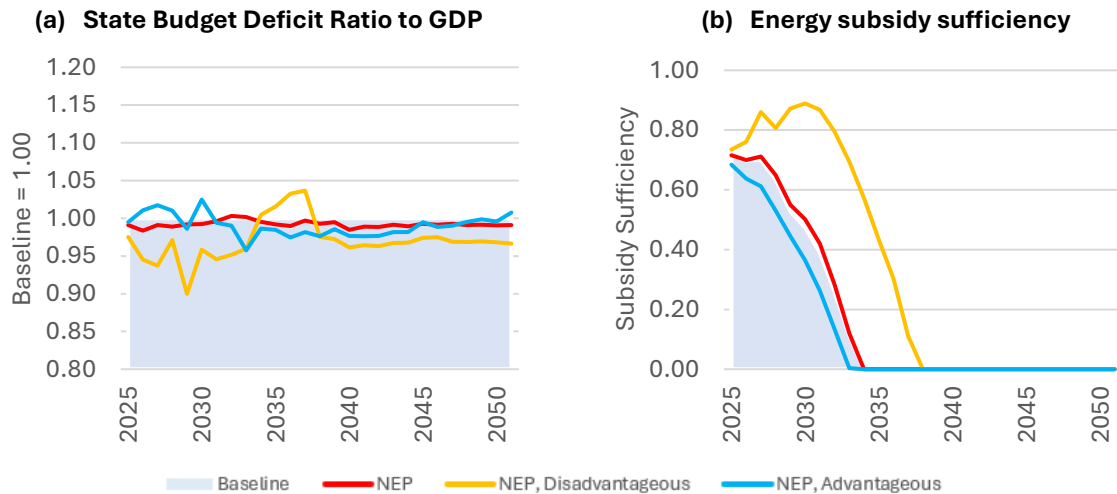


Figure 6.81. Effect of NEP policy on state budget deficit and energy subsidy sufficiency.

Figure 6.84 The increase in household expenditure for electricity in the NEP policy would depend on their income level. As with previous results, the aspiring middle-income and middle-income households are the ones who could be most affected by the rise in electricity price since both groups have a relatively large electricity expenditure, but their income level is modest. In 2050, the NEP policy could cause their expenditure for electricity to increase by 24.5% and 23.7%, respectively. Note that the increase has not accounted for other energy expenditure, namely LPG. Combined the share of energy expenditure in their household income could be close to 20%, which could lead them to reduce their overall consumption in the economy. The increase in electricity price which pushed an increase in price level could temporarily increase job creation, but unemployment still increases at the same year as shown in Figure 6.85. In the long run, the NEP policy does not have a significant effect on unemployment where it hovers around the baseline value.

The increasing share of RE in the NEP policy led to a lower emission in the power sector as shown in Figure 6.86, although there was an increase in CO₂ emissions until 2045. The deciding factor is the thermal power plant efficiency – as exemplified in the advantageous case – and electricity demand – as exemplified by the disadvantageous case – which could lower CO₂ emissions directly.

In terms of land use, the NEP policy may eventually require more land for power plants as depicted by Figure 6.87 due to the higher share of RE, particularly for bioenergy, solar, and wind. Only at a disadvantageous case could the land use for power plants be lower than the baseline because of the lower demand and lower RE. Nonetheless, the advantageous case could lead to a higher land availability because of the tank-to-wheel efficiency of the ICE engine in the transportation sector which reduces the consumption of biofuels.

Figure 6.88 shows the implication of the less consumption of coal in the power sector, which would decrease the need for coal exploration and thus for reserves in general. As for mineral resources, the increased adoption of BEV in the transportation sector and RE in the power sector could reduce its physical stock. However, should the delay in developing public transport network be minimized as prescribed in the advantageous uncertainty, the extraction of the minerals could be greatly reduced and resulting in more resources in quantity as shown in Figure 6.89.

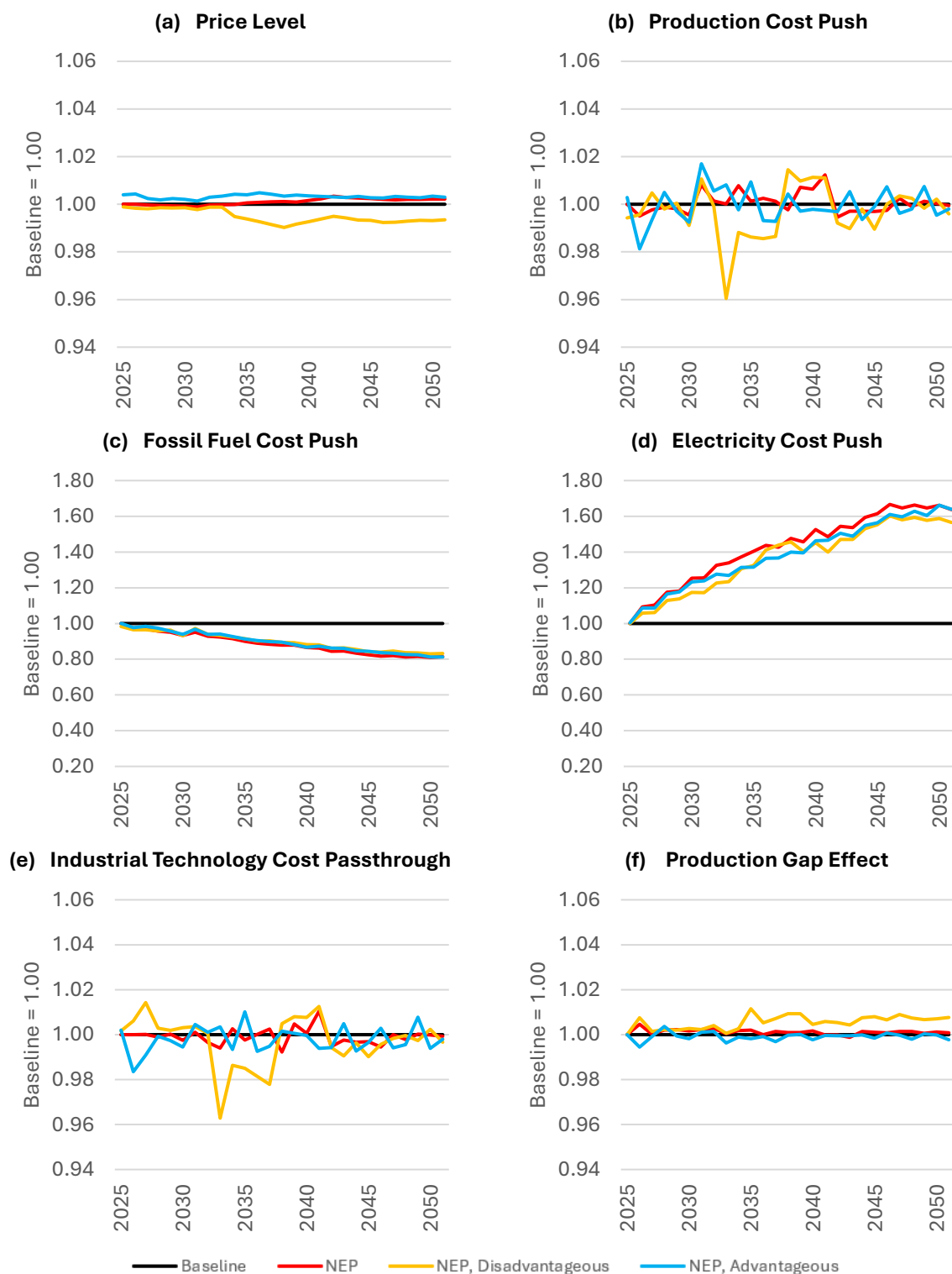


Figure 6.82. Effect of NEP policy on price level

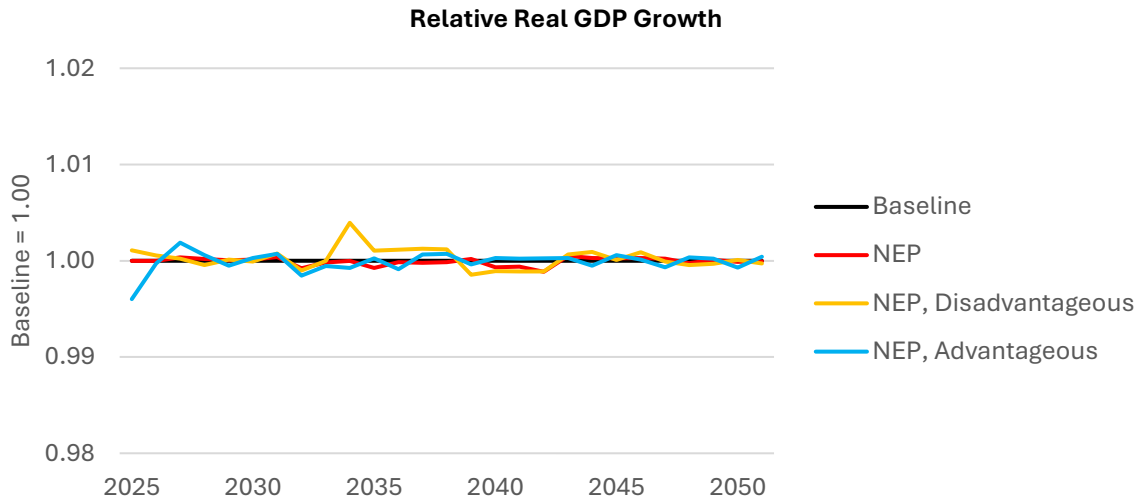
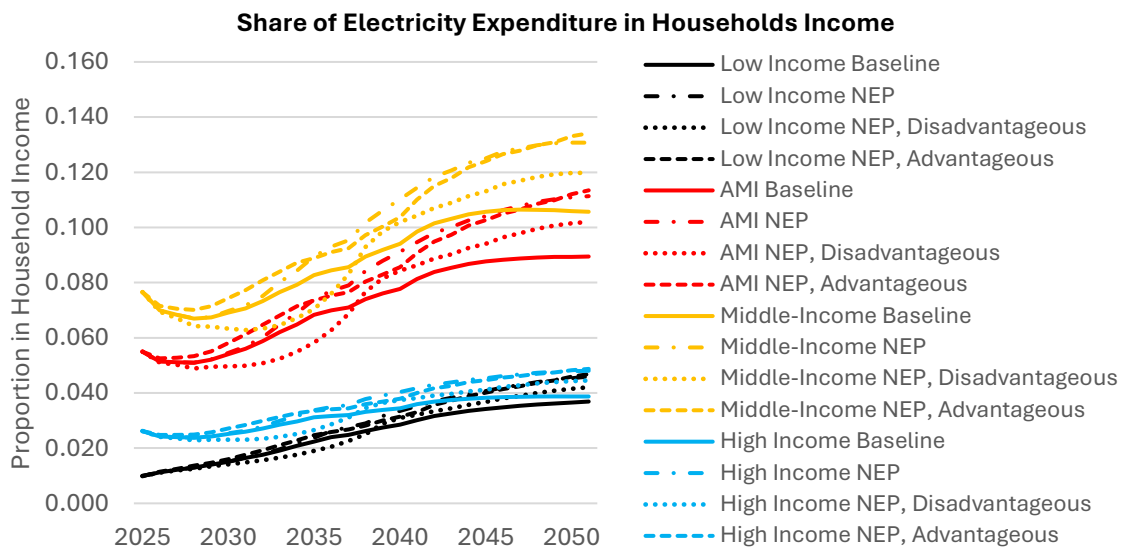


Figure 6.83. Effect of NEP policy on real GDP growth.



Note: AMI = Aspiring Middle-Income

Figure 6.84. Effect of NEP policy on household expenditure for electricity.

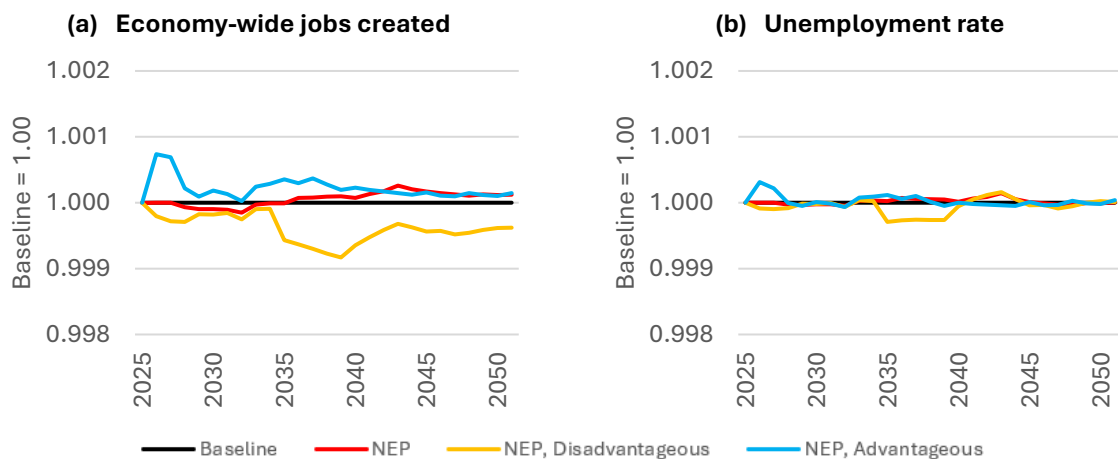


Figure 6.85. Effect of NEP policy on labour demand and unemployment rate.

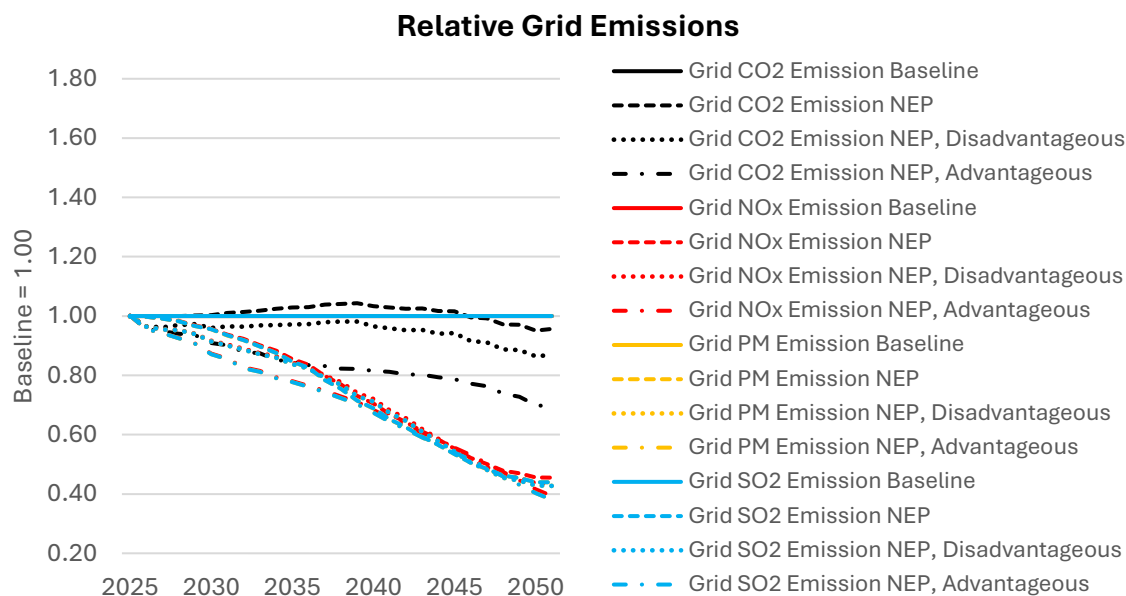


Figure 6.86. Effect of NEP policy on emissions from the power sector.

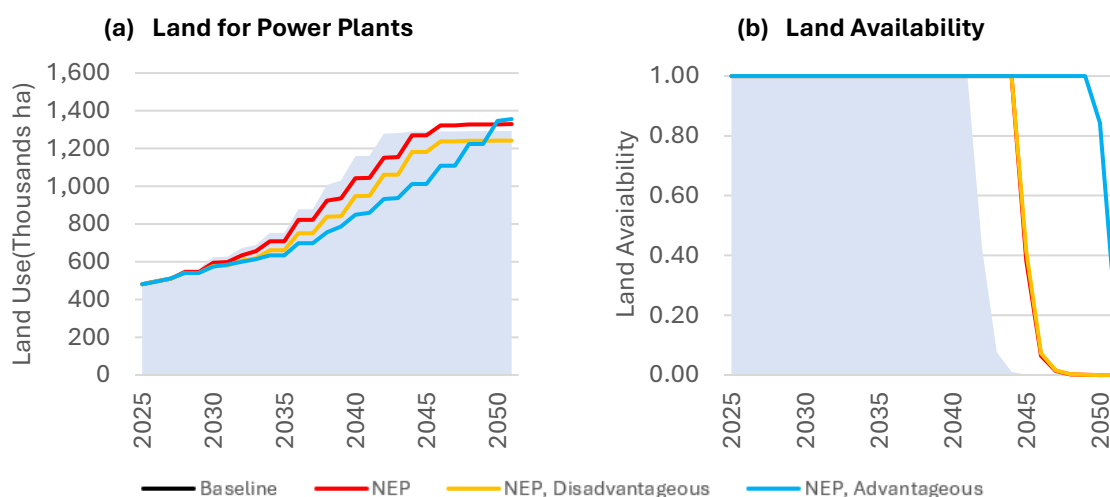


Figure 6.87. Effect of NEP policy on land use for power plants and land availability.

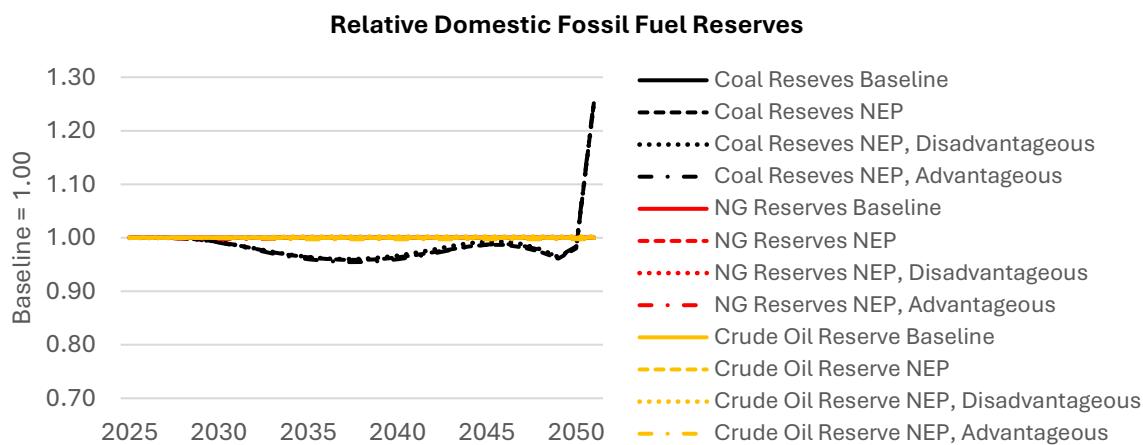


Figure 6.88. Effect of NEP policy on fossil fuel domestic reserves.

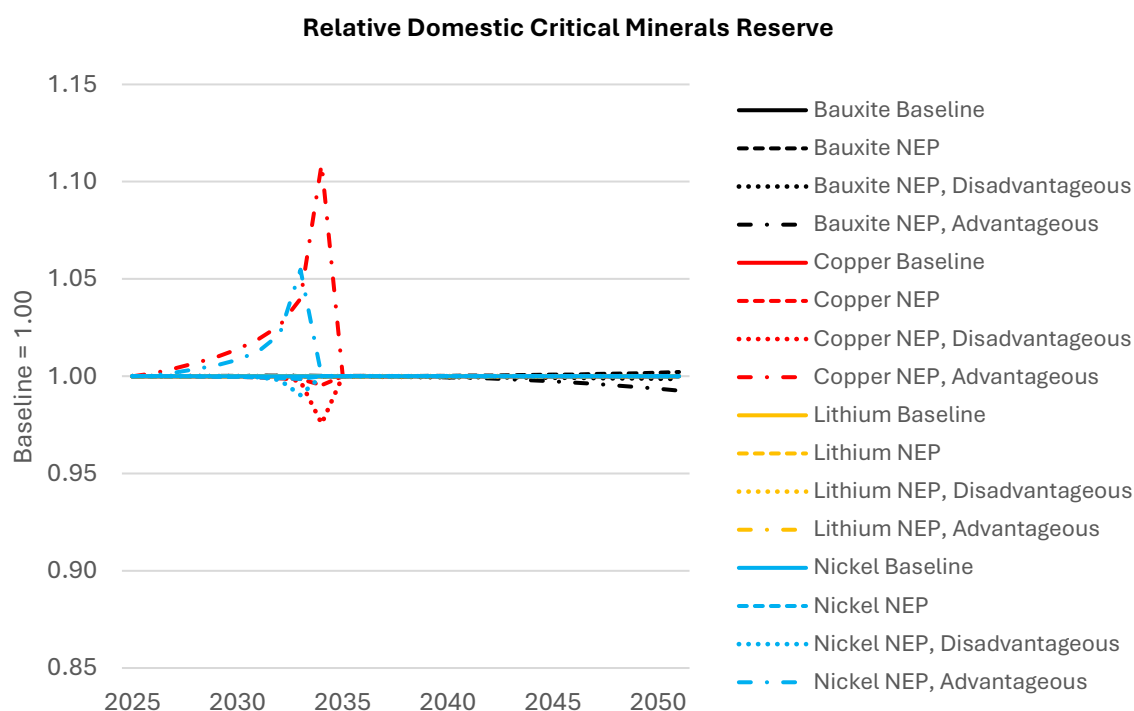


Figure 6.89. Effect of NEP policy on critical minerals domestic reserves.

6.6.2. Green Technology Utopia Scenario (GTU)

In this scenario, the GOI looks to attain the highest possible green technology adoption in both the power sector and the demand sector. The power sector is aimed to have a high adoption of renewables in their power mix while the residential sector is tasked with increasing the switch to electric stoves as well as rooftop solar. The transportation sector aims to maximize their BEV adoption by implementing a ban on ICEV starting from 2040 based on the Zero Emission Vehicles Declaration³⁹² in addition to implementing the Improve-focused policy set explained in Chapter 3's scenario analysis (see Table 3.2). In doing so, the government power sector increases the FIT in the power sector and applying the recommended carbon tax. In addition, the GOI plans an early retirement of CFPP which is to be completed within 5 years and to ban future any kind of CFPP to be installed. To ensure the state budget is sufficient to support the policies, the fossil fuel subsidy is reduced. Specifically for LPG, the government set its subsidy based on the energy subsidy budget sufficiency to both reduce state budget burden and push the adoption of electric stoves. Depletion premium is not yet applied in this scenario. The policy parameter values are presented in Table 6.8.

The more ambitious energy transition policy in the GTU scenario increased the share of RE in the power mix. Figure 6.90 shows that the RE share could reach increase 26.2% in 2038, which is higher than compared to NEP scenario (23.2%). However, the RE share eventually reached the same plateau with the NEP scenario at around 29% in 2042 due to the resource availability constraint if the rate of renewables development is twice than the baseline. When the renewables development rate is lagging as in the disadvantageous case, the RE share could instead be lower than the baseline towards the end of the simulation.

One of the consequences of the higher RE share is a higher electricity price, as shown in Figure 6.91 which could be between 33% to 57% higher than the baseline depending on the uncertainties. With the policies in the GTU scenario implemented, the demand for electricity

increased significantly despite the increase in electricity price because of the aggressive adoption of BEV which share could reach 51% in 2050. However, like the previous scenario, the BEV share could significantly drop – in this case to 35% – if the public transportation development delay could be minimized and the tank-to-wheel efficiency of hybrid vehicles is improved. In addition, the electricity consumption in the residential sector could also increase significantly due to the massive adoption of electric stoves.

Table 6.8. The values of the uncertainty parameters in the GTU scenario

Parameters	Scenario Value
Supply-side policy	
FIT	+50%
Carbon tax	33.6 USD/ton
CFPP early retirement and ban	Ban with early retirement in 5 years
Fossil fuel subsidy	-50%
Depletion premium	Not applied
Demand-side policy	
<u>Residential Sector</u>	
Rooftop solar incentives	100%
Electric stoves	100%
Support for access to 2200VA power	100%
LPG incentives	-50%, subject to budget sufficiency
<u>Transportation Sector</u>	
BEV incentives	100%
ICEV sales ban	Starting 2035
Biofuel Land Availability Restriction	0%
Public transportation Expansion factor	2.5%
Public transportation expansion frequency	Every 8 years

The effect of electricity price due to the higher RE share on demand could be observed in the industrial sector whose consumption decreased 4%. However, the higher RE share also increased the electrified production pathway adoption in the industrial sector, leading to higher electricity demand compared to in the NEP policy which demand decreased 11% because of the implemented policies in that scenario.

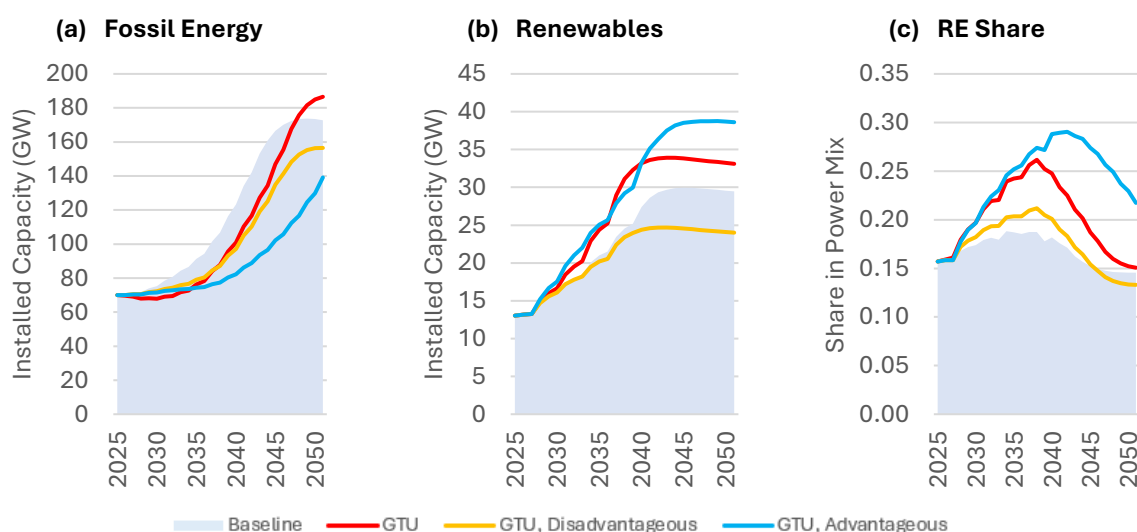


Figure 6.90. Fossil energy and renewables share in the power mix under the GTU scenario.

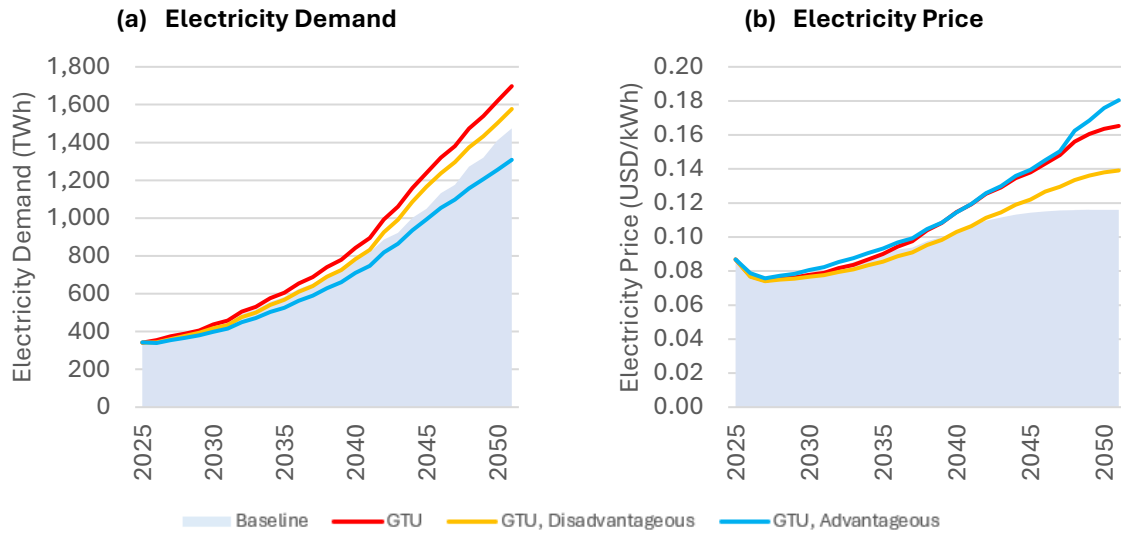


Figure 6.91. Electricity demand and price under the GTU scenario.

As with the NEP policy, the GTU policy is shown to have a positive impact on the state budget and subsequently the energy subsidy sufficiency as can be seen in Figure 6.92. However, the effect is greater because of the reduced subsidy for the fossil fuels in addition to the higher carbon tax rate. The effect of the GTU policy on the state budget deficit ratio is driven mostly by the reduction of fossil fuel subsidy as can be compared with the result in Figure 6.65. The difference between the GTU policy and only applying fossil fuel subsidy reduction is that the state budget deficit is not approaching the baseline because of the additional state revenue from carbon tax and depletion premium. The LPG subsidy is also now subject to budget sufficiency, hence increasing the fiscal space.

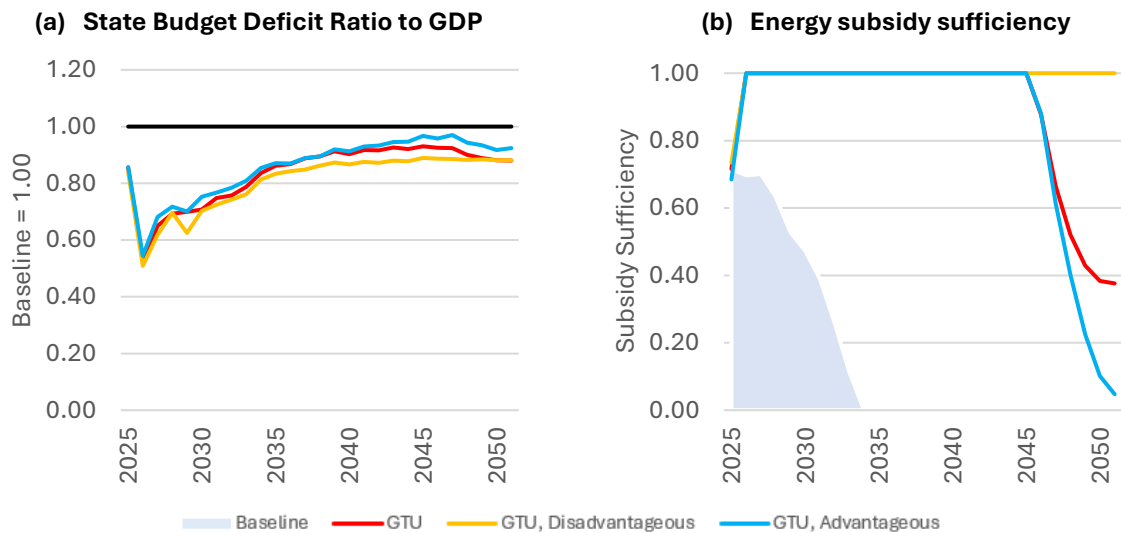


Figure 6.92. Effect of GTU policy on state budget deficit and energy subsidy sufficiency.

While the effect of the GTU policy on the state budget is favourable, it could lead to a constantly increasing price level compared to the baseline. Even when compared to the NEP policy, the increase in price level could be much higher. At its highest point, the increase in price level in the NEP policy was 0.5% higher than the baseline and then decreased to 0.3% at the end of simulation. In case of the GTU policy, the price level could be 2.5% and the gap to the baseline continues to increase. The reason for the continuous increase compared to the baseline is attributable to the increase in electricity price. In addition, the increased state

revenue from carbon tax and depletion premiums means an increase on government spending as explained in Sections 6.4.3 and 6.4.5. The impact of the policy can be subdued when the price of fossil fuel – particularly crude oil – is lower than the baseline as demonstrated by the disadvantageous case (shown as yellow lines in Figure 6.93). In the end, the higher inflation leads to lower real GDP growth as shown in Figure 6.94.

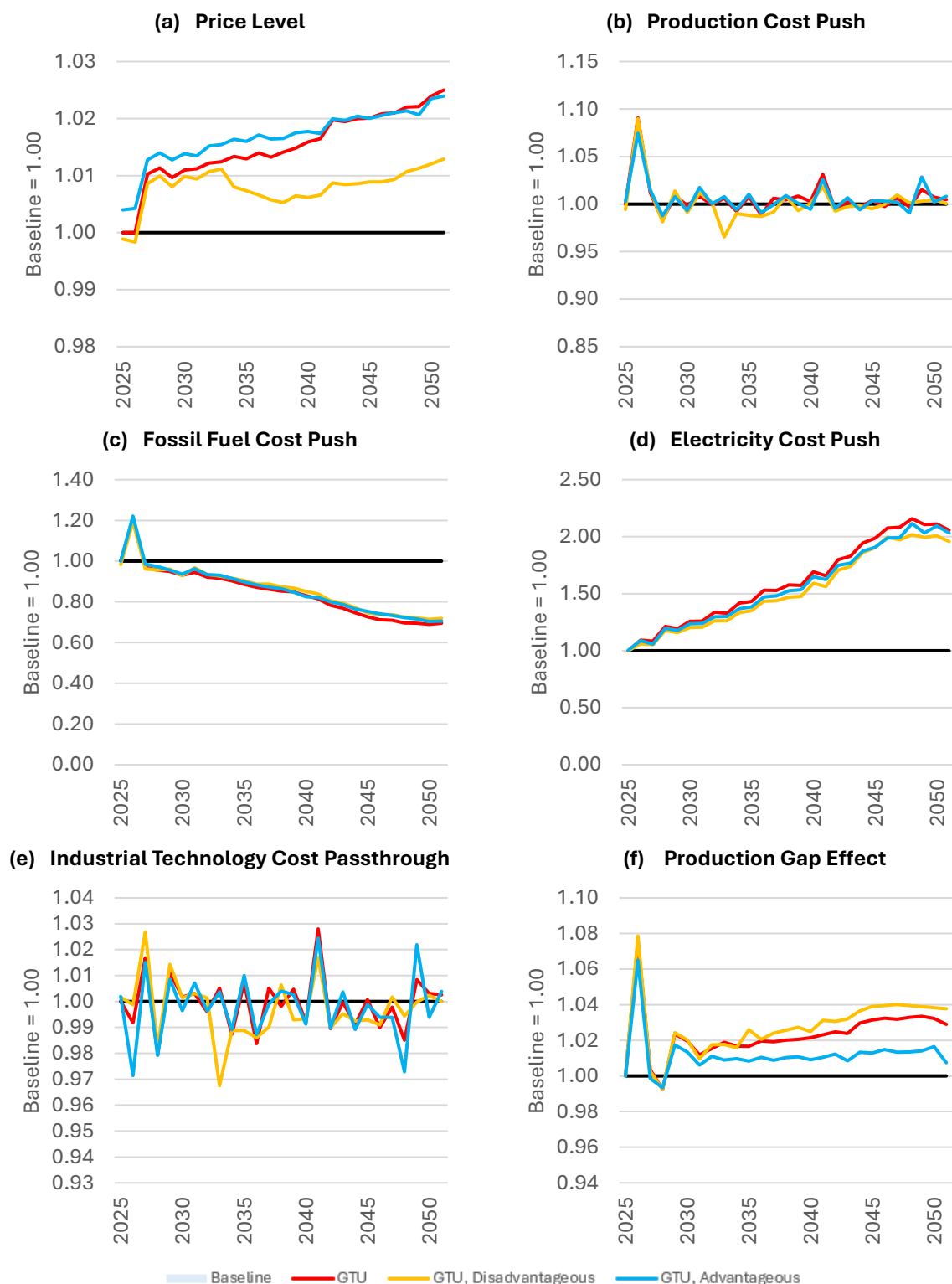


Figure 6.93. Effect of GTU policy on price level.

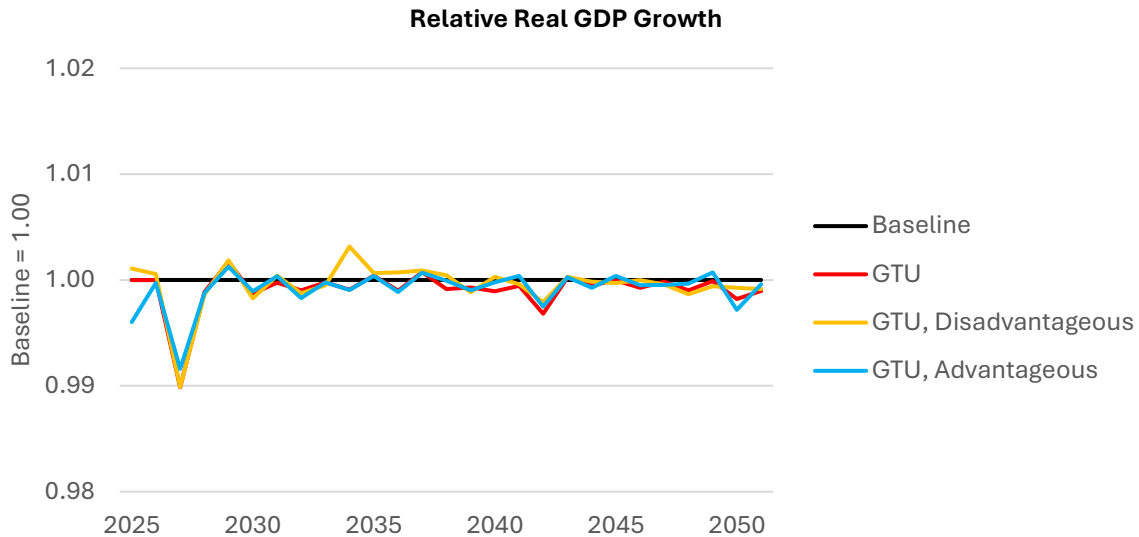
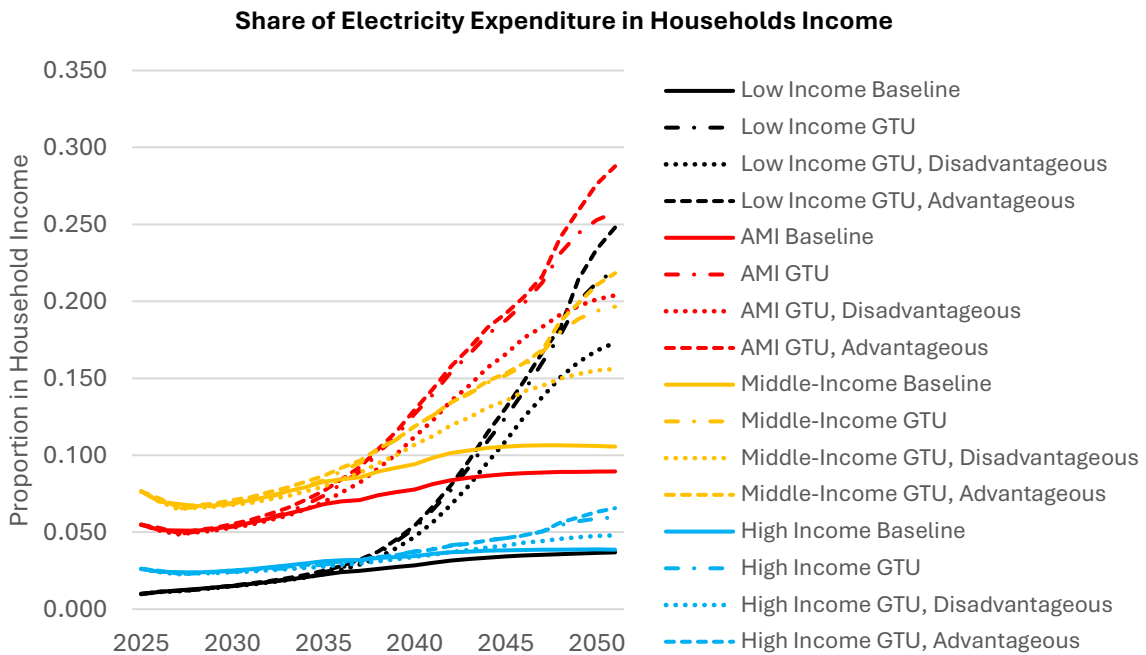


Figure 6.94. Effect of GTU policy on real GDP growth.

The GTU policy effect on household expenditure on electricity can be considered harmful. Figure 6.95 shows that while in the NEP policy aspiring middle-income and middle-income households are the one most affected, in the GTU policy low-income households had to suffer the most since their electricity expenditure increased from only around 3.7% to between 17.3% and 24.8%. The significant increase in electricity expenditure is due to the increased adoption of electric stoves and electricity price at the same time. As a result, the low-income households' expenditure for energy jumped from 7.2% to 22.6%. At the national level, the implementation of GTU policy is also not beneficial. While it could increase job creation, the 'natural' unemployment rate could be increased due to the higher layoff rates as shown in Figure 6.96.



Note: AMI = Aspiring Middle-Income

Figure 6.95. Effect of GTU policy on household expenditure for electricity.

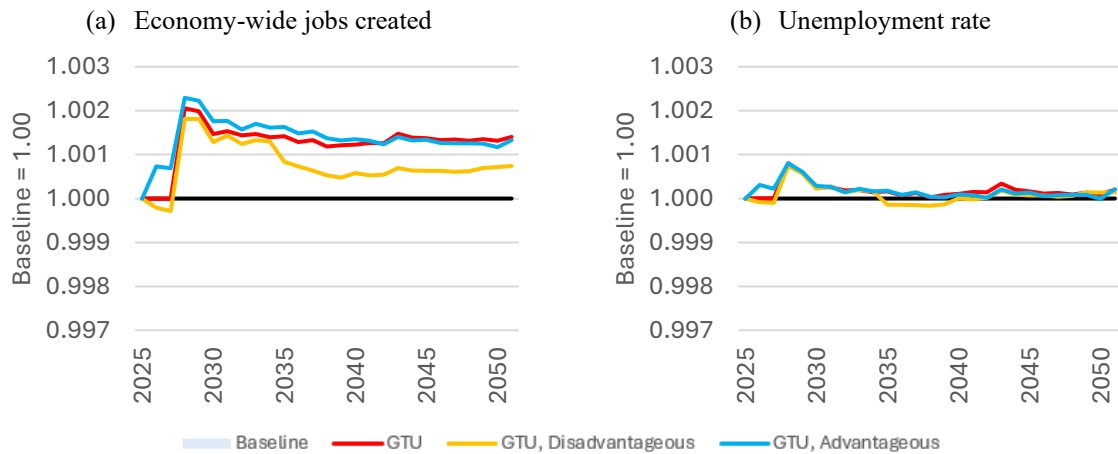


Figure 6.96. Effect of NEP policy on labour demand and unemployment rate.

The increased electricity demand as the effect of the GTU policy could lead to a higher CO₂ emission from the baseline (see Figure 6.97). The increased demand is exacerbated by the increase in bioenergy power generation which has a higher CO₂ emission factor even compared to coal. Only under the advantageous uncertainty can the carbon emissions be lower than the baseline, owing to improvements in fossil-based power generation thermal efficiency and lower electricity demand due to less BEV adoption in the transportation sector.

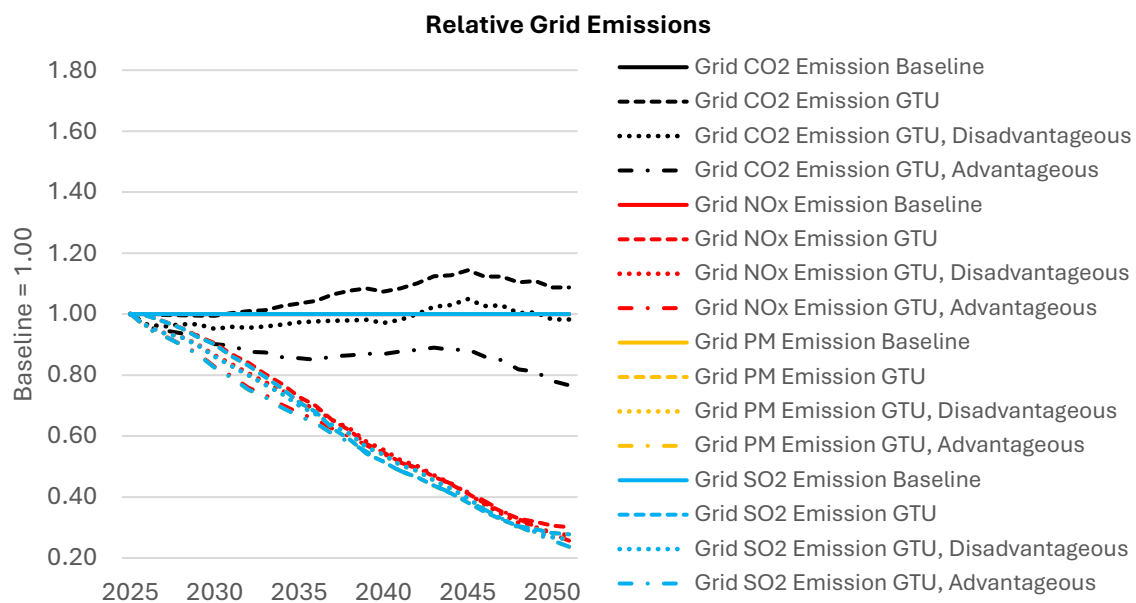


Figure 6.97. Effect of GTU policy on emissions from the power sector.

The land-use for power plants generally follows the changes in electricity demand, except when RE share is higher due to the increased adoption of bioenergy power generations. On the other hand, the increased adoption of BEV due to the ban of ICEV in the transportation sector also reduces biofuel consumption which increases overall land availability as shown in Figure 6.98.

Figure 6.100 shows that the higher adoption of BEV, however, could increase the extraction of critical minerals as can be observed by the decreasing resources of bauxite. While copper and nickel are equally intensively used for BEV, their physical stock could have been completely depleted by 2035 even under the baseline simulation which explains the indifference in the

result with the GTU policy implementation. Meanwhile, coal reserves could be lower than the baseline due to less consumption (see Figure 6.99).

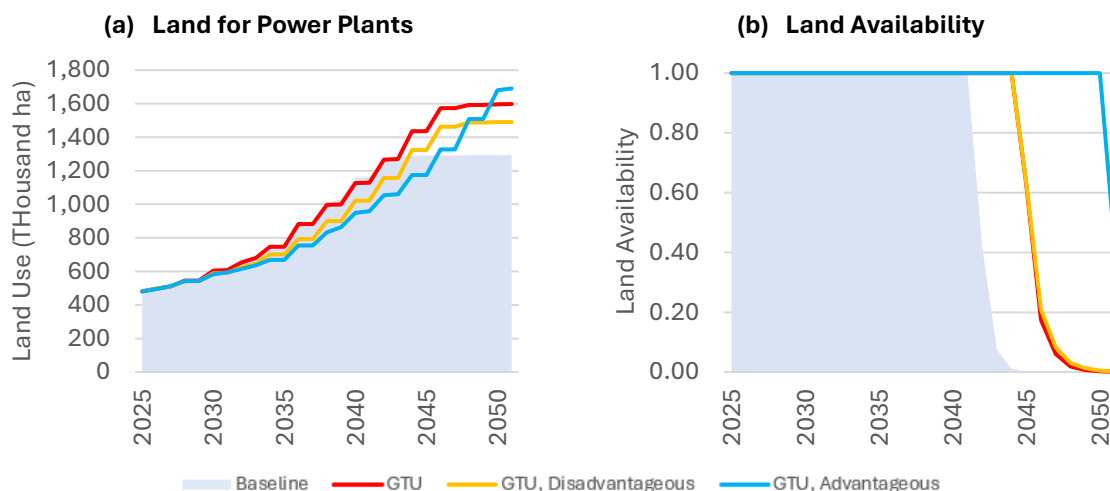


Figure 6.98. Effect of GTU policy on land use for power plants and land availability.

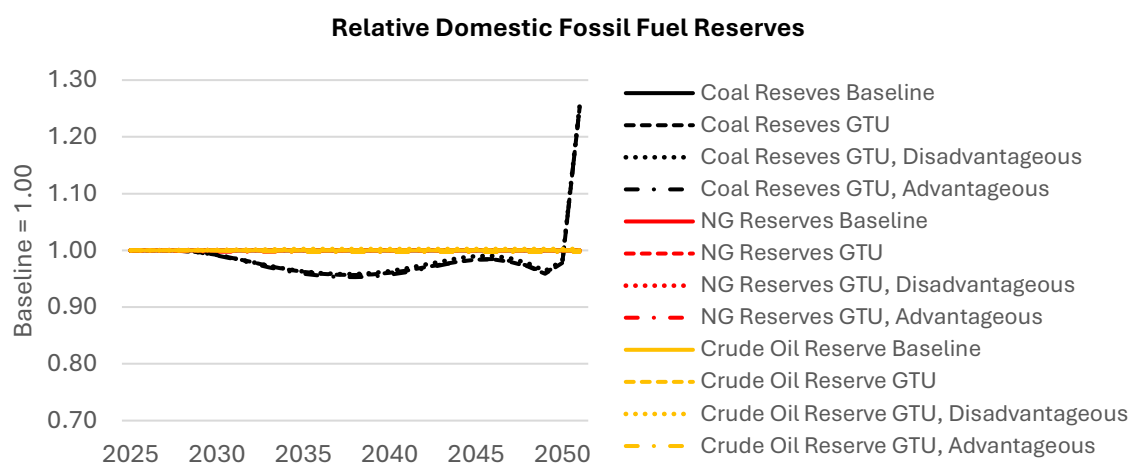


Figure 6.99. Effect of GTU policy on fossil fuel domestic reserves.

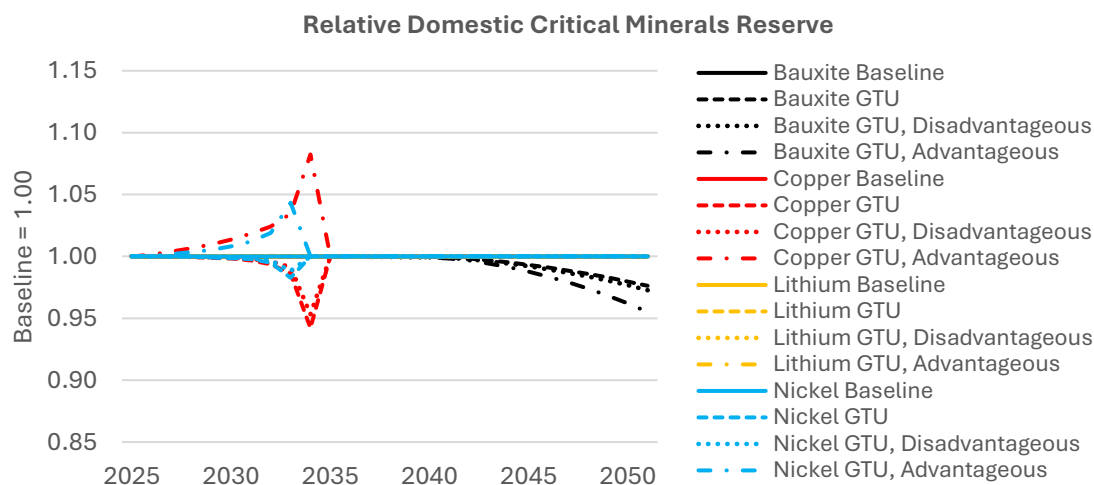


Figure 6.100. Effect of GTU policy on critical minerals domestic reserves.

6.6.3. Sustainable Energy Transition Scenario (SET)

Instead of maximizing the adoption of RE and green technologies on the demand-side, the GOI looks to minimize the economic, social, and environmental impacts of the transition. On the demand-side, the government does not provide any incentives for electric stoves in the residential sector but provides degressive incentives for the adoption of rooftop solar according to household income. In the transportation sector, the government focuses on Shift policies instead of Improve as illustrated in Chapter 3's scenario analysis (see Table 3.2). In the supply-side, the government avoids the increase in electricity price by controlling the transition from fossil-based generation to RE. While they still provide a FIT to support RE adoption, they focus on disincentivizing policies on fossil fuels such as carbon tax, depletion premium, and the early retirement and ban of CFPP. However, they avoid reducing fossil fuel subsidies immediately to maintain price levels in the economy, but it will be subject to state budget sufficiency. The policy parameter values are presented in Table 6.9.

Table 6.9. The values of the uncertainty parameters in the ST scenario

Parameters	Scenario Value
Supply-side policy	
FIT	-50%
Carbon tax	33.6 USD/ton
CFPP early retirement and ban	Ban with early retirement in 10 years
Fossil fuel subsidy	Subject to budget sufficiency
Depletion premium	Discount rate 5%
Demand-side policy	
<u>Residential Sector</u>	
Rooftop solar incentives	Low-income = 100%
	Aspiring-middle income = 50%
	Middle income = 25%
	High income = 0%
Electric stoves	0%
Support for access to 2200VA power	0%
LPG incentives	Subject to budget sufficiency
<u>Transportation Sector</u>	
BEV incentives	0%
ICEV Sales Ban	Not Applied
Biofuel land availability restriction	30%
Public transportation expansion factor	10%
Public transportation expansion frequency	Every 4 years

Compared to the other scenarios, the SET policy shows a constantly increasing share of RE in the power mix (see Figure 6.101). The relatively unchanged electricity demand compared to the baseline as shown in Figure 6.102 and the ban of CFPP helped the RE share to increase overtime. However, even this set of policies is vulnerable to uncertainties. In both the advantageous uncertainty settings, the share of RE continues to decrease after reaching its maximum of 26.9% in 2048 but then increases again. The reason for this temporary decrease in RE share is the higher share of fossil-based power generation due to the higher thermal efficiency which contributes to its increased economic benefit. On the other hand, the share of RE in the disadvantageous case (yellow line in Figure 6.101) could be lower – although still showing an increasing trend – than if there were no changes in the uncertainties (red line in Figure 6.101) because of the slower rate of renewables development. The benefit of the SET

policy is the lower electricity price (see Figure 6.102) despite the higher RE share in the power mix, attributable to the budget sufficiency which helped the government to continue provide subsidy as shown in Figure 6.103. In addition, the electricity demand can still be lower than the baseline despite the lower electricity price.

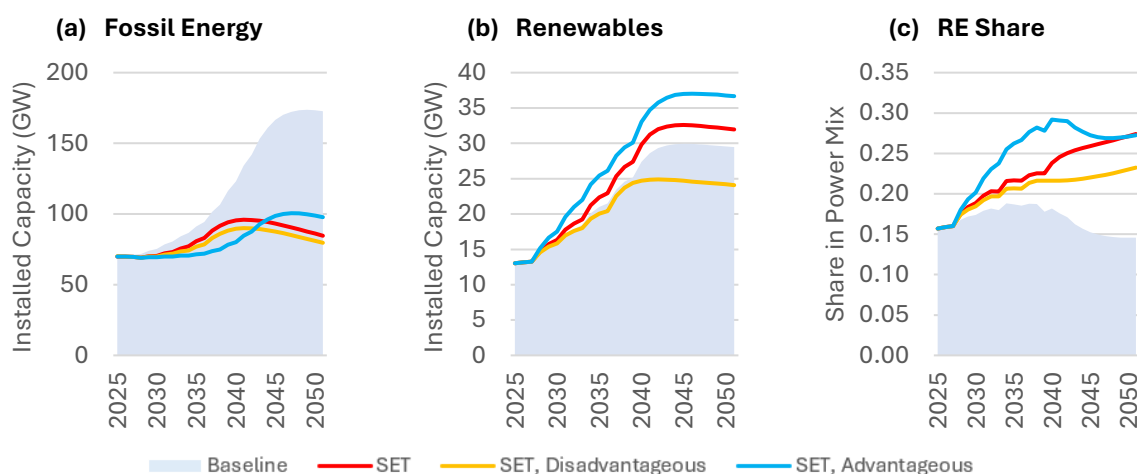


Figure 6.101. Fossil energy and renewables share in the power mix under the SET scenario.

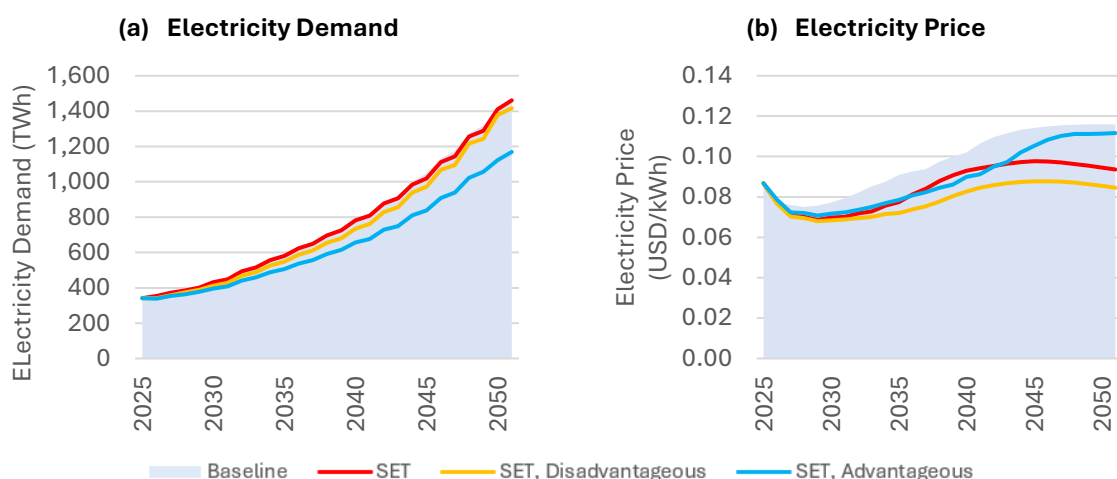


Figure 6.102. Electricity demand and price under the SET scenario.

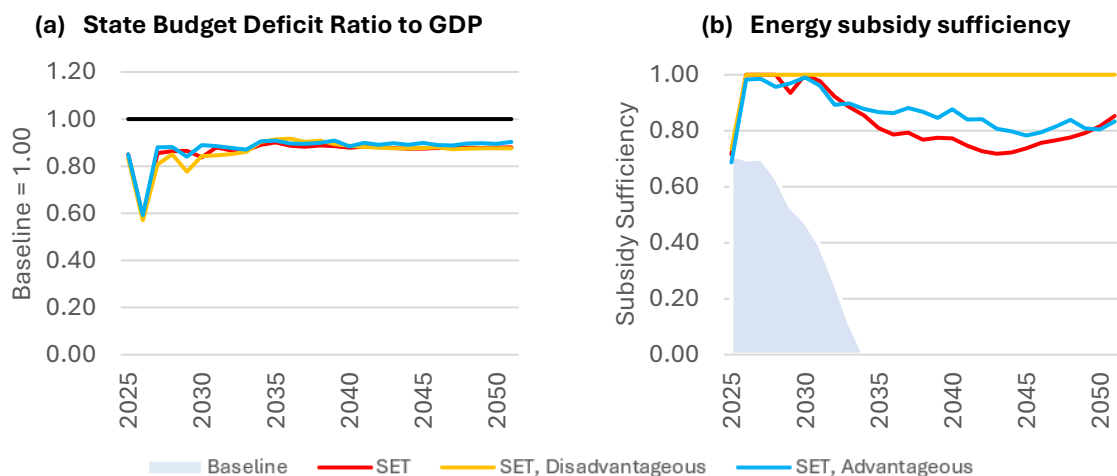


Figure 6.103. Effect of SET policy on state budget deficit and energy subsidy sufficiency.

Another benefit of the SET policy is the lower state budget deficit ratio to GDP as shown in Figure 6.103. The lower electricity demand and lower electricity price also improves the energy subsidy sufficiency which feedback to the electricity price itself. Unfortunately, the price level could still be higher than the baseline in this scenario, driven by the increased government spending linked to increased revenue from the carbon tax and depletion premium implemented (see Figure 6.104). In addition, the shift in final energy mix due to the reduced consumption of fossil fuels in the transportation sector makes the economy more sensitive to electricity price. With the increasing share of RE and increased fossil-based generation cost, price level could also increase overtime. The resulting real GDP growth due to the inflation is shown in Figure 6.105.

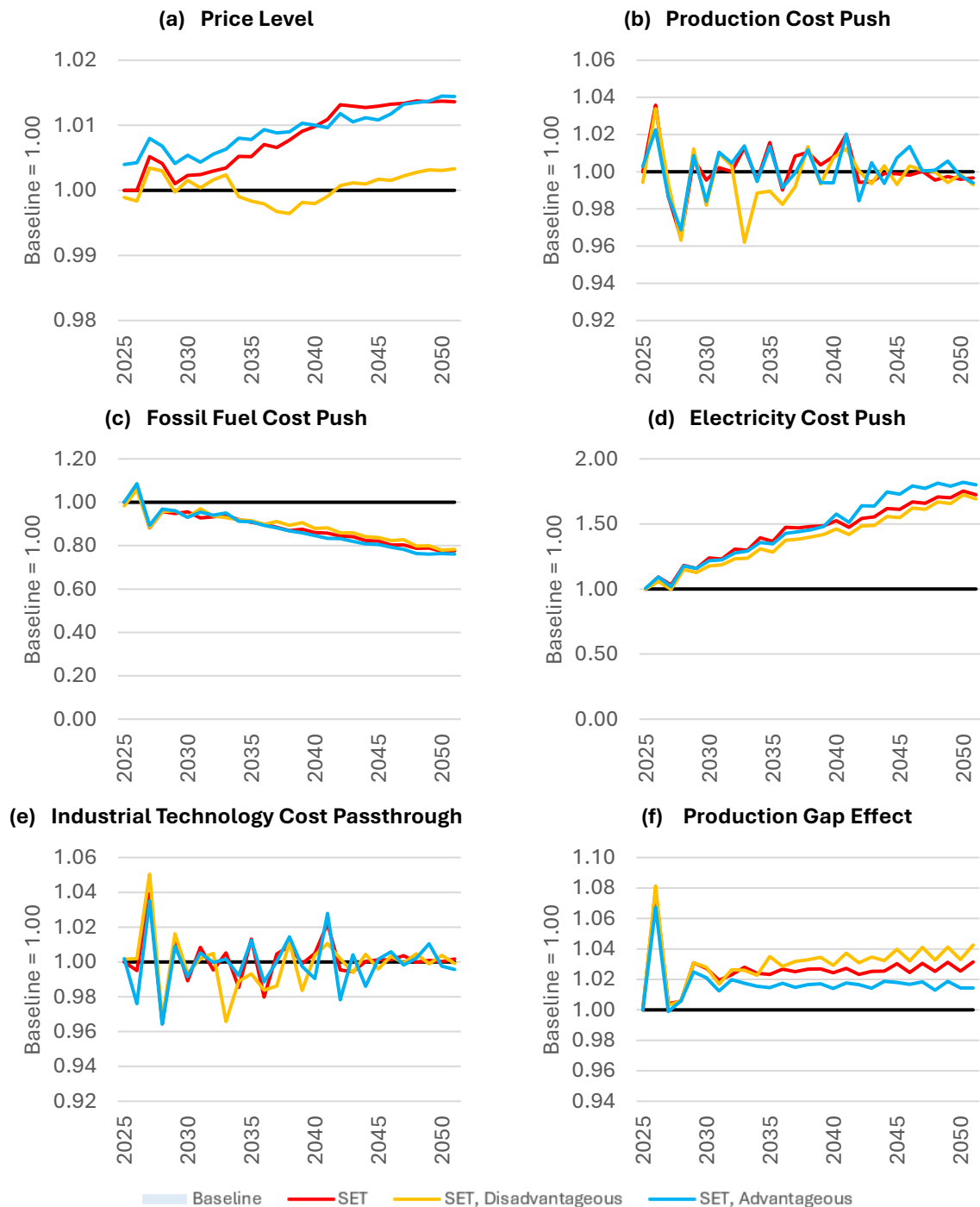


Figure 6.104. Effect of SET policy on price level.

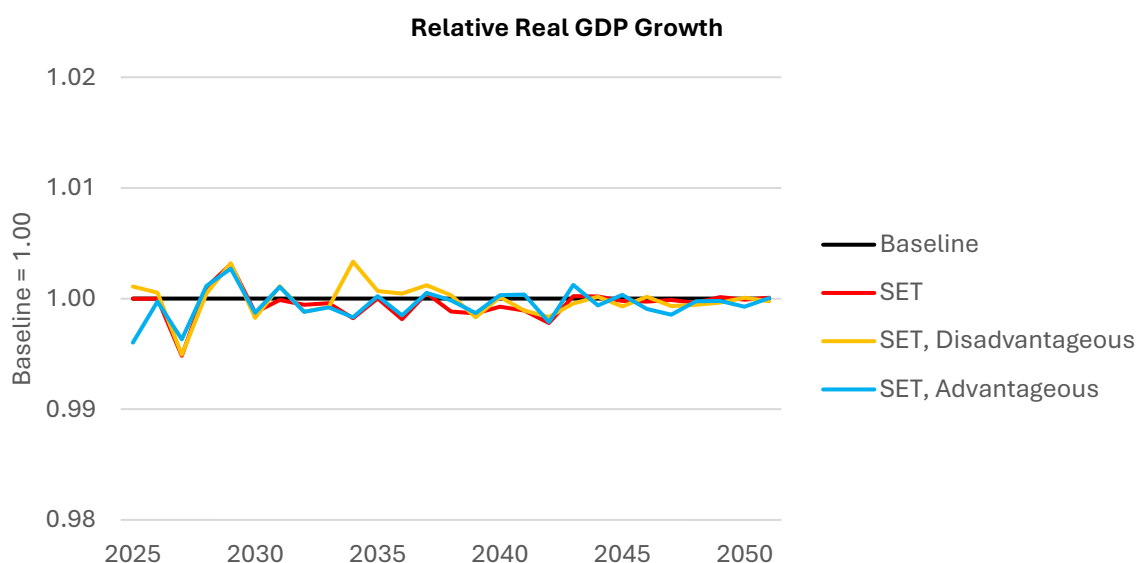
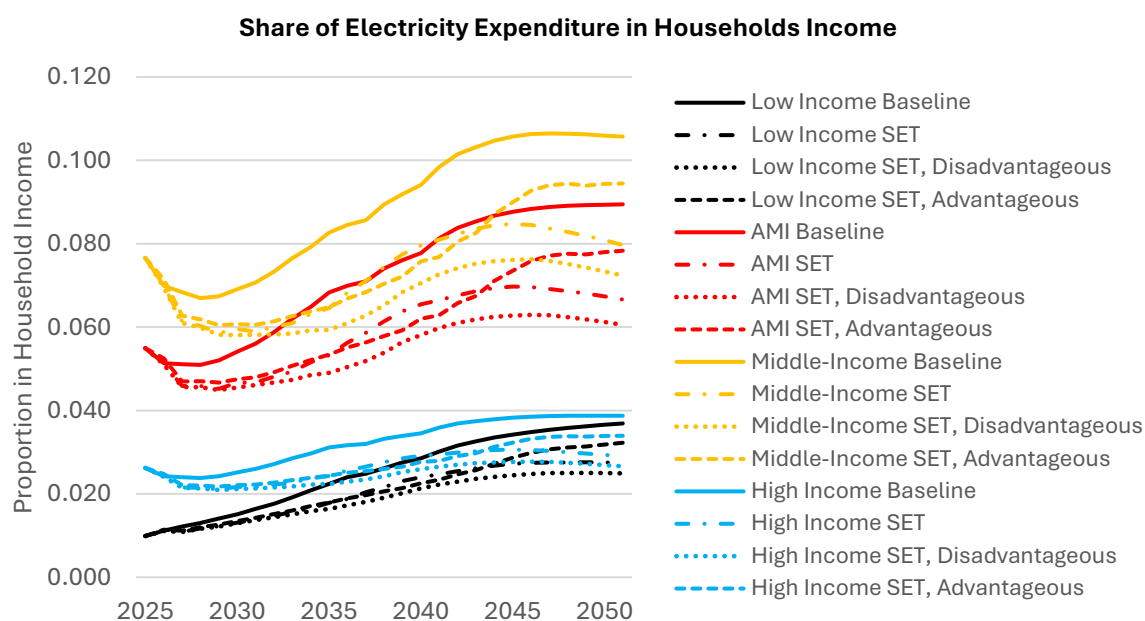


Figure 6.105. Effect of SET policy on real GDP growth.

Figure 6.106 shows that the lower electricity price under the SET policy is shown to be beneficial also at the household level, where the share of electricity expenditure in the household income is lower than the baseline in all income levels. In an advantageous case where RE share is highest and the cost of fossil fuel is also higher than the baseline, the electricity cost is also highest compared to the other two cases (see Figure 6.102). This leads lower energy subsidy budget sufficiency (see Figure 6.103) which increases the electricity price, and in turn a higher share for electricity expenditure in the household income. Nonetheless, the share is still lower than the baseline. In terms of jobs creation and unemployment, while the continued increase in electricity price which pushed price level could lead to more job creation, it could still lead to higher unemployment as shown in Figure 6.107 although closer to the baseline compared to the GTU policy.



Note: AMI = Aspiring Middle-Income

Figure 6.106. Effect of SET policy on household expenditure for electricity.

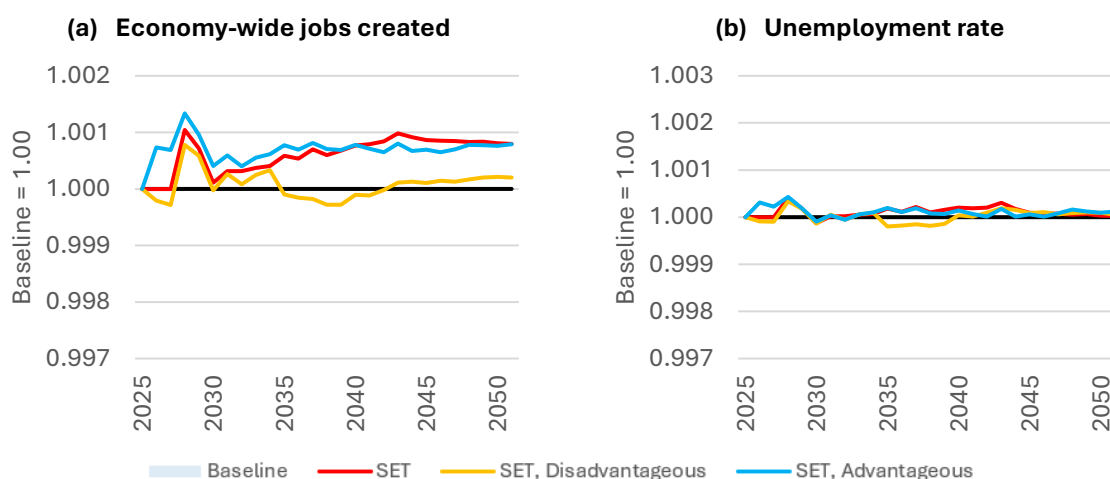


Figure 6.107. Effect of SET policy on labour demand and unemployment rate.

Like the previous scenarios, the higher share of RE in the SET policy could increase the use of bioenergy power generation and thus resulting in a higher CO₂ emissions compared to the baseline (see Figure 6.108). However, the lower electricity demand helped the emissions to be not too far off from the baseline. In the case of advantageous and disadvantageous uncertainties, the carbon emissions could be lowered from the baseline. While the reduction in carbon emissions in the disadvantageous case is due to the lower demand, the reduction in the advantageous case is because of the improved thermal efficiency in the fossil-based power generation. In terms of land-use, Figure 6.109 shows that the lower electricity demand leads to a less land used for power plants. The seemingly less land availability compared than the baseline is due the 30% conserved land constraint addition in this policy whereas in other scenarios there is no such restriction, linked to the Improve-focused policy of the transportation sector. Thus, while the land availability is lower than the baseline, the conserved land in the SET policy is much larger. When the policy is implemented, the conserved land would be 56 million hectares as opposed to zero in other scenarios. In addition, the land availability could be sustained for a longer period under the advantageous case.

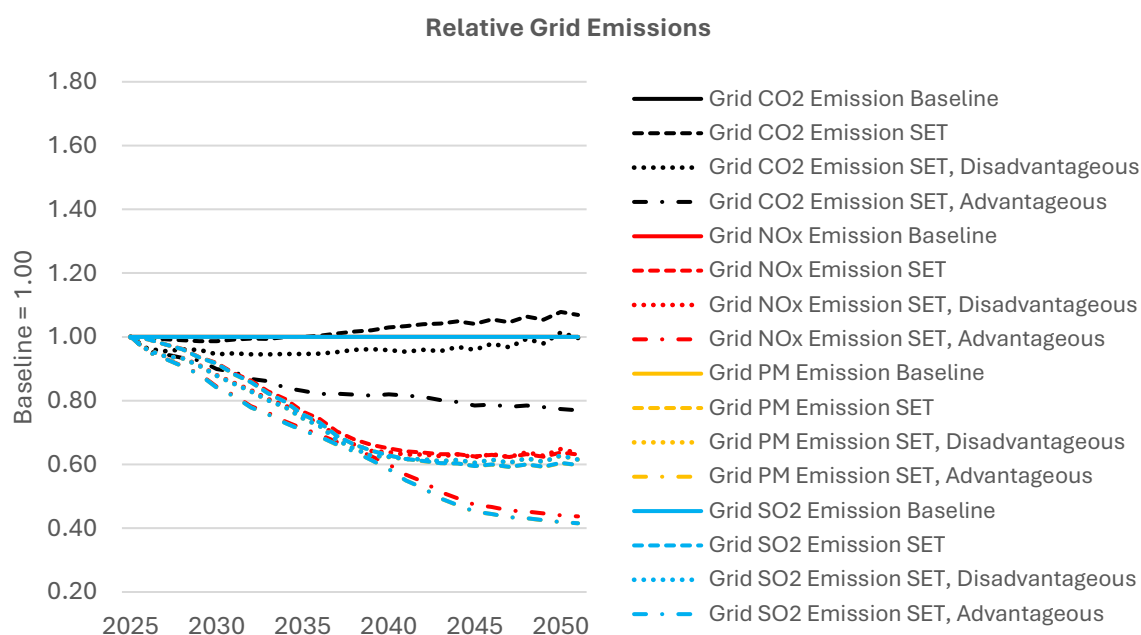


Figure 6.108. Effect of SET policy on emissions from the power sector.

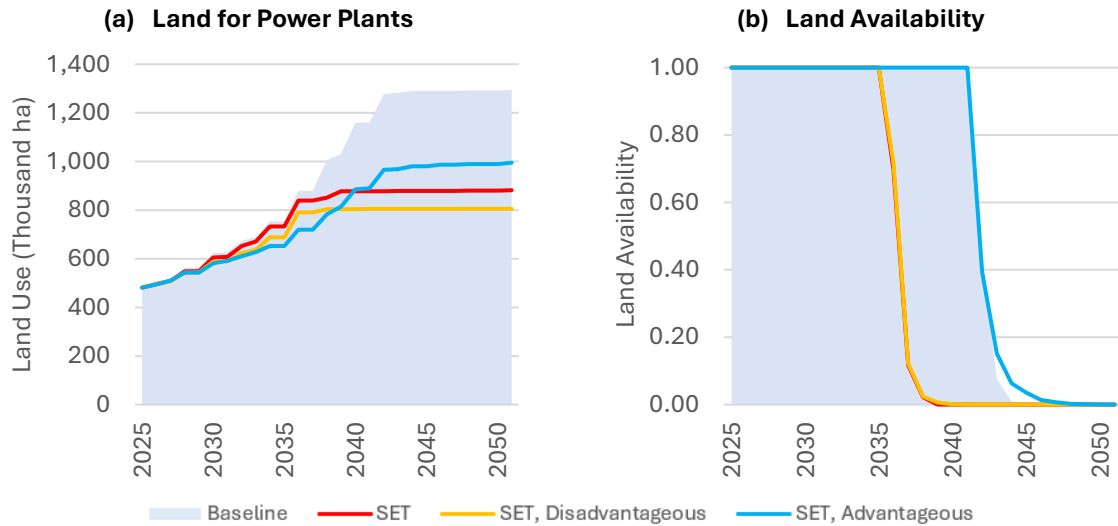


Figure 6.109. Effect of SET policy on land use for power plants and land availability.

Figure 6.110 shows that the lower coal demand leads to lower reserves but eventually the lack of extraction could result in higher reserves at the end of simulation. In case of mineral resources, the lower adoption of EV (from 25% share in 2050 to 18%) decreases mineral extraction. In time, however, the physical stock of copper and nickel could still be depleted as shown in Figure 6.111. On the other hand, bauxite resources could be slightly higher compared to the baseline.

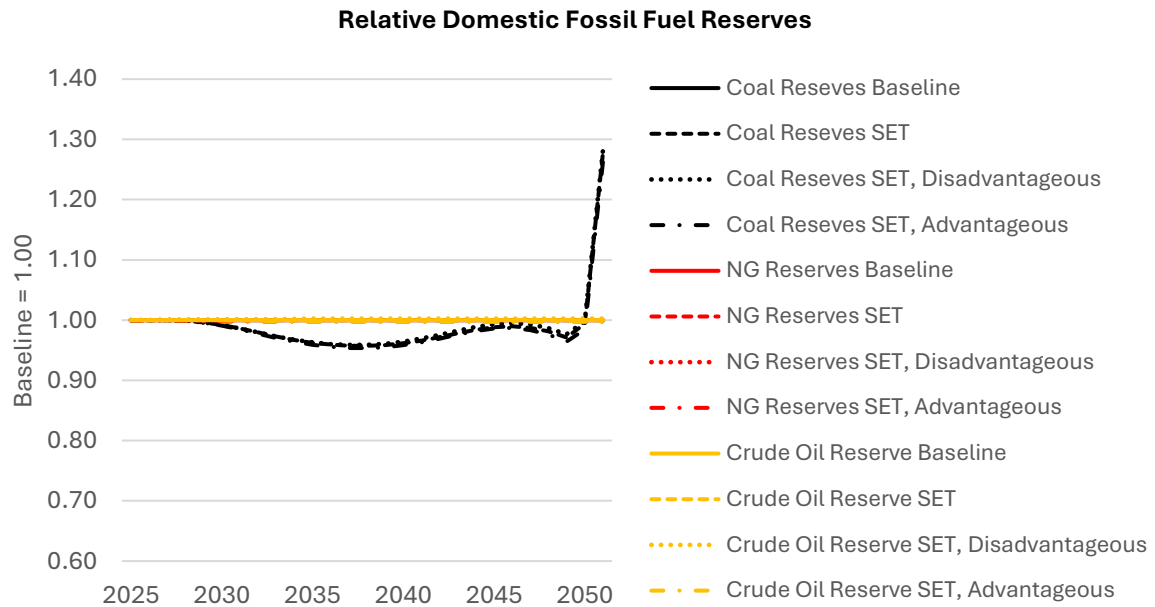


Figure 6.110. Effect of SET policy on fossil fuel domestic reserves.

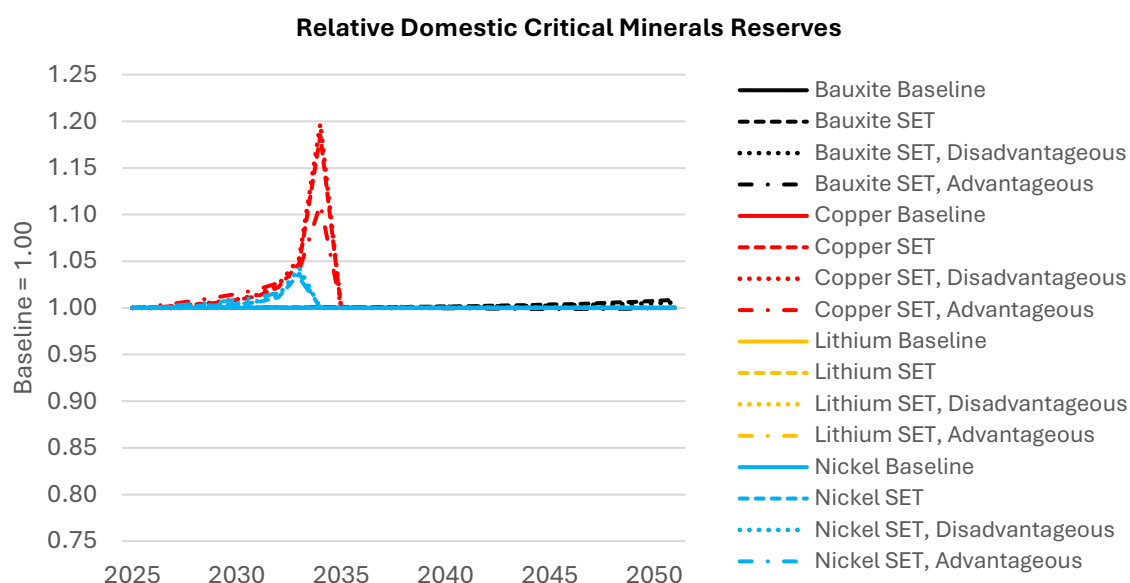


Figure 6.111. Effect of SET policy on critical minerals domestic reserves.

6.6.4. Comparison of scenarios

Figure 6.112 summarizes all the scenarios effect on the observed indicators. The value shown of each scenario are relative to the best performing scenario in each indicator, including the baseline. The scenario with the best result is given a score of 100. Note the term ‘best’ could mean the highest or the lowest whichever is favourable for the respective indicators. For example, a high score for RE share indicates the highest share of RE but a high score for grid CO₂ emission means the lowest.

All scenarios could improve the share of RE, except for the NEP and GTU when the uncertainty turned out to be disadvantageous. Under this uncertainty case, the slow renewables development rate cannot match the increasing electricity demand hence the power sector has no choice but to increase fossil-based power generation. The lag is further exacerbated in in the GTU scenario due to the heavy electrification in the residential and transportation sectors. Only the SET can offer a consistently higher RE share compared to the baseline in all cases of uncertainty. The SET is also the only policy that can improve electricity price due to the lower burden on the state budget which could lead to more sustained subsidy.

The lowest electricity price due to the SET policy, however, does not necessarily lead to the lowest price level in the economy. The combination of higher government spending from additional revenue from a carbon tax as well as a depletion premium and the decreasing subsidy rate for fossil fuel could cause price levels to increase. The same also happens in the GTU policy although to a greater extent since the price of electricity also increased significantly. Among the scenarios, the NEP policy could lead to the lowest price level since fossil fuel would continue to be subsidised and not be reduced. In addition, the much lower income from carbon tax would mean less government spending which could cause a lesser effect on price level. Nonetheless, the difference between each policy on price level is very small, indicating that all policy has a minimum impact on price level, and consequently real GDP growth. The strength of the SET policy could also be felt in the social dimension where it performed the best in the aggregate share of electricity expenditure on household income. However, at the national level its effect on jobs creation and unemployment rate is not so different with the other policies owing to its relatively similar impact on inflation.

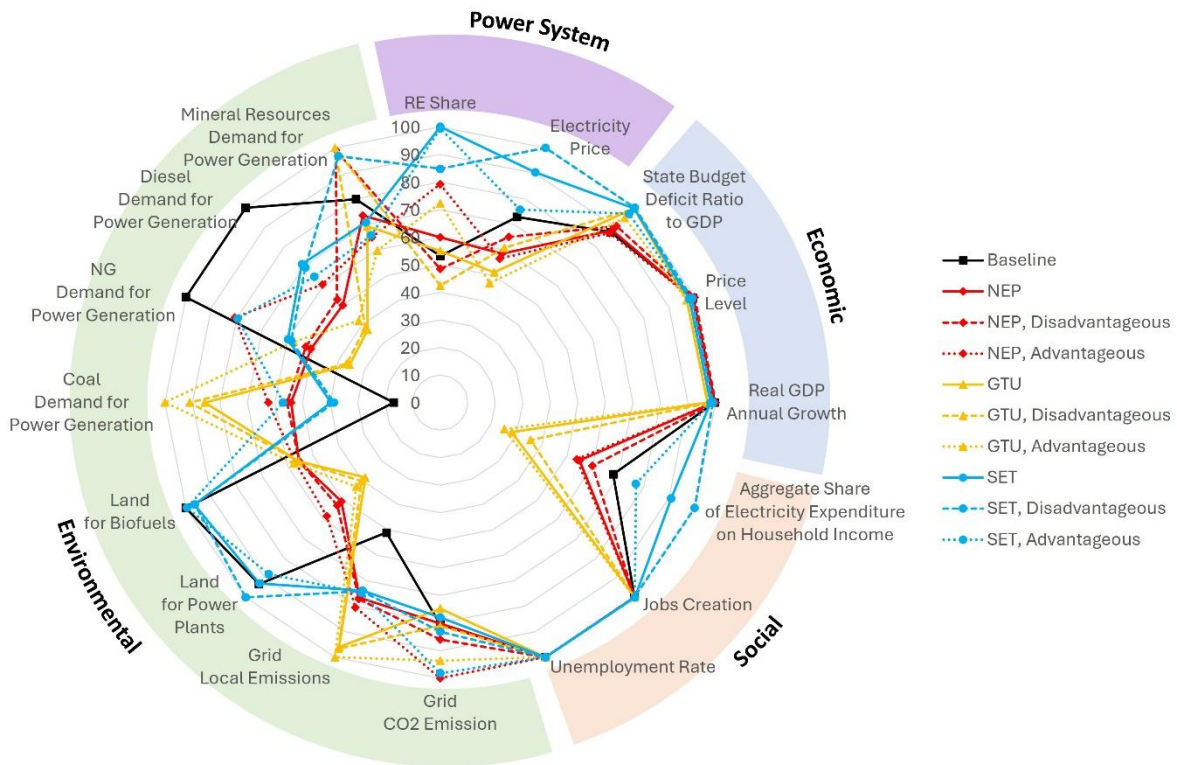


Figure 6.112. Overall comparison of the policy economic, social, and environmental outcomes

The policy performance in the environmental indicators is mixed. In terms of CO₂, the cumulative emission in the NEP policy is the lowest among all scenarios. However, considering the source, the share of biogenic CO₂ emission in the SET is the highest which means potentially lower life-cycle emission in this scenario. On the other hand, while all policies lead to lower local emissions in the power sector which includes NO_x, PM, and SO₂ emissions, the GTU policy provided the least impact. Although the policy did not result in the highest RE share, it does result in the lowest CFPP share in the power mix due to its more aggressive early retirement and ban policy. The SET policy again performed better compared to NEP and GTU policy for land use indicators, but it led to more coal demand due to its higher share of CFPP and higher electricity demand due to the resulting lower electricity price. However, the demand for natural gas and diesel in the power sector would be less compared to the NEP and GTU policy although still higher than the baseline because of the higher share of gas-fired power plants and diesel power plants in place of the early retired and banned CFPP. The SET policy also performed well in terms of minerals demand for the power sector competing with the GTU policy. However, the higher share of RE in the power mix compared to the GTU tells a more optimal resource extraction for the objective of increasing RE in the power mix.

6.7. Discussion

The model built in this Chapter is a quantification of the conceptual model built in Chapter 2, thus it incorporates the three energy transition dynamics in that qualitative model. Firstly, the conceptual model describes the substitution of primary resources which in the case of the power sector is mainly coal. Under the baseline, the substitution could not happen because the cost of generating electricity using coal is consistently lower than the other technologies, i.e. the demand can be considered inelastic to price because of technological, environmental, and regulatory constraint as explained in the technology adoption dynamics. The shift could happen

after intervention in the system where the ban and early retirement of CFPP was shown to be the most effective because it forcefully necessitates the substitution.

The qualitative feedback from price to demand was structured through technology adoption process in the supply side as well as the demand side. In the power sector, the increasing price of fossil fuels through increased the economic benefit of adopting renewable energy generation which in turn reduces fossil fuel demand. Similarly, in the demand-side a higher fossil fuel price increases the economic benefit of using an electrified technology. The price and supply-demand dynamics for a certain commodity is not included in this research because of the nature of the electricity price in Indonesia which is subsidized and regulated by the government. For the other energy commodity, they are modelled exogenously because their price would follow the global supply and demand dynamics which is outside of this study scope. While fossil fuel price is still modelled as an exogenous factor, the supply of fossil resources is modelled endogenously. The reduced demand of fossil resources would reduce the need for exploration and thus potentially reducing reserves as demonstrated multiple times as exemplified in Figure 6.88, Figure 6.99, and Figure 6.110. These dynamics would affect the resource availability of the respective energy and the resource with a more sustainable supply would be more in demand as governed by the technology adoption mechanism.

The model in this Chapter has also captured the resource constraints to energy supply, focusing on land constraints. With the increasing population and growing economy, the finite land is used for basic human needs such as food and housings to infrastructures. However, among all purpose, most land-use could be allocated for energy production in all the scenario analysed. Within the energy production, most of the land are to produce biodiesel which is used both in the power sector and transportation sector. The plateauing power generation installed capacity as shown in multiple occasions such as in Figure 6.79 (NEP scenario), Figure 6.90 (GTU scenario), and Figure 6.101 (SET scenario) is due to the depleted land availability. This land constraint could become an energy security issue in the future as Indonesia need to import some of their energy supply, including electricity. It is important to note that the term ‘depleted’ is the SET scenario is different than in NEP or GTU since in the SET scenario the land availability is constrained by the obligated conserved area whereas in it is physically constraint in the NEP and GTU. While the water constraint has not been included in this model due to data limitations, the land availability has showed that energy production is not limitless hence policies in sustainable consumption as demonstrated in the SET policy should be more focused on in the future. Additional water constraint would affect bioenergy production and could further reduce energy production, which further emphasized the energy demand reduction policies.

The bi-directional relationship between the economy and energy consumption explained in Chapter 2 is captured in this model through several links. Chapter 3 explains how GDP per capita and labour dynamics affects trip generation and mode shift in the transportation sector, and in turn energy consumption. Likewise, changes in GDP per capita drives household income dynamics which then affects energy consumption behaviour in the residential sector as explained in Chapter 4. GDP and price level also affect Industrial demand as modelled in Chapter 5. In all demand sectors, economic variables also influence technology adoption which further affects energy consumption including electricity. The electricity demand then affects technology adoption in the power sector which will change electricity price. Together with fossil fuel, the consumption and price of electricity feeds back to the economy through changes in price level which then affects real GDP growth and labour dynamics. The conceptual model

in Chapter 2 also includes state budget into consideration, to which the model built in this Chapter have shown to be another limitation in the energy transition efforts through policy test (See Section 6.4) and scenario analysis (Section 6.6).

This model confirms the hypothesis formulated in Chapter 2 which theorized the economic and resource capacity limitation in the power sector energy transition. This model also answers the need for a wider perspective in the energy transition as mentioned by del Crespo et al³⁴ and the need for a quantitative approach that incorporates the complexity of the interconnection of multiple sectors in the transition³⁵. The result of this research differs with the power mix projection done by Reyseliani et al. where they found the share of solar power would be the most dominant RE in 2050²⁶⁶. In contrast, this model result showed that solar would have a very small share even within RE, outnumbered by bioenergy power generation. The reason for these discrepancies could be in the factors for the technology adoption where the projection they made is based on least-cost optimisation while this model incorporates other variables such as resource availability, reliability, and regulatory variables as described in Figure 6.2. However, the result of this study confirms their findings of an increased generation cost due to the increased share of RE although in a different magnitude subject to policy and uncertainties. In addition to generation cost, the inclusion of economic and social impacts of the transition in this study requires the observation of electricity price for the consumers. The result of this study concludes that the increase share of RE does not necessarily increase electricity price if there is sufficient state budget to support its subsidy as demonstrated in the SET policy.

6.8. Conclusion

Indonesia's final energy demand in each demand sector, including electricity, could increase exponentially in the next decades. With the current dependence in coal, it is imperative for the power sector to decarbonise. The GOI goal to reach RE share of at least 31% by 2050 remains to be questioned with the barriers in the transition. This Chapter aims to quantitatively investigate the structural barriers of the energy transition in the power sector. In addition, this chapter aims to quantitatively investigate the necessary policies to sustainably transition in the power sector from the economic, social, environmental perspective as well to identify the roles of each stakeholder in the transition.

The result of the model shows that the RE goal maybe difficult to reach by 2050 without the proper policy. In addition, there are economic, social, and environmental consequences to the policy implementation that needs to be considered. The NEP policy showed that modestly pushing for energy transition both in the supply and demand side may prove to be insufficient to achieve the RE share target. On the other hand, aggressively forcing green technology adoption could be harmful socially and environmentally in addition to not achieving the RE target by 2050 as demonstrated by the GTU policy, since it led to the highest electricity cost burden on households and highest local emissions from the power sector. Focusing on sustainable consumption as in the SET policy could offer the least negative impact on the economic, social, and environmental indicators – indicating the better policy for a sustainable energy transition. However, the judgement may be different in the eyes of different problem owner.

The model built in this chapter adds to the knowledge of energy transition assessment by incorporating a whole system perspective. The model quantitatively clarifies the intricate dynamics between the supply-side and demand-side energy transition with the economic, social, environmental system which previously was done qualitatively. This research confirms the

economic and resource limitation of the energy transition in the power sector and further prescribe for a sustainable-consumption-focused policy to reach the desired goal of high RE while minimizing economic, social, and environmental impacts of the transition. Although the model is built upon the Indonesian case, most of its system structure is general. If the model is to be used in another country, the system parameters – for example, fertility rate and death rate for the population dynamics, the industrial demand driver coefficients, or the technology adoption weights – would need to be adjusted to keep the model valid and relevant.

Aside from scientific contribution, this Chapter also provides with Practical policy implications. The interconnection between sectors and dimensions in this model emphasized the importance of coordination between stakeholders which were grouped as energy users, energy producers, operators, and legislators in Chapter 2. Energy users – further grouped into the residential, transportation, and industrial sectors – are responsible for the choices they make when adopting a technology and the energy consumption behaviour. The electricity producers may assist in increasing the share of RE by putting higher importance on emissions to air, but this may expose them to financial risk. While the legislators could ease the financial risk of adopting RE in the producer's side, they may have difficulties in mitigating the technical risk of grid reliability issue due to the higher share of RE in the operator's side. In addition, the legislators, i.e. the GOI, also need to consider the economic, social, and environmental impacts of their policy. Based on this study result, the GOI could balance this risk by focusing on policies that promotes sustainable energy demand. For example, focus on public transportation network development instead of BEV adoption in the transportation sector, enforcing energy efficiency standards in household appliances for the residential sector, and promoting circularity in the industrial sector which is particularly true for the base metals industry.

Chapter 7

Conclusion

7.1. Thesis Summary

Indonesia's energy demand is expected to continue rise and electricity will be one of the key final energies in the future. Meanwhile, the power sector is still dependent on coal, making efforts to reduce CO₂ emissions problematic. The government aims to reduce greenhouse gases by 29% by 2030 and increase renewables in the power sector to 31% at least by 2050. However, the shift to renewable energy, while align with emission reduction goals, could have unintended consequences. While the government plans policies to push for renewables adoption in the power sector, they could negatively impact the economy, reduce GDP, and increase deficits. These challenges underline the importance of viewing the energy transition from a systems perspective, considering economic, social, and environmental impacts rather than focusing solely on emissions reduction. This multicriteria goal raises an important question about how to sustainably expand renewable energy adoption in Indonesia's power sector from economic, social, and environmental standpoints.

The energy transition is happening both on the supply side, with shifts in the power sector, and on the demand side, with sectors like residential and transportation adopting electric technologies such as stoves and vehicles. While the potentially increasing electricity demand could open opportunities for renewable adoption, the power sector may still rely on fossil fuels if policies are not supportive. Given the complexities of technology adoption, a bottom-up approach is needed, as top-down strategies struggle with issues like energy price elasticity. To address these challenges, system dynamics is proposed. This research also integrates policy analysis framework to guide the proposed policy development.

This thesis is broken down into five parts of analysis:

1. Chapter 2 lays the foundation for the study by providing an overview of the energy transition from a whole system perspective. It qualitatively examines the economic, social, and environmental impacts of the renewable energy shift in the power sector. By incorporating structural feedback between energy, economic, and environmental systems, the chapter presents a model for assessing various energy policies. Using a combination of system dynamics modelling and a policy analysis framework, it explores these challenges. The chapter also introduces a dynamic hypothesis, suggesting that rising energy demand could potentially stall the transition to renewables in the power sector due to economic and resource constraints.
2. Chapter 3 chapter study examines the impact of policies on the future energy and resources demand in the transportation sector, one of three major energy users identified in Chapter 2. The sector serves as an important discussion related to the power sector since vehicle electrification has become the central policy. The results show that the policies can decrease energy demand from the transportation sector, but there will be shifts in the primary energy mix. However, the policy increased future electricity demand significantly. Coal will be more in demand than gasoline in the future even under the 31% renewables goal. The demand for critical minerals would also be substantial following the increase in renewables. While Indonesia has one of the largest nickel reserves, it would still require other critical

minerals that could threaten Indonesia's energy security. Furthermore, the massive land use required to meet the renewables goals could be a limiting factor in achieving the set goals. This finding serves as valuable information for the policymakers when planning energy and resource supply to meet the emission target.

3. Chapter 4 aims to explore the impact of electric stoves and rooftop solar adoption on electricity demand in the residential sector – currently the largest electricity consumer in Indonesia. In addition, this chapter also evaluates the implications of the technology adoption on energy security in the household and national levels. The result showed that electric stove may improve all the household and national energy security indicators, except for national energy due to the increased electricity consumption. The adoption of rooftop solar may improve energy affordability at the household level, while at the national level it could reduce grid emissions. Pushing for the adoption of electric stove could be more cost-effective to promote both household and national energy security compared to rooftop solar, since rooftop solar would require a massive adoption for its benefit to manifest while electric stoves would only require half of the adoption level.
4. Chapter 5 explores the energy transition dynamics in the Industrial Sector – the last major energy user as mentioned in Chapter 2. Like the other sectors, the industrial sector is also pushed for production pathway electrification as a way to decarbonize. Due to the complexity of the transition, it is important to understand the key uncertainties in the adoption of technology to which steel industry is taken as a case study. The results conclude that GDP growth and renewables development rate as the key uncertainties to the electrified production pathways. In addition, supply security of the alternative fuel for the electrified production pathway to be an important adoption factor by the steel industry case. Aside from providing the energy and electricity demand in the sector, the findings in this study could potentially be useful for the industries and policy makers alike to design a comprehensive decarbonization strategies.
5. Chapter 6 discusses the supply-side transition, namely the power sector itself. Following the electricity demand changes in the previous chapters, this chapter aims to quantitatively assess these barriers and explore the necessary policies for a sustainable energy transition, considering economic, social, and environmental perspectives, as well as stakeholder roles. The model results indicate that the RE target may be difficult to achieve by 2050 without effective policies. The NEP policy suggests that modest efforts on both the supply and demand sides may be insufficient, while the GTU policy, which aggressively pushes for green technology adoption, could have harmful social and environmental impacts and still fail to meet the RE target. In contrast, the SET policy, focusing on sustainable consumption, produced the least negative impact across all indicators, making it the most effective approach for a sustainable transition, although perspectives may vary among stakeholders.

The five chapters provides answers the four research questions:

1. Who are involved and what factors exist in the renewable energy transition?

Using the whole system perspective, Chapter 2 describes the systems involved in the energy transition in the power sector can be broken down into the economic system, environmental system, primary energy system, and the power sector itself. Actor analysis in Chapter 2 defines the actors that are involved in the transition are legislators, energy producers, and energy consumers.

2. What are the dynamics of the energy transition on the supply and demand side of the system?

Chapter 2 starts answering this research question by qualitatively identifying the energy transition in the power sector will be met with structural barriers in the system which are energy price-demand balancing forces, state budget constraints, and environmental capacity. Chapter 3 until Chapter 5 describes the transition in demand side would greatly impact the transition in the supply-side (Chapter 6), especially for it to achieve to 31% renewable electricity goal. quantitatively proves this dynamic hypothesis. The structural barrier and the ever-increasing electricity demand could eventually limit the possibility to increase renewables capacity in the power sector, rendering the share of RE to eventually decrease after a certain limit.

3. How do the current policies and regulations affect economic, social, and environmental indicators?

Chapter 2 qualitatively answers this research question by using two examples of policies to increase renewables in the power sector and shows that both could be limited by state-budget constraints and energy price-demand balancing forces. Chapter 3 until Chapter 6 shows quantitatively that current policies do not lead to a sustainable outcome. For example, pushing EVs does not lead to a more sustainable energy consumption in the transportation, while adopting electric stoves could lead to an energy security trade-off between the household and the national levels. Similarly, aggressively pushing renewable electricity in the power sector could lead to an increased electricity price which spills over to price level and unemployment while not achieving the desired renewables target.

4. What policies are necessary for a sustainable energy transition?

Chapter 3 has hinted that a structural change in the demand-side is necessary for a sustainable energy transition. In the case of the transportation sector, such change is enabled by pushing the use of public transportation instead of promoting electric vehicles or biofuels. Chapter 6 holistically assessed this strategy by showing that policies focusing on promoting sustainable consumption provided the least negative economic, social, and environmental impacts, which also enabled a steady increase in renewable electricity share in the power sector.

This research contributes to the literature for energy transition where it provided a whole system perspective by integrating economic, social, and environmental systems with the power system. Chapter 2 of this research has identified the national economic and environmental capacity as the structural barriers of the energy transition through the inclusion of feedback between the economic system, social system, environmental system and the power sector. Chapter 2 also proposes the use of multidimensional indicators when assessing energy transition pathway instead of focusing only on carbon emissions. The bottom-up approach used in Chapter 3 until Chapter 5 in determining the energy demand in each sector, technology adoption model, and the whole system perspective used in this research bridge the weakness of using top-down analysis in dealing with energy price elasticity. By breaking down the model into supply-side and demand-side as shown in Chapter 3 until Chapter 6, this research can assess the interaction between supply-side and demand-side policies of the energy transition and its effect on the economic, social, and environmental indicators in addition to sector specific policy. Finally, despite the model is built upon the Indonesian case study, the model

uses a more generalized system structure unlike common system dynamics model which usually is unique depending on the focused problem. By having a general system model, the model can be more flexibly applied and expanded for different issues by parameter adjustments.

7.2. Future work

Despite the extensive work done for this research, it is not short of limitation which should be addressed in future works. The limitations of this research are listed below:

1. Regarding the transportation sector in Chapter 3, future work could also investigate the cost-effectiveness of the policies in reducing emissions, particularly carbon emission. Future studies could also expand the model by including a shifting structure in the domestic and freight transportation. This study has shown how a shift-focused policy could reverse energy intensity, which would also mean a reversal of emissions. However, this study has not formulated a specific policy to reduce the emissions which is aligned with international climate agreements. Thus, it is important for future studies to explore the necessary policies for this issue.
2. Specific to the steel industry case study in Chapter 5 and related to the transportation sector, this study has not included the endogenous adoption rate of fuel cell vehicles which could affect hydrogen supply and demand. The model can also be improved by adding feedback within the already established variables, for example feedback to the maximum hydrogen injection rate which now is modelled as an uncertainty factor.
3. While the estimation of the industrial sector's production volume in Chapter 5 (and in turn energy demand) have included price level as an endogenous factor, it is still based on a regression model. The model can be further expanded by using a more bottom-up demand estimation as in the residential and transportation sector.
4. The discussion of residential sector energy transition in Chapter 4 is limited to the adoption of two technologies relevant to the energy transition within the residential sector. The adoption of technologies for other energy services, for example air conditioning which was shown to be the main contributor in the sector's electricity consumption should be explored in future work. In addition, future work could also use the bass diffusion model as built in this work to explore the adoption of energy efficient home appliances, since its importance in improving energy security was shown. Furthermore, the effect of building design effect on energy consumption have not included. The inclusion of this factor into the model would be crucial since many researchers have emphasized the role of building design to energy consumption³⁹³.
5. The power sector model built in Chapter 6 has not considered nuclear technology as one of the options in the power sector. In 2032, Indonesia is expected to have their first nuclear power plant installed. Should the technology be included in the model, it would alter the relative benefits of each power generation technologies. Nuclear power plants could potentially reduce the attractiveness of coal or gas-fired power plants as baseload provider in terms of technological and economical benefit. If paired with early retirement and ban of CFPP, it could be the dominating power plant together with bioenergy. However, it is still unclear regarding the acceptability of the technology. Thus, the inclusion of nuclear should be investigated in future works.
6. Chapter 2 discussed the substitution dynamics of primary resources to which this study has not discussed specifically. While this study has included the supply and demand dynamics of fossil fuels, future work could expand the model by including the similar dynamics for

the primary resources such as water, biomass, and minerals. The inclusion of water constraint could enrich the model discussion as it could affect bioenergy production which could also be expanded to the energy-water-food nexus discussion.

7. The economic model is built upon a closed economy according to Yamaguchi's work²⁹. Future work may consider expanding it as an open economy which could affect the energy demand in the industrial sector since it would include imports and exports. In addition, future works could also explore the price dynamics of primary resources which have not been included in this research.
8. The advantages of SET policy defined in Chapter 6 of having larger subsidy support which resulted in lower electricity price could come with unwanted effect in the economy in the form of economic inefficiency, deadweight loss, and overconsumption⁵⁰ that has not been discussed in this research.
9. While the model was developed to be used for national scale analysis, the general structure of the model could also be used at a smaller scale. Considering the archipelagic features of Indonesia, future work could address the energy transition in individual islands or network of islands, which would highlight the effect of resource availability on the transition in the power sector.

List of Publications

Journal Papers

1. **Review of Policies for Indonesia’s Electricity Sector Transition and Qualitative Evaluation of Impacts and Influences Using a Conceptual Dynamic Model**
Teuku Naraski Zahari, Benjamin McLellan
Energies 16(8):3406. DOI: 10.3390/en16083406
Time of Publication: 12 April 2023
2. **Sustainability of Indonesia’s Transportation Sector Energy and Resources Demand under The Low Carbon Transition Strategies**
Teuku Naraski Zahari, Benjamin McLellan
Energy. Volume 311, 133385. DOI: 10.1016/j.energy.2024.133385
Time of Publication: 1 December 2024
3. **Adoption of the Hydrogen-based Steel Production Under the Uncertainty of Domestic Hydrogen Availability: An Indonesian Case Study**
Teuku Naraski Zahari, Benjamin McLellan
International Journal of Hydrogen Energy. Volume 97, Pages 549-570. DOI: 10.1016/j.ijhydene.2024.11.442
Time of Publication: 6 January 2025
4. **Assessments of the Energy Security Impacts of Two Energy Transition Technologies in the Residential Sector in Indonesia**
Teuku Naraski Zahari, Benjamin McLellan
Technological Forecasting & Social Change
Time of Submission: 29 November 2024 (Under Review)

E-Book

1. Evaluation of the “Shift” and “Improve” Strategies in Achieving Sustainable Urban Transportation
Teuku Naraski Zahari, Benjamin McLellan
EcoDesign for Circular Value Creation: Volume II. DOI : 10.1007/978-981-97-9076-0
Time of Acceptance: 11 September 2023 (In press)

Papers not included in the thesis

Journal papers

1. **Reverse Logistics Network Design for Plastic Waste Management in Jakarta: Robust Optimization Method.**
Romadhani Ardi, Syifa Nurkamila, Dyas Latiefah Citraningrum, Teuku Naraski Zahari.
International Journal of Technology, Vol 14, No 7 (2023). December 2023. DOI: 10.14716/ijtech.v14i7.6681
2. **Examining The Effectiveness of Policies for Developing Battery Swapping service Industry.**
Andri D. Setiawan, Teuku Naraski Zahari, Armand Omar Moeis, Akhmad Hidayatno.
Energy Reports 9(December 2023):4682-4700, April 2023. DOI: 10.1016/j.egyr.2023.03.121
3. **Investigating policies on increasing the adoption of electric vehicles in Indonesia.**
Andri D. Setiawan, Teuku Naraski Zahari, Fara Jetira Poerba, Armand Omar Moeis, Akhmad Hidayatno.
Journal of Cleaner Production 380(5):135097. November 2022. DOI: 10.1016/j.jclepro.2022.135097

International Conference

1. **Extending Life Cycle Assessment with System Dynamics: Case Study of Industrial Plastics Waste Environmental Impacts and Circularity.**
Teuku Naraski Zahari, Benjamin McLellan
The 16th Biennial International Conference on EcoBalance, EcoBalance 2024, Sendai, Japan.
2. **Life cycle assessment of mechanical recycling and utilization for plastic bags of uncontaminated post-industrial polyethylene film in Japan**
Ahdo Kim, Teuku Naraski Zahari, Nobuteru Edayoshi, Pin Juo Chou, Toshiki Yamamoto, Pin Yen Chou, Kei Saito, Benjamin McLellan
The 16th Biennial International Conference on EcoBalance, EcoBalance 2024, Sendai, Japan.

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