Energy Transition in Singapore: A System Dynamics Analysis on Policy Choices for a Sustainable Future

by

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Abstract

95% of Singapore's electricity is generated from imported natural gas, which poses fundamental economic and security risks. Solar power is the only local renewable energy resource available but it is insufficient to meet all electricity demand. There is value to consider what Singapore can do to maintain competitive advantage as a country while diversifying its electricity generation landscape and lowering its greenhouse gas emissions. A system dynamics model was built and different key policy scenarios were simulated to observe potential outcomes of Singapore's electricity landscape by 2100. Model findings suggest that the current Business-As-Usual (BAU) path of focusing on energy efficiency initiatives, maximizing local solar resources, and continual usage of natural gas fired plants is a good short-term to mid-term strategy but a poor long-term strategy. The recommended strategy of adding nuclear into the energy mix through offshore floating nuclear plants has the lowest long-run socioeconomic costs. Adding both nuclear and importing renewable based electricity as part of the ASEAN Power Grid as a strategy requires the highest total infrastructure investments. Both alternatives provide reliable outcomes in lowering greenhouse gas emissions and have the potential to promote greater multilateral relationships and economic co-development between Singapore and its neighbors.

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Table of Contents

ABSTRACT **3**

ACKNOWLEDGEMENTS **5**

LIST OF FIGURES **9**

LIST OF TABLES **10**

LIST OF ACRONYMS **11**

CHAPTER 1 | INTRODUCTION **13**

- **1.1 | GENERAL INFORMATION** 13
- **1.2 | MOTIVATION AND THESIS QUESTION** 15

CHAPTER 2 | LITERATURE REVIEW **17**

- **2.1 | SINGAPORE'S GEOGRAPHICAL CIRCUMSTANCES** 17
- **2.2 | ECONOMIC REVIEW** 17
- **2.3 | CURRENT PLAN FOR MEETING ELECTRICITY DEMANDS AND EMISSION TARGETS** 19
- **2.4 | ASEAN'S GROWING ENERGY NEEDS** 20
- **2.5 | NUCLEAR POWER FOR SINGAPORE** 22
- **2.6 | ENERGY TRANSITION REPRESENTATION** 24
- **2.7 | SYSTEM DYNAMICS** 25

CHAPTER 3 | SINGAPORE'S ELECTRICITY LANDSCAPE TRANSFORMATION MODEL **27**

- **3.1 | BASIC MODEL AND BROAD NARRATIVE** 27
- **3.2 | DETAILED DESCRIPTION OF SUB-CATEGORIES IN THE STOCK-AND-FLOW MODEL** 30
  - ***3.2.1: Electricity Demand and Supply*** *31*
  - ***3.2.2: Pricing*** *35*
  - ***3.2.3: Infrastructure Investment*** *40*
  - ***3.2.4: Local and Overseas Capacity*** *44*
  - ***3.2.5: Electricity Generation*** *48*
  - ***3.2.6: Emissions Level*** *49*
  - ***3.2.7: Energy Related Jobs*** *51*
  - ***3.2.8: Energy Security*** *53*
  - ***3.2.9: Social Needs*** *54*
  - ***3.2.10: Policy*** *55*
  - ***3.2.11: Model Dashboard*** *58*

CHAPTER 4 | SCENARIOS AND MODEL RESULTS **60**

- **4.1 | SCENARIO SETUP** 60
- **4.2 |RESULTS** 61
  - ***4.2.1. Capacities*** *61*
  - ***4.2.2. Price*** *63*
  - ***4.2.3. Demand Supply Balance*** *65*
  - ***4.2.4. Emissions*** *66*
  - ***4.2.5. Energy Security*** *70*
  - ***4.2.6. Job Prospects in Energy Market*** *70*
  - ***4.2.7. Extended Runs & Resource Limits*** *71*

4.2.8. Sensitivity Analysis *72*

CHAPTER 5 | CONCLUSION **79**

5.1 | IS THERE A BEST OPTION? 79
5.2 | MODEL LIMITATIONS 81
5.3 | POSSIBLE FUTURE RESEARCH 82

REFERENCES **85**

APPENDIX I : EQUATIONS OF THE SINGAPORE ELECTRICITY LANDSCAPE TRANSFORMATION MODEL 97
APPENDIX II : DESCRIPTIVE TABLES FOR THE SINGAPORE ELECTRICITY LANDSCAPE TRANSFORMATION MODEL 137

List of Figures

Figure 1.1: Proportions of Electricity Consumption by Sectors in Singapore from 2005 to 2017 13
Figure 1.2: Electricity Fuel Mix in Singapore from 2005 to 2017 14
Figure 1.3: Thesis Question 16
Figure 2.1: ASEAN Interconnection Projects 21
Figure 2.2: Current and Envisaged Electricity Trade Relationships in ASEAN 22
Figure 2.3: Categorization and Definition of STET Models by Li et. al. (2017) 25
Figure 3.1: Causal Loop Diagram of Singapore's Electricity Generation Transformation Model 28
Figure 3.2: Electricity Demand and Supply Stock and Flow Sub-model 32
Figure 3.3: Pricing Sub-model 36
Figure 3.4: Actual vs Simulated Energy Price (BAU) from 2010 to 2018 40
Figure 3.5: Infrastructure Investment Sub-Model 42
Figure 3.6: Local and Overseas Capacity Sub-Model 45
Figure 3.7: Generation Sub-model 48
Figure 3.8: Emissions Sub-model 50
Figure 3.9: Nonlinear Function of Normalized GHG for Adjusted Desired GHG Emissions 51
Figure 3.10: Job Market Creation Sub-model 52
Figure 3.11: Nonlinear Function of Normalized GJC for Adjusted Target for GJC 52
Figure 3.12: Energy Security Sub-model 54
Figure 3.13: Social Needs Sub-model 54
Figure 3.14: Policies Sub-models 56
Figure 3.15: Nonlinear function for Carbon Tax 56
Figure 3.16: Nonlinear Function for Boost Infrastructure Investment 57
Figure 3.17: Sample Dashboard View (BAU) 59
Figure 4.1: Local Installed Capacities in the Three Scenarios 62
Figure 4.2: Overseas Installed Capacities in the Three Scenarios 62
Figure 4.3: Total Installed Capacities 63
Figure 4.4: Electricity Prices 64
Figure 4.5: Cost of Electricity to Society 64
Figure 4.6: Current Peak Demand: Generating Supply Ratio 66
Figure 4.7: CO2 Emissions from the Three Scenarios 67
Figure 4.8: Peak Demand Changes between BAU and Optimistic Energy Efficiency Measures 68
Figure 4.9: Generating Supplies: Peak Demand Ratio 68
Figure 4.10: Changes in Energy Prices Under Different Energy Efficiency Scenarios 69
Figure 4.11: CO2 Emissions Under Different Energy Efficiency Scenarios 69
Figure 4.12: Herfindahl-Hirschman Index and Proportion of Non-Baseload for the Three Scenarios 70
Figure 4.13: Job Market Potential of the Three Scenarios 71
Figure 4.14: Demand Supply Balance for Extended Runs for the Three Scenarios 72
Figure 4.15: Demand Supply Balance with Percentiles 73
Figure 4.16: Electricity Price with Percentiles 73
Figure 4.17: Total Electricity Price Paid: GDP with Percentiles 74
Figure 4.18: Cumulative Expenditure in USD (2010) with Percentiles 74
Figure 4.19: GHG Emissions with Percentiles 75
Figure 4.20: Job Market Data with Percentiles 76

List of Tables

Table 2-1: GDP and GDP Per Capita Data for ASEAN Member States (2017)[25] 18
Table 3-1: Color Code for Subsequent Stock-and-Flow Diagrams... 30
Table 3-2: Population Data Used 31
Table 3-3: Demand Change Rates from Energy Efficiency Initiatives (Demand Curtailment).................. 33
Table 3-4: Estimated Resource Limits 42
Table 3-5: Adjustable Variables in Dashboard View 58
Table 4-1: Parameter Changes for Supply Scenarios 60
Table 5-1: Summary of Findings Between Options... 79
Table II-1: Descriptions for Variables in [1] Demand-Supply Balance.. 137
Table II-2: Descriptions for Variables in [2] Pricing.. 141
Table II-3: Descriptions for Variables in [3] Infrastructure Investment 147
Table II-4: Descriptions for Variables in [4] Electricity Capacity 150
Table II-5: Descriptions for Variables in [5] Electricity Generation.. 157
Table II-6: Descriptions for Variables in [6] CO2 Emissions.. 159
Table II-7: Descriptions for Variables in [7] Energy Related Jobs 164
Table II-8: Descriptions for Variables in [8] Energy Security 166
Table II-9: Descriptions for Variables in [9] Social Needs... 168
Table II-10: Descriptions for Variables in [10] Policy 170

List of Acronyms

Acronym	Definition
AMS	ASEAN Member States
ASEAN	Association of Southeast Asia Nations
BAU	Business-As-Usual
CAGR	Compound Annual Growth Rate
CLD	Causal Loop Diagram
EE	Energy Efficiency
EIA	U.S. Energy Information Administration
EMA	Energy Market Authority of Singapore
GDP	Gross Domestic Product
GEF	Grid Emission Factor
GHG	Greenhouse Gases
HAPUA	Heads of ASEAN Power Utilities/Authorities
HDI	Human Development Index
HHI	Herfindahl-Hirschman Index
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost of Electricity
LNG	Liquefied Natural Gas
NCCS	National Climate Change Secretariat
NDC	Nationally Defined Contribution
NEA	National Environment Agency
NUS	National University of Singapore
O&M	Operations and Maintenance
OFNP	Offshore Floating Nuclear Power
PNG	Piped Natural Gas
SD	System Dynamics
WTE	Waste-to-Energy

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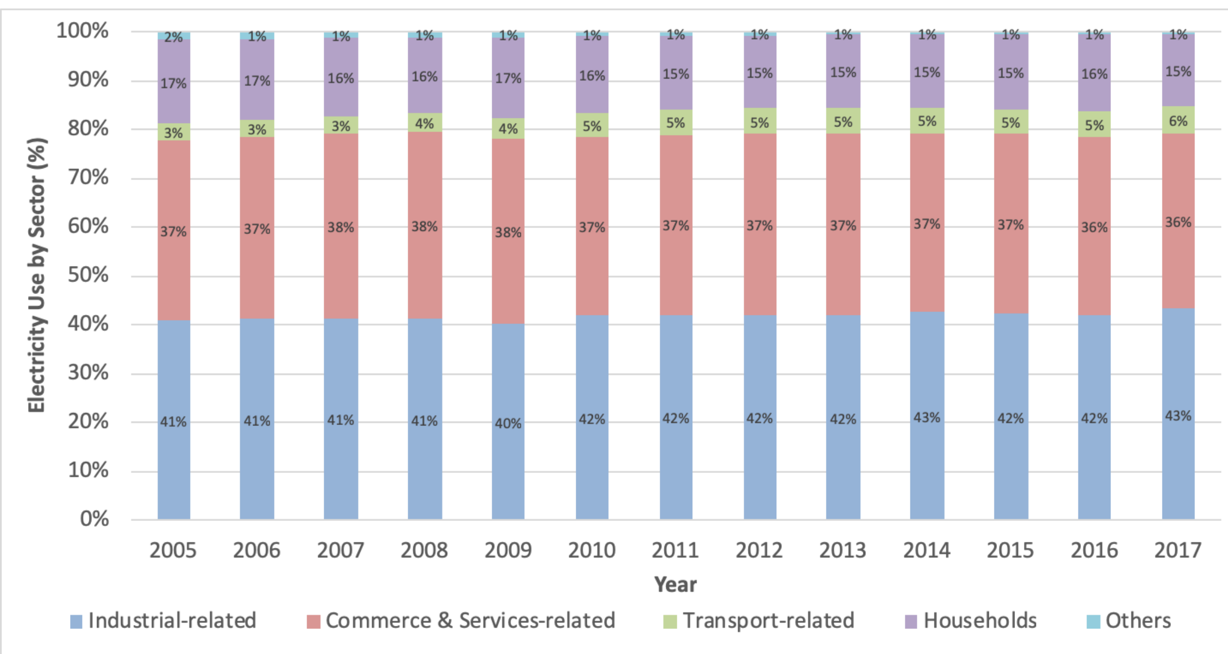
Chapter 1 | Introduction

1.1 | General Information

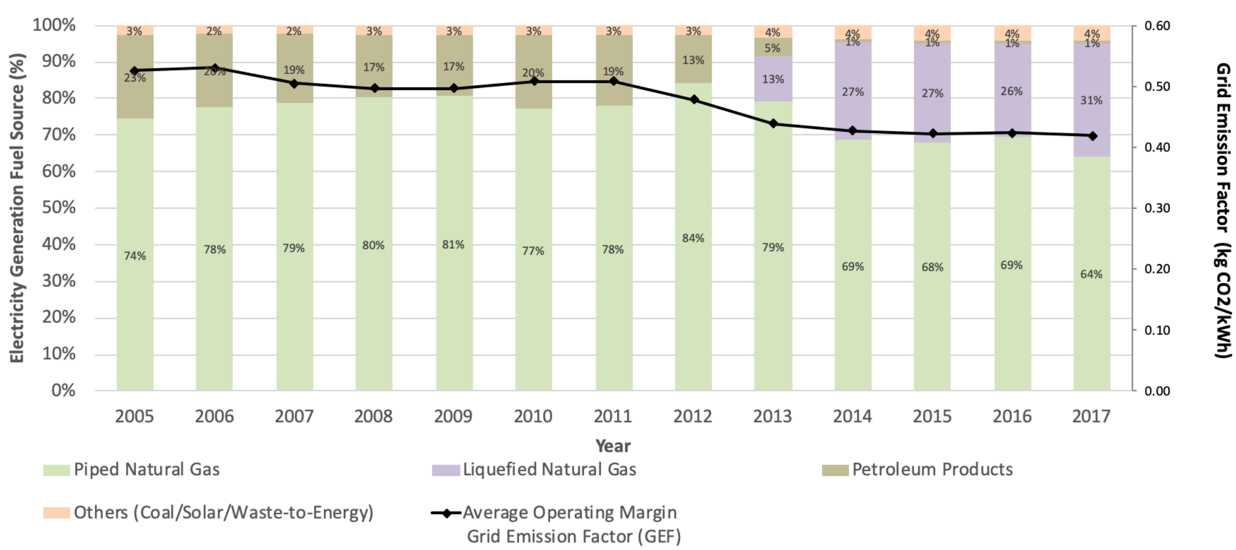
Electricity Use in Singapore. Electricity use has become an important part of modern development where it has brought about many conveniences in our daily lives.[1,2] In Singapore, electricity's role has gone beyond the basic conveniences as it has vital roles in driving economic activities. Since 2005, approximately 75% of electricity demand has consistently been for the industrial and commerce & services-related sectors while the households and transport sectors accounted for the remaining demand (See **Figure 1.1**). In actual amounts, electricity use grew from 36.8 to 49.9TWh, reaching an average of 8,838kWh per capita in 2017.[3,4] In relative terms, this has placed Singapore as the 17th highest in the world for electricity consumption per capita.[5]

Figure 1.1: Proportions of Electricity Consumption by Sectors in Singapore from 2005 to 2017



Lack of Electricity Source Diversity. Looking further into the energy sources used for electricity generation, Singapore has transitioned from being powered by a majority of petroleum products and natural gas to one where it is now 95% natural gas (Refer to **Figure 1.2**).[4] This has helped in lowering the Grid Emission Factor (GEF), where a large decline is observed from 2013 onwards as natural gas takes up a higher proportion. As seen from **Figure 1.2**, the government has diversified the electricity energy sources to incorporate Liquefied Natural Gas (LNG) since 2013, and has imported LNG from countries such as Australia, Qatar, Indonesia, Angola, Malaysia, United Arab Emirates, Egypt, Algeria, and Equatorial Guinea in 2017.[4,6] The largest majority (64% in 2017) of electricity energy source is from Piped Natural Gas (PNG), which was sourced from Singapore's two immediate neighbors, Malaysia and Indonesia.[7] Such a scenario indicates a lack of diversity in energy types, and Singapore's electricity prices would be highly sensitive to changes in natural gas prices[8], which could therefore translate into a potential economic risk. The high PNG dependency would also pose a security risk to Singapore by making it susceptible to electricity disruptions when there are failures in the pipelines or increased regional geopolitical tensions. For example, in 2004, a PNG leak from the Indonesia pipelines led to an extended blackout in certain areas in Singapore.[9]

Figure 1.2: Electricity Fuel Mix in Singapore from 2005 to 2017



Limited Electricity Source Alternatives. One might consider that Singapore could turn to other electricity sources such as renewables or nuclear energy in view of the potential economic and security risks from the high natural gas reliance, coupled with the increased international pressures for countries to lower their greenhouse gas (GHG) emissions.[10] However, Singapore's geographical realities has led to severe limitations in the type and magnitude of renewable energy sources that can be deployed as energy source alternatives.[11] Nuclear options were considered before but there has been no development in recent years and there have been considerable negative public opinions about it since the Fukushima incident.[12–14] As one of the Signing Parties within the Paris Agreement 2015[10], Singapore has set a Nationally Determined Contribution (NDG) goal of reducing its emissions intensity 36% from its 2005 levels by 2030.[15] Therefore, crossed with the realities, limitations, and various considerations, the Singapore government has remained centrally focused in curtailing electricity demands through energy efficiency initiatives, encouraging solar deployment, and improving solar efficiency through research and development efforts in order to build towards a city-of-the-future while fulfilling the goals set forth in the first NDC.[11,15]

1.2 | Motivation and Thesis Question

Motivation. While there is great value in building a nation that is highly efficient in its electricity use, Singapore's high reliance on natural gas remains as a concern in the energy security dimension, both economically and geopolitically. This has also been identified by the World Energy Council's Trilemma Index, where Singapore achieved a score of D in the Energy Security category while achieving an overall score of A in the Energy Equity and B in the Environmental

Sustainability categories respectively.[16] While its reliance on natural gas might be the most economic choice currently, such a policy option might run contrary to international pressures in years to come. Therefore, there might be value for Singapore to rely on its solid economic and political foundations to take on larger scale alternative electricity generation projects to better prepare itself for cases where natural gas usage might become more restrictive or too expensive to consider. With this in mind, the research question shown below in **Figure 1.3** was identified, where this thesis would attempt to answer it.

Figure 1.3: Thesis Question

What can Singapore do to maintain a long-term competitive advantage while diversifying its electricity generation landscape and lowering its greenhouse gas emissions?

Approach. To answer the thesis question, there would first be a review the context surrounding Singapore's national circumstances, the regional's plan for electricity development, and on System Dynamics (SD) as a tool for studying energy transitions. An SD approach was then applied to enable a common visual understanding of the energy transition interaction complexities between the key areas in the electricity generation landscape. A simplified projection model of the electricity market was then developed to observe how the dynamics of the energy landscape might evolve under different scenarios till 2100. The thesis would then conclude with a discussion on some of the model limitations and what some future work might be.

Chapter 2 | Literature Review

2.1 | Singapore's Geographical Circumstances

Singapore is a 687km^2 sized city-state island located 167km north of the Equator.[17,18] It is the 19th smallest countries in the world by size with a total population of 5.64 million (2018's figures), translating into a density of 8,209 people/km^2, which makes it the third most dense country in the world.[3,19,20] It borders Malaysia and Indonesia as its two closest neighboring countries and it is connected to Malaysia via two land-linked bridges. The highest geographic feature stands at 166m and there are no active volcanos within the country.[18] Average wind speeds are considered low at 2.5 m/s.[21] The average annual solar irradiance stands at 1,580 kWh/m^2/year with a daily sunshine (> 120W/m^2) duration range of 4 to 11 hours over the year.[21,22] The estimated total resources solar resource is about 5,000 MWp.[23] Essentially, solar power forms the only viable source of renewable energy for electricity generation and the current estimated limit could only fulfil up to 53% of current peak demand when the solar irradiance is maximally getting to the solar panels.[24]

2.2 | Economic Review

Main Economic Activities. Singapore has an advanced economy comprising high-technology industries such as oil-refining, electronics and high-precision manufacturing, and knowledge-intensive activities for communications, information, and finance services.[17] In the Southeast Asian region, Singapore ranks 3rd for total Gross Domestic Product (GDP) while it has the highest

GDP per capita. See **Table 2.1** for the summary of the 2017 GDP and GDP per capita of the member states in the Association of Southeast Asian Nations (ASEAN).[25]

Table 2-1: GDP and GDP Per Capita Data for ASEAN Member States (2017)[25]

Ranking	Country	GDP (Billions U.S. Dollars)	Ranking	Country	GDP per capita (U.S. Dollars)
1	Indonesia	1,015.29	**1**	**Singapore**	**59,990.06**
2	Thailand	455.32	2	Brunei Darussalam	28,278.43
3	**Singapore**	**336.68**	3	Malaysia	9,827.67
4	Malaysia	314.71	4	Thailand	6,730.56
5	Philippines	313.60	5	Indonesia	3,884.72
6	Vietnam	220.38	6	Philippines	2,988.90
7	Myanmar	66.72	7	Lao P.D.R.	2,555.09
8	Cambodia	22.23	8	Vietnam	2,353.36
9	Lao P.D.R.	17.07	9	Cambodia	1,387.94
10	Brunei Darussalam	12.13	10	Myanmar	1,267.38

High Regional and International Connectivity. Singapore is also home to one of the world's busiest shipping ports and airports. For shipping, the ports of Singapore handle an approximate 30.9 million Twenty-Foot Equivalent Unit (TEU) of cargo, making it the second busiest ports in the world in 2016, ranking behind Shanghai, China that handled 37.13 million TEU of cargo.[26] It is also the world's busiest transshipment port, connecting more than 600 ports across 120 countries worldwide.[27] The Changi International Airport, which has been named as the best airport in the world since 2013 and for many years before that, handles an annual passenger volume of 62.2 million in 2017, making it the 18th busiest airport in the world.[28,29] These data show that Singapore has the capability to and has established a robust connectivity infrastructure, making it a highly connected hub in the region that is well poised to take on larger roles in the future for the country and for the world economy.

2.3 | Current Plan for Meeting Electricity Demands and Emission Targets

Energy "Switches". According to the Ministry of Trade and Industry and the Energy Market Authority, Singapore main approach to providing reliable electricity while demand grows amidst growing challenges brought on by climate change would be through four main "switches".[30] They are namely: 1) Natural Gas; 2) Solar; 3) Regional Power Grid; 4) Emerging Low-Carbon Alternatives. Natural gas fired power plants will continue to be a mainstay in providing for baseload electricity in Singapore and the government is encouraging generating companies (Gencos) to improve their efficiencies through relevant grants. The target for solar is to reach 350MWp by 2020, 2,000 MWp by 2030, with 200MW of storage capacity by 2025. Singapore is also exploring how it can tap onto regional power grids to access renewable and cost-effective electricity options that may be realized through increased bilateral cooperation or regional initiatives. Lastly, the government is looking at emerging low carbon alternative technologies such as carbon capture or hydrogen fuel cells that can help Singapore lower its carbon footprint.[30]

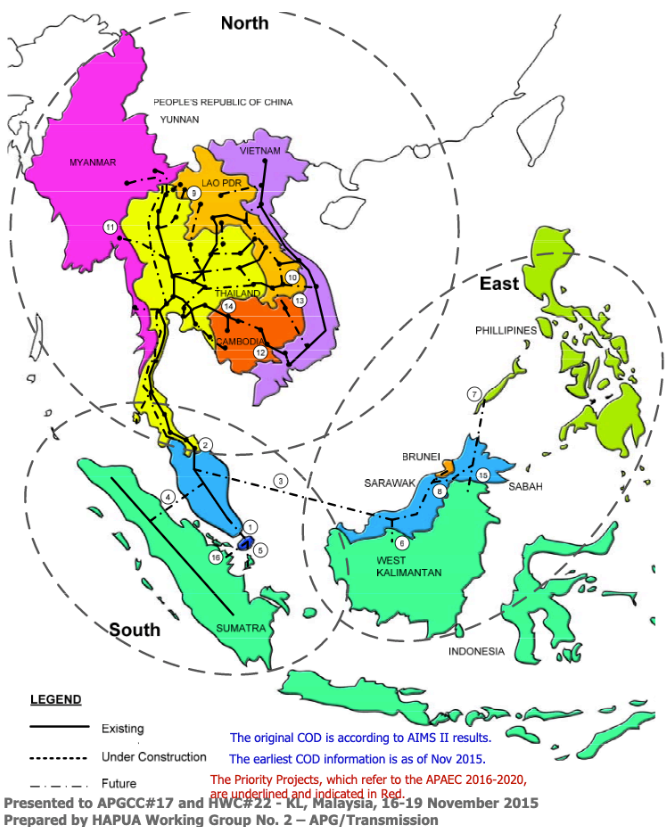
Energy Efficiency Measures. As Singapore has limited renewable energy options available to generate reliable baseload electricity, many of the measures proposed by the government are centrally focused on energy efficiency measures to reduce the energy intensity and carbon footprint of the nation.[11] The energy efficiency measures promoted by the government goes through the multi-agency committee, the Energy Efficiency Programme Office (E2PO), which was established in 2007 and it is by the National Environment Agency, together with the Energy Market Authority.[31] Business owners for Industrial facilities could leverage on funding incentives to implement energy initiatives or participate in programs that would allow easier access to financing and knowledge resources to achieve their energy efficiency targets.[32]

2.4 | ASEAN's Growing Energy Needs

Fulfilling ASEAN's Energy Demand Growth. The energy demands of the countries in ASEAN is expected to increase from 556.28 Mtoe to 1414 Mtoe in 2012 to 2030.[33] According to the latest outlook report by the International Energy Agency (IEA), the energy demand by 2040 in ASEAN in its Stated Policy Scenario would most likely be fulfilled by the indigenous production of fossil fuel resources, where the increase electrification would help more people gain electricity access but the needs would mostly be fulfilled by coal and gas while increased transportation needs would be fulfilled by oil.[34] The major implications of such a scenario include the shift in which ASEAN becomes a net energy importer that would be sensitive to cost and energy security instead of the previous role as a net energy exporter. GHG emissions would continue to rise while air quality deteriorates.[34] IEA's report also projected an alternative scenario, namely the Sustainable Development Scenario (SDS), that was projected to yield many benefits for the region through increased deployment of energy efficiency measures and renewable energy technologies, namely in solar, hydro, and wind. This can be achieved when regional electricity trading increase through the ASEAN Power Grid and when there are policy improvements that can address investment risks within the region to promote capital flow.[34]

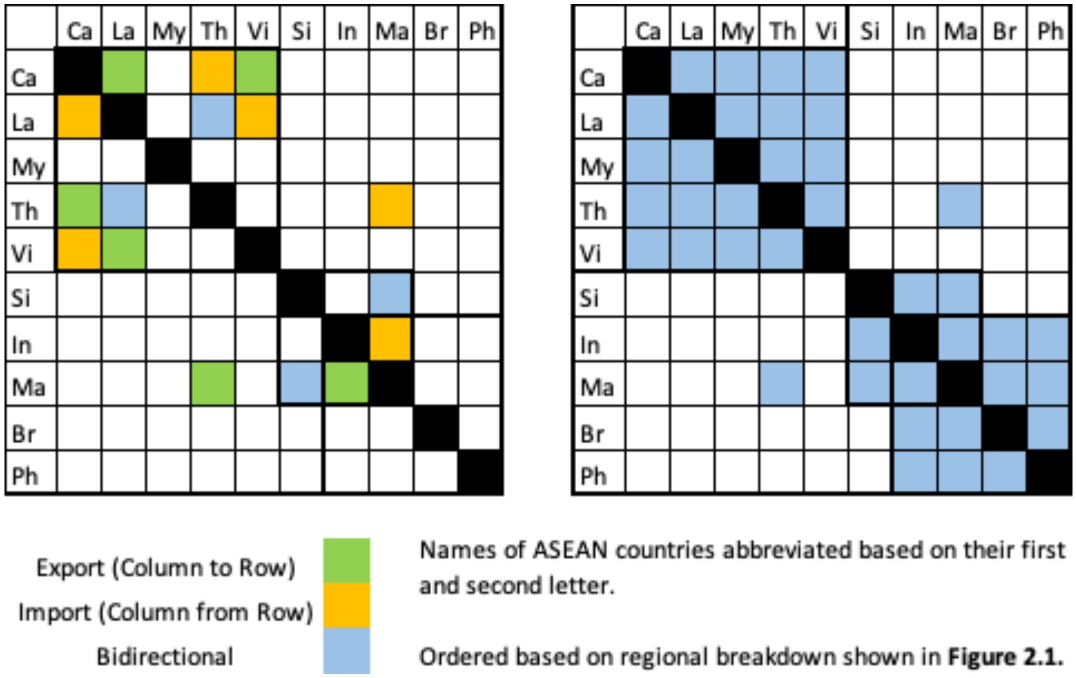
ASEAN Power Grid. The ASEAN Power Grid (APG) was introduced in 1997 in order to allow for regional power trading between ASEAN member states (AMS) to improve energy security, improve economics of power system development, expand electricity access, integrate variable renewable resources, and stimulate economic development of the region.[34,35] However, realized development remained largely bilateral in nature as multilateral trading has been hampered by differing national level opinions.[34] **Figure 2.1** shows the transmission connectivity plan between AMS that was developed by the Heads of ASEAN Power Utilities/Authorities (HAPAU) in 2015[33,36] and **Figure 2.2** depicts the current and envisaged power trading connectivity through a Design Structure Matrix (DSM). **Figure 2.2** shows that there are a lot more connectivity required between countries before the final goal of multilateral trading of electricity power would be achieved. For Singapore specifically, it currently has bidirectional power lines connected with Malaysia that was mainly for security and backup[34] and there might be submarine connections between Singapore and Indonesia beyond 2020, according to the HAPAU 2015 report.[33,36]

Figure 2.1: ASEAN Interconnection Projects



		Original COD	Earliest COD
1)	P.Malaysia - Singapore		
•	Plentong – Woodlands	Existing	Existing
•	P.Malaysia - Singapore (2nd link Plentong - Woodlands)	2018	post 2020
2)	Thailand - P.Malaysia		
•	Sadao - Bukit Keteri	Existing	Existing
•	Khlong Ngae - Gurun	Existing	Existing
•	Su Ngai Kolok - Rantau Panjang	2014	TBC
•	Khlong Ngae – Gurun (2nd Phase, 300MW)	2016	TBC
3)	Sarawak - P. Malaysia	2015 - 2021	2025
4)	P.Malaysia - Sumatra	2015	2021
5)	Batam - Singapore	2015 - 2017	post 2020
6)	Sarawak - West Kalimantan	2012	2015
7)	Philippines – Sabah	2020	TBC
8)	Sarawak - Sabah – Brunei	2020	
•	Sarawak –Sabah	2020	2020
•	Sarawak – Brunei	2012-2016	2019
9)	Thailand - Lao PDR		
•	Roi Et 2 - Nam Theun 2	Existing	Existing
•	Sakon Nakhon 2 – Thakhek – Then Hinboun (Exp.)	2012	Existing
•	Mae Moh 3 - Nan - Hong Sa	2015	2015
•	Udon Thani 3- Nabong (converted to 500KV)	2017	2019
•	Ubon Ratchathani 3 – Pakse – Xe Pian Xe Namnoy	2018	2019
•	Khon Kaen 4 – Loei 2 – Xayaburi	2019	2019
•	Nakhon Phanom – Thakhek		2015
•	Thailand – Lao PDR (New)	2015 - 2023	2019-2023
10)	Lao PDR – Vietnam	2011 – 2016	2016 - 2020
•	Xekaman 3 – Tranhmy	Existing	Existing
•	Xekaman 1 – Pleiku 2		2016
11)	Thailand - Myanmar	2016 - 2025	2018-2026
12)	Vietnam - Cambodia (New)		
•	Chau Doc – Takeo – Phnom Penh	Existing	Existing
•	Tay Ninh – Stung Treng	2016	TBC
13)	Lao PDR – Cambodia	2011	post 2018
14)	Thailand - Cambodia (New)	2015 - 2017	post 2020
•	Aranyaprathet – Banteay Meanchey	Existing	Existing
•	Thailand – Cambodia	2015-2017	post 2020
15)	East Sabah - East Kalimantan	Newly Proposed	TBC
16)	Singapore – Sumatra	2020	post 2020

Figure 2.2: Current and Envisaged Electricity Trade Relationships in ASEAN



2.5 | Nuclear Power for Singapore

Considering Alternate Baseload Technologies. Due to Singapore's limited geographical features, there would be limited ability for Singapore to provide renewable energy generated electricity for its neighbors. Considering that large proportion of electricity produced by natural gas fired plants, it would most likely remain the mainstay for generating baseload electricity at least for the next few decades. There are other baseload technologies available such as coal, oil, and nuclear. The former two were no longer considered by the government as they have larger carbon footprints than natural gas fired plants.[30] Nuclear power plants would be an alternative baseload technology that has less emissions than natural gas fired plants.[37] Including nuclear energy into the electricity mix could create excess capacity that could be exported to neighboring countries instead of having the neighboring countries using technologies that produces more pollution, such as coal fire plants.

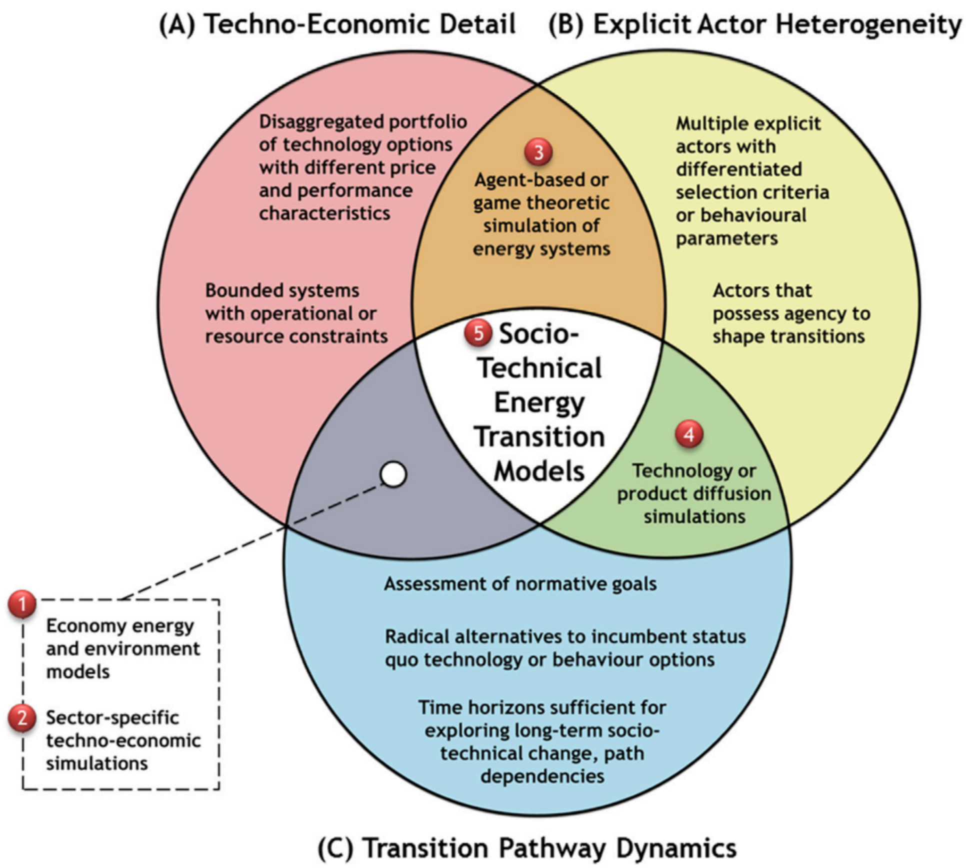
National Sentiments on Nuclear Power Plants. Building nuclear power plants for Singapore has been considered by the Singapore government before and a pre-feasibility study was conducted in the early 2011.[38] The official position from that study was that nuclear technologies then were not feasible for deployment and the government would continue to monitor technology development before committing further.[11,38] According to Ho et. al. (2018), the perceptions towards nuclear energy in Singapore were found to be generally unsupportive while the study participants understood that it could bring about many benefits.[13] As such, if nuclear was an option that would be developed, the government would need to address the concerns and ensure that there are sufficient measures implemented.

Offshore Floating Nuclear Plants (OFNP). Research in the National University of Singapore have previously suggested that offshore floating nuclear plants (OFNP) for Singapore might be feasible solution for deploying nuclear in Singapore.[38] OFNPs has the potential to eliminate earthquake and tsunami accident precursors, offering many safety and security features by design.[39] It could potentially leverage on Singapore's years of shipbuilding and rigbuilding capabilities to create an integrated solution that can work for Singapore.[40] The latest operationalized floating nuclear power plant, the $70MW_e$ *Akademik Lomonosov*, was built by the Russian state-owned atomic energy corporation, ROSATOM and it started operations in 2019.[41–43] China has plans to build 20 offshore floating nuclear power plants for oil and gas operations and the first platform is expected to be operational by 2021.[44,45] While the *Akademik Lomonosov* might be the most recent floating nuclear plant built for industrial activities, it's relatively low electricity output might have limited utility to serve Singapore's electricity needs. Larger scale feasible designs such as the VBER-300 (Russia), OFNP-300 (USA), and OFNP-1100 (USA) would be more suitable candidates to provide sufficiently large electric power while achieving the benefits that OFNPs can bring to Singapore and its neighbors.[38,39,46,47]

2.6 | Energy Transition Representation

The Needs for Modelling. The desire for a more sustainable future where net GHG emissions is zero or less require significant changes in aspects of policy choices, technologies, and lifestyle behavior.[48,49] Representing the potential behavior and choices between the relevant stakeholders through socio-technical energy transition (STET) models can thus help stakeholder understand the different potential outcomes, leading to new perspectives. While all decisions are based on mental models, and all models are wrong, representation remains important as it brings about a reference point in which valuable discussions can then be made.[50] It is also helpful in allowing us to understand the limits of the model where there might be missing factors during the development of mental models.[49,50] There are many models that have been used to understand energy transition and to address different policy questions, such as the popular MARKAL/TIMES model that is considered a linear-programming least-cost model approach.[49,51] These models are useful in finding optimal energy mix solutions and can be complemented by other models to better capture complexities arising from multiple feedback loops, nonlinear dynamics, and delays that can influence uptake and usage of different electricity production technologies.[49,52] Using the definition by Li and Strachan (2017), STET models should ideally capture the notions of Techno-Economic Detail, Explicit Actor Heterogeneity, and Transition Pathway Dynamics, as shown in **Figure 2.3**. However, when models try to have a wider breath to cover all three categories, it may end up trading off sufficient representations in depth and thus it is important for the modelers and people reading the models to be aware of the central problem that the model aims to show, the model's boundaries and performance limitations.[49,50,53]

Figure 2.3: Categorization and Definition of STET Models by Li et. al. (2017)



2.7 | System Dynamics

Using System Dynamics for Energy or Environmental Modelling. System dynamics (SD) models have been used in different levels of complexity to represent the problem of energy transition and energy-economic-environmental modelling. One of the most notable examples was the 1972 model developed by MIT on request by the Club of Rome thinktank, where it was used to understand the implications of continued worldwide growth, postulating the limits of economic and population growth.[54] In more recent times, SD has been used to represent energy transition or electricity markets for different parts of the world, such as Germany, India, Kenya, Norway, Oman, and Switzerland.[52,55–59] Each model studied different aspects of how economic or social conditions and decisions may affect changes in energy prices, investment in technologies, capacity changes et. cetera. In Singapore's case, there has been one SD related article that discussed how introducing nuclear energy may lower Singapore energy prices and emissions over five years, which was a considerably short time as compared to other energy system modelling.[60] As SD modelling is dependent on the equations and data inputs used by the modeler, insufficient representation, inadequate equations and unreliable data used to start off the model can lead to model outputs that may not be representative of actual behaviors and erroneous conclusions may be drawn from the model.[53,61] As such, it is important for modelers to find reliable data, ensure all equations are fully documented, where assumptions are listed and referenced so that future readers may be able to understand limitations within the model. Depending on the chosen level of modeling complexity and representation, SD usage in causal loop diagrams can provide a visual reference of key interactions in the complex problem for social technical energy transition while detailed analysis of model interactions and outputs can be studied through the relevant stock-and-flow models.[53,56]

Chapter 3 | Singapore's Electricity Landscape Transformation Model

Introduction. This chapter would first describe the causal loop diagram (CLD), basic narrative, and key alternative policy directions that could be done to change the Singapore's electricity landscape. **Section 3.2** would explain what goes into the detailed stock-and-flow (S&F) model of each CLD components. This would allow a basic understanding of how different factors come together before transiting to **Chapter 4** where the results from the stock-and-flow model interactions under different policy scenarios would be discussed. The models were built using Ventana Systems's Vensim® DSS Macintosh Version 7.3.7 Single Precision (henceforth VensimDSS) software and was made accessible by the MIT Academic Use License. The detailed model's full documentation of the detailed equations for each variable has been listed in alphabetical order in **Appendix 1**. The list of simplified variable description in the detailed S&F model can be found in **Appendix 2**, categorized in order of appearance in **Section 3.2** and alphabetically within each sub-section. The information was generated through a feature found in VensimDSS. All data discussed henceforth and the model file have been made available on the Internet.[1]

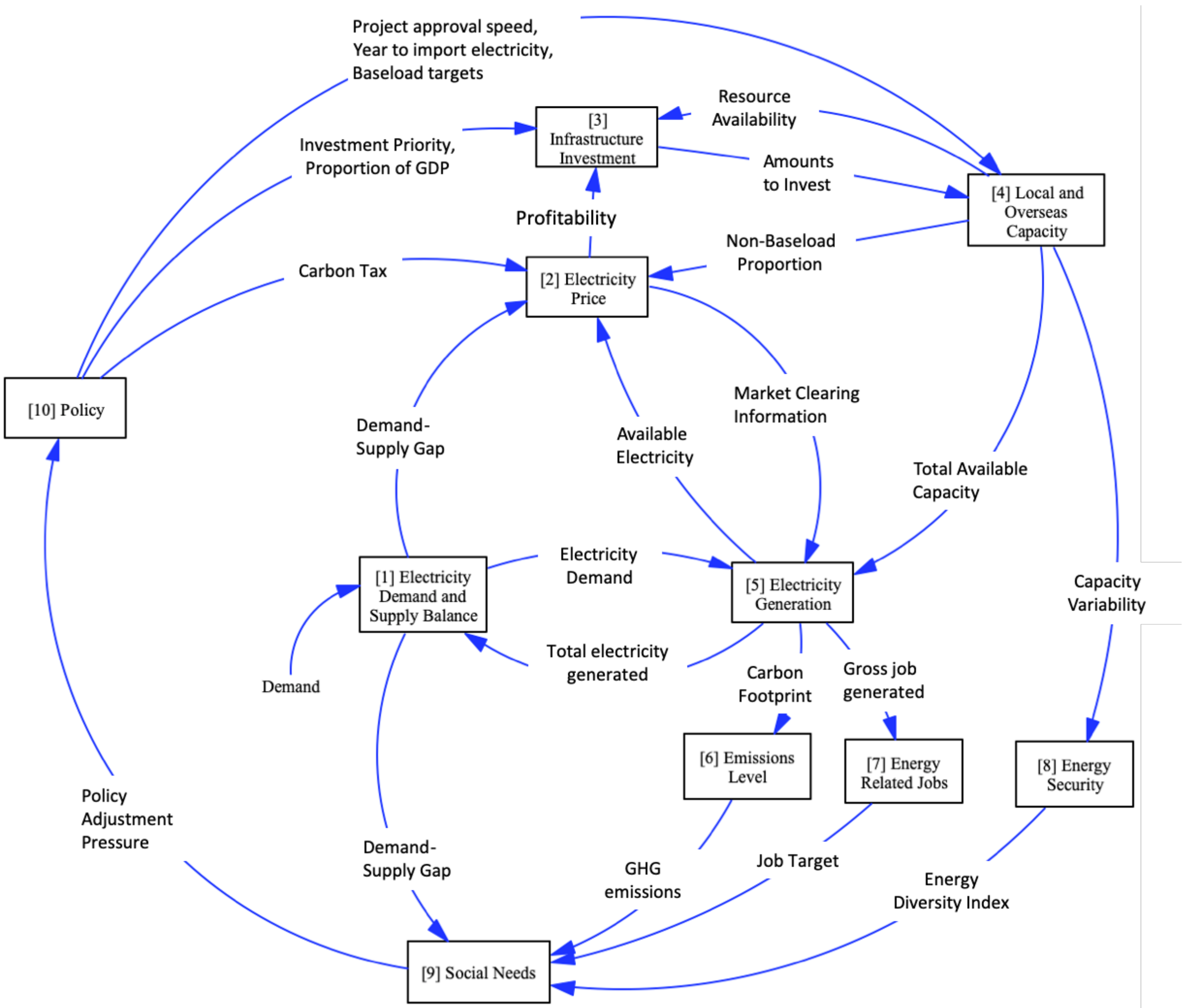
3.1 | Basic Model and Broad Narrative

Representing Socio-Technical Interactions. Singapore's electricity generation landscape was first simplified into a CLD that comprised ten key interacting components, as shown in **Figure 3.1.** It was inspired by the work of many System Dynamics (SD) modelers examining energy

[1] All model and data files can be found in the following link: http://bit.ly/ZhiyuChen_MIT_Thesis_Files. The author can be contacted at judechen@alum.mit.edu.

transition.[53,56–58,62–65] The CLD representation allowed for a simpler narrative of the dynamic complexities that goes on between the economy, technology, and social groups. In **Figure 3.1**, key variables that were passed between components have been indicated with arrows and it was aimed at highlighting the most important connections between components. Each interacting component has a S&F model that were built in separate view tabs within one model file in VensimDSS to allow the various component to interact together in a dynamic behavior. The S&F models would be discussed more in **Section 3.2**.

Figure 3.1: Causal Loop Diagram of Singapore's Electricity Generation Transformation Model



Basic Narrative. Electricity demand arises from the population's activities. The electricity market fulfils the demand through electricity generation from the available capacity and a sensible market price considering the demand-supply balance and costs for the companies. The long-term profitability potential and resource availability then incentivizes investments from more generation companies which will increase the total available capacity over time. Having more capacity available will then fulfil the growing demand.

Aside from fulfilling the market, there are other effects brought on by the electricity generation which are considered here, namely the GHG emissions, energy security, and the energy sector job market. The gaps between what are set as targets and what are fulfilled create social needs that comes together to create policy pressure. Greater policy pressure then drives policy implementations into the different levels of the electricity market such as the pricing, investment, and capacity in the electricity sector. While what was described above might seem like a relatively linear interaction, there are interactions within and between the various components that do so continuously and that is what leads into dynamic behaviors that creates emergent complexity and tradeoffs for the different stakeholders.

Alternate Possibilities Explored. Different policy conditions can be explored using the detailed same stock-and-flow model for internal comparison. In this thesis, the dynamic outcomes of a baseline and two alternative policy conditions were explored. The first alternative studied was the import of electricity from offshore floating nuclear power (OFNP) plants. The second alternative was importing electric from renewables from neighboring countries and OFNP plants. The alternatives were made with due considerations from the thesis question. Having these alternatives might help Singapore lower its reliance on natural gas and thus help lower economic risk. While importing electricity from renewable sources from neighboring countries does not necessarily lower the geopolitical risks, it might help Singapore in achieving lower emissions outcome and thus it might be useful to consider this alternative alongside the other benefits of increased bilateral cooperation, which would be aligned to what the plan was for the ASEAN power grid.[33,66] The alternative electricity generation landscapes are observed in many countries of the European Union too so it would be worthwhile to consider what the possibilities might be when applied to Singapore's regional context.[67]

3.2 | Detailed Description of Sub-Categories in the Stock-and-Flow Model

Initial Setup. The stock-and-flow model started at the year 2010 and projected forward to 2100, with time units in years. As there were random number generators used within some equations in the model, a random seed number was set at 1234 for consistency whenever it was used. The random seed number formed the reference number for pseudo-random number generation in the software. Variables used in the S&F models discussed henceforth would be indicated in italicized font and indicated with <> brackets. **Table 3-1** provides an explanation for the color code to the subsequent S&F model diagrams.

Table 3-1: Color Code for Subsequent Stock-and-Flow Diagrams

Variable's Color	Significance
	Variables/constants used only in the current view of the stock-and-flow model.
	Key constants that might be adjusted for sensitivity analysis or policy scenario.
	Constants from other interacting component's stock-and-flow model.
	Variables from other interacting component's stock-and-flow model.
	Variables that would be passed over to another interacting component's

3.2.1: Electricity Demand and Supply

Base Demand Modelling. The demand component is built as an exogenous input into the overall model largely based on the demand model described in by Nian (2015) from the Energy Studies Institute of the National University of Singapore (NUS).[68] As Singapore is considered an advanced economy with high electricity penetration, the base demand is assumed to be directly proportionate to the population, thus named as *<Population Based Electricity Demand>*.[68] This is shown in the blue dotted region in **Figure 3.2**. Population data such as the 2010 total population data and the population growth rate was estimated based on the data provided by the projections reported by the Institute of Policy Studies, NUS[69] and is summarized in **Table 3-2**. Instead of a Total Fertility Rate (TFR) approach, the reported projections under different scenarios were converted to a compounded annual growth rate (CAGR) (**Equation 1**) and applied from 2010 onwards. The medium growth projection, calculated to be 0.6462%, was used and represented as *<Population Growth Rate>*. The *<Electricity Demand Per Capita>* was assumed to remain constant[68] and was estimated at 8,587.776kWh/capita, which was the average demand per capita for Singapore from 2004 to 2014, as reported in the World Bank and the International Energy Agency (IEA).[70]

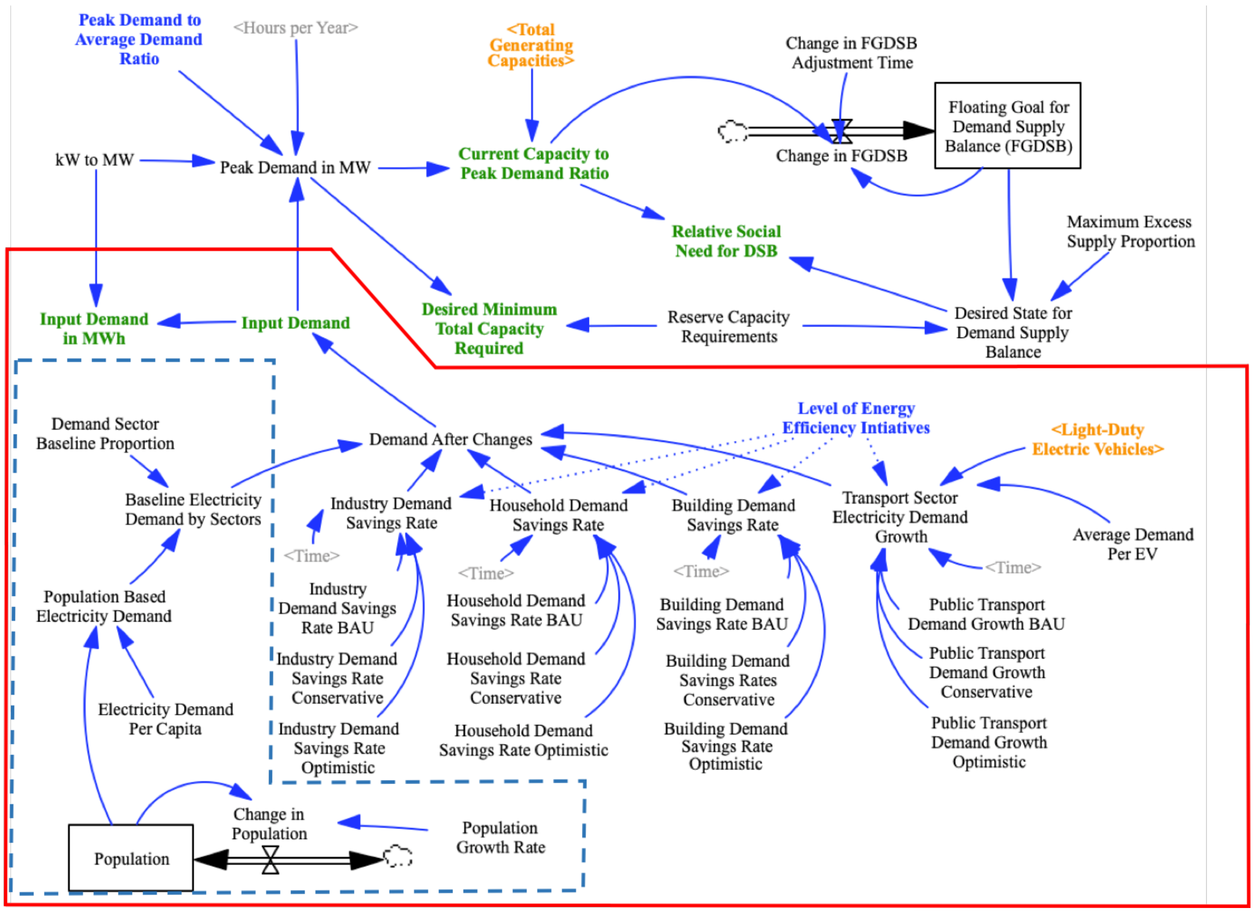
Equation 1: Compound Annual Growth Rate

$$CAGR = \left(\frac{Future\ Value}{Present\ Value}\right)^{\frac{1}{Number\ of\ Periods}} - 1$$

Table 3-2: Population Data Used

Population Scenario	Year 2010 (Millions)	Year 2050 (Millions)	CAGR (2010 to 2050)
Low Growth	5.034	6.118	**0.489%**
Medium Growth	5.034	6.525	**0.651%**
High Growth	5.034	7.305	**0.935%**

Figure 3.2: Electricity Demand and Supply Stock and Flow Sub-model



Demand Change Modelling. After the *<Population Based Electricity Demand>* was formed, it was then divided according to the National Climate Change Secretariat (NCCS) sectoral groups with specific proportions as indicated in brackets: Industry (43%), Buildings (31%), Transport (5%), Household (18%), and Others (3%).[68] It is assumed that the proportions between categories remains unchanged over time. The model on energy efficiency initiatives for electricity demand proposed by Nian (2015) was also adopted here, as shown by the region marked by the red-polygon in **Figure 3.2**. In brief, the model established three different energy efficiency (EE) scenarios, namely Business-As-Usual (BAU), Conservative, and Optimistic. Each EE scenario had different penetration rates all five categories mentioned above except Others and for two time phases.[68] The first time phase (2010 to 2030) expected that hardware penetration rates to be low and efficiency was achieved through system management of people and operations. The effects of hardware changes were assumed to be more dominant in the second phase (2030 onwards).[68] The different effects then translated into effective changes in demand percentages as compared to initial input. The changes in demand have been summarized in **Table 3-3**.[68] Rates till 2100 was linearly extrapolated based on the second phase rates (2030 to 2050) in Nian (2015).

Table 3-3: Demand Change Rates from Energy Efficiency Initiatives (Demand Curtailment)

Cate-gory	Industry (%)			Building (%)			Transport						Household (%)		
							Light-Vehicle EV Penetration (%)			Cumulative Public Transport Demand (GWh)					
Year	**B**	**C**	**O**	**B**	**C**	**O**	**B**	**C**	**O**	**B**	**C**	**O**	**B**	**C**	**O**
2030	1.0	1.5	2.5	3.0	6.0	12.0	0.0	0.0	3.0	1740.0	1741.5	1745.0	0.5	1.0	2.5
2050	3.0	5.0	7.0	6.0	7.5	15.0	0.0	1.0	5.0	1740.0	1743.0	1760.0	1.0	2.0	5.0
2100	8.0	13.75	18.25	13.5	11.25	22.5	0.0	3.5	10.0	1740.0	1746.75	1797.5	2.25	4.5	11.25
Legend:	**Negative values**			**Positive values**			**B: Business-As-Usual**				**C: Conservative**		**O: Optimistic**		

All sectors except Transport had a decrease in electricity demand compared to the initial demand. The Transport sector's increase in electricity demand was due to the increased penetration of Light-Vehicle Electric Vehicles (EV) and increased public transport system (subways & electric buses) electricity needs. The component of EV penetration modelling would be discussed in **Section 3.2.6** as vehicle emissions were calculated there. The <*Level of Efficiency Initiatives*> variable shown in **Figure 3.2** above can take on a value of 0 (BAU), 0.5 (Conservative), or 1 (Optimistic) to function as a switch mechanism for the right lookup for the calculations in the corresponding savings rates.

Demand-Supply Balance (DSB). After adjusting the demands according to the level of energy efficiency initiatives, the demand is then summed up into <*Input Demand*> for further use by other parts of the model. The <*Peak Demand in MW*> variable was calculated by adjusting <*Input*

Demand> with a <*Peak Demand to Average Demand Ratio*> variable. The <*Peak Demand to Average Demand Ratio*> was determined through historic monthly load data from the Energy Market Authority (EMA).[71] Data provided included the monthly average and maximum loads across the four load centres in Singapore. The total average and maximum loads each month were calculated and compared to determine how much higher is every month's maximum compared to the average. The median value from Aug 2010 to Sep 2019 used.

The <*Current Capacity to Peak Demand Ratio*> was calculated by dividing the <*Total Generating Capacities*> by the <*Peak Demand in MW*>. The <*Total Generating Capacities*> is the net total installed capacity available to generate electricity after incorporating grid losses, capacity utilisation, and seasonal availability factors. The <*Desired Minimum Total Capacity Required*> was set as equal to the <*Peak Demand in MW*> plus a <*Reserve Capacity Requirements*>, which was currently mandated at 30% of peak demand.[24] The <*Relative Social Need for DSB*> was calculated by dividing the <*Desired State for Demand Supply Balance*> by the <*Current Capacity to Peak Demand Ratio*>. To determine the <*Desired State for Demand Supply Balance*>, a floating goal mechanism was used.[53,56] The mechanism was chosen as the final goal state of DSB would not be fixed as there can be other forces driving the DSB beyond the mandated 30%. It was assumed the <*Maximum Excess Supply Proportion*> was 100%. Thus, the <*Desired State for Demand Supply Balance*> was bounded between 1.3 to 2. This meant that if the <*Floating Goal for Demand Supply Balance*> dropped below 1.3, the <*Desired State for Demand Supply Balance*> would hold at 1.3. If the <*Desired State for Demand Supply Balance*> was higher than the current state (>1) this signifies that the more capacity would be required, and this has been reflected through the <*Relative Social Need for DSB*>.

3.2.2: Pricing

Calculating Levelized Cost of Electricity (LCOE) and Marginal Costs. The cost factors that goes into the power plants needs to be first calculated before the investment profitability and energy price were determined. The LCOE methodology has been a common method that have been used to compare the profitability potential across different electricity generating technologies.[72,73] When it comes to bidding into the market for wholesale generation, it was assumed that electricity generation companies would bid based on their marginal costs and other considerations such as market demand and supply balance.[74,75] The same concept was thus applied in the model. The model to determine *<LCOE>* and the *<Expected Marginal Cost>* is shown in the green area indicated in **Figure 3.3** and the LCOE formula is shown in **Equation 2**. The *<Expected Marginal Cost>* cost calculation is similar to LCOE calculation, but without the *<Depreciated Investment Cost DIC>* component.

Equation 2: Levelized Cost of Electricity

$$LCOE\ (USD/kWh) = \frac{OIC \times CRF + O\&M_{Fixed}}{\frac{8760hrs}{year} \times Capacity\ Factor} + FC\ \times Heat\ Rate + O\&M_{Variable},$$

where CRF: Capital Recovery Factor,
FC: Fuel Cost,
OIC: Overnight Investment Cost,
$O\&M_{Fixed}$: Fixed Operations and Maintenance,
$O\&M_{Var}$: Variable Operations and Maintenance.

The data for OCC, $O\&M_{Fixed}$, $O\&M_{Variable}$, CRF, and capacity average lifetime were obtained from the Intergovernmental Panel on Climate Change (IPCC) Working Group III's report.[76] Waste-to-Energy's data was not listed and its corresponding assumptions was proxied by the Biomass-CHP's data in the report. The CRF is a factor that coverts the OCC into a constant annuity at an interest rate that was assumed to be 5% here over the plant's expected lifetime.[76] The CRF formula is shown in **Equation 3** below.

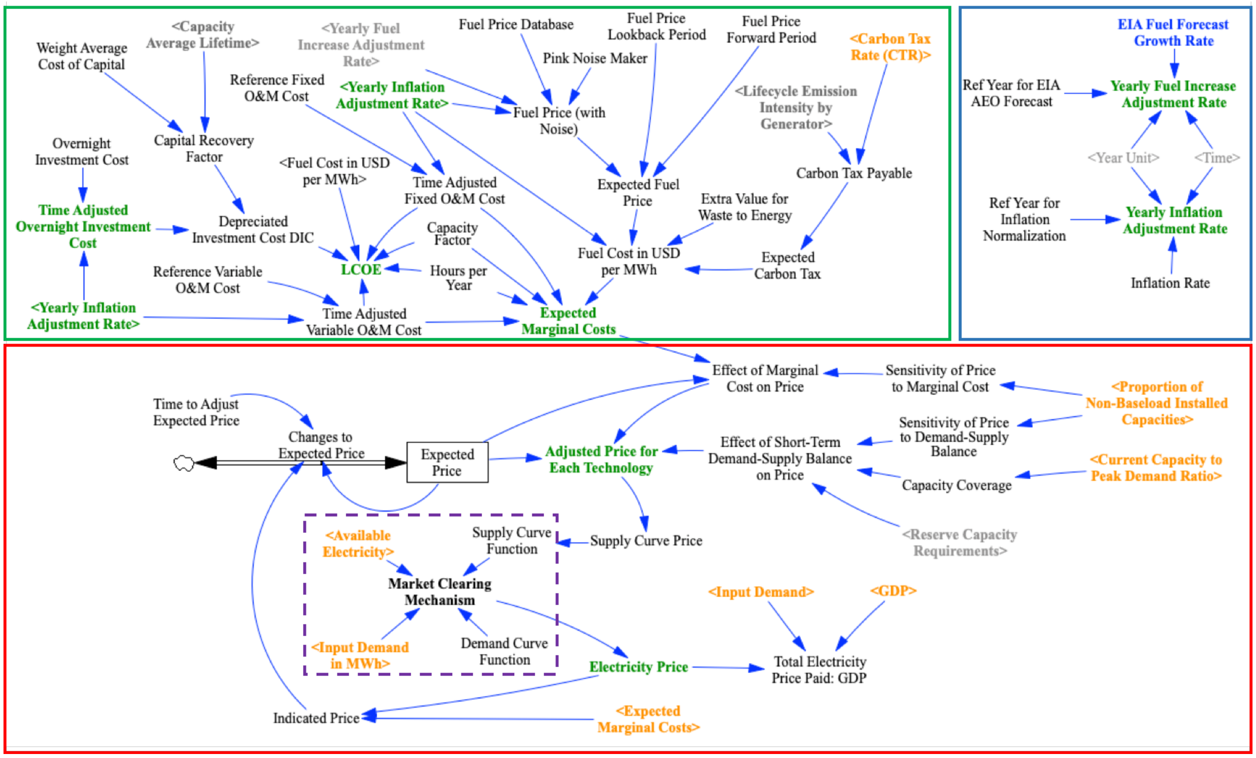
Equation 3: Capital Recovery Factor

$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$, where

i = Weight Average Cost of Capital (5%)

n = Capacity Average Lifetime

Figure 3.3: Pricing Sub-model



Fuel Cost Calculation. In Singapore, electricity market generator companies use reported to be using oil forward fuel oil swaps contracts to determine the natural gas import prices.[77] As a proxy, the Brent Index data from 2010 to 2018 reported by the Intercontinental Exchange was used for the natural gas price in the *<Fuel Price Database>* variable.[78] The fuel price data for all other technologies were obtained from the Intergovernmental Panel on Climate Change (IPCC) Working Group III's report.[76] Specifically, only nuclear had fuel cost while the other technologies were at zero and waste-to-energy's (WTE) fuel cost was assumed at zero.[76] WTE's "fuel" was based on waste collected from its business operations and thus the cost was assumed as part of its operating costs. Additionally, as WTE was able to sell the ash products produced, an *<Extra Value for Waste to Energy>* component was added to reflect this possibility and the data was from the IPCC report.[76] Price data for natural gas and nuclear fuel beyond 2019 onwards included a pink noise mechanism with a standard deviation of 10% to mimic price movements observed in the Brent Index data. Carbon tax has been introduced in September 2019 at approximately 3.7USD/tonneCO2 and this has been included in the model through the *<Carbon Tax Rate>* variable. The *<Carbon Tax Rate>* was expected to adjust endogenously over time in the model and the mechanism on how that would be done would be covered in **Section 3.2.10**.

Estimating Undersea Transmission Cost. To import electricity, Singapore would require undersea transmission cables. Thus, the *Overnight Investment Cost* component would need to be adjusted upwards to include the transmission cables cost accordingly. It was assumed that undersea cables would be approximately 150km in length and that would require additional 200,000 USD/MW for each overseas technology. The estimation was calculated based on the data provided by the Joint Resource Centre of the European Commission on the SAPEI, a 730M€, 700MW HVDC, 450km long submarine cable that was also the world's deepest submarine cable as of 2015.[79]

Reference Costs Adjustment Factors. The model for the adjustment factors is shown in the blue rectangle region in **Figure 3.3**. The reference data obtained from the IPCC WG-III's report were all based in 2010's dollars[76] and were time adjusted with an inflation factor to estimate a future investment. The inflation rate was estimated at 1.6% based on median value of annual year-on-year core inflation rates reported by the Monetary Authority of Singapore and the Department of Statistics, Singapore from 2000 to 2018.[80] Fuel cost growth rates for natural gas and nuclear fuel were based on the reference rates provided by the EIA that included a series of scenarios that have a nominal annual growth rate at 3.5% and a range between 3.2 % to 3.8% growth till 2050, for high and low oil and gas extraction technology scenarios respectively.[81]

Determining Energy Price. The SD approach to model price setting is largely based on the price-setting process described by Sterman (2000)[53] and as shown in the red box within **Figure 3.3**. Price adjustment for each electricity generating technology arose through a few factors, namely: previous price as reference, demand-supply balance and the variable cost of production.[53] This is shown in **Equation 4**. This mechanism described in Sterman (2000) was based on the observations that prices provide information about the equilibrium but there are effects from different factors that adjusts the prices and shifts the equilibrium accordingly.[53] This is similar to an anchor-and-adjustment mechanism that included effects of short-term demand-supply balances and marginal costs.

Equation 4: Adjusted Price for Each Technology

$$Adjusted\ Price\ for\ Each\ Technology = Expected\ Price\ \times\ f_1(Cue)_1 \times\ f_2(Cue)_2,$$

where $f_1(Cue_1)$ = Effect of Marginal Cost on Price
$f_2(Cue_2)$ = Effect of Short-Term Demand-Supply on Price

The *<Effect of Marginal Cost on Price>* took on the form shown in **Equation 5**, which was extracted from Sterman (2000). If the *<Sensitivity of Price to Marginal Cost>* was at zero, the effect of marginal cost would be ignored in Equation 4's formulation. On the other end, at 1, the price would be heavily anchored on marginal cost. For this model, the *<Sensitivity of Price to Marginal Cost>* variable has the form of 1 - *<Proportion of Non-Baseload Installed Capacities>*, indicating that as non-baseload capacities increase, the effect of marginal cost on price would decrease.

<u>Equation 5: Effect of Marginal Cost on Price</u>

$$Effect\ of\ Marignal\ Cost\ on\ Price = 1 + f_{MC}\left(\frac{Expected\ Marginal\ Costs}{Expected\ Price} - 1\right),$$

where f_{MC} = Sensitivity of Price to Marginal Cost
= 1 – Proportion of Non-Baseload Installed Capacities.

The *<Effect of Short-Term Demand-Supply Balance on Price>* variable took on the form shown in **Equation 6**. The simple power function was used here and the sensitivity factor was used as the exponent where it has the form of *<Proportion of Non-Baseload Installed Capacities> - 1* as it should have negative values to model that higher capacity coverage leads to lower prices.[53]

<u>Equation 6: Effect of Short-Term Demand Supply on Price</u>

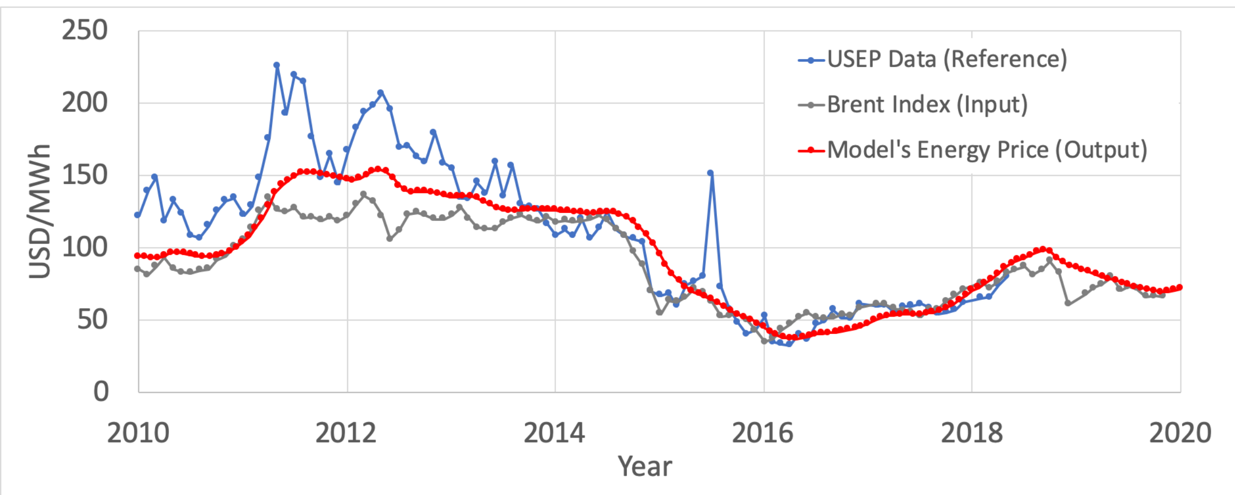
$$Effect\ of\ Short\_Term\ Demand\_Supply\ Balance\ on\ Price = \left(\frac{Capacity\ Coverage}{Reserve\ Capacity\ Requirements}\right)^{f_{DSB}},$$

where f_{DSB} = Sensitivity of Price to Demand-Supply Balance
= Proportion of Non-Baseload Installed Capacities – 1

<u>Market Clearing Mechanism</u>. After the *<Adjusted Price for Each Technology>* has been modelled, the next critical component was to model the market clearing mechanism, which required the establishment of the demand and supply curves, shown in the purple dotted box region in **Figure 3.3**. The demand curve was assumed to be inelastic with a demand equals to the *<Input Demand in MWh>*. The supply curves of each generation technology were built into a composite supply curve based on the *<Adjusted Price for Each Technology>* and *<Available Electricity>*, which the latter indicates the amount of electricity available by each technology to generate after incorporating grid losses, capacity utilization, and capacity factor. This variable is similar to the <*Total Generating Capacities*> described before but it is specified for each technology rather than the net total and it is also in the MWh form instead of the MW form.

Comparing Electricity Price with Actual Data. Actual electricity prices, namely the Uniform Singapore Electricity Price (USEP), from 2010 to 2018[82] was compared with the output data of the Business-As-Usual scenario from the model and it is shown in **Figure 3.5**. The model's energy price output (red line) seemed to follow similar trends to the USEP (blue line) reported by the Energy Market Authority (EMA). According to the Singapore Energy Statistics 2018 report, the spikes in the USEP for the 2011 and 2015 periods were due to unforeseen circumstances in planned and unplanned maintenance scheduling.[82] It was thus concluded that the proposed model has captured the dynamics of the actual energy price sufficiently.

Figure 3.4: Actual vs Simulated Energy Price (BAU) from 2010 to 2018



3.2.3: Infrastructure Investment

Investment Priorities Amongst Different Generating Technologies. The model component to focus on is shown in the purple box of **Figure 3.4**. The variable <*Investment Resource Allocation*> takes in the total amount of money that might be invested, represented by <*Annual Investment in Electricity Infrastructure*>, which was based on a proportion of GDP, and allocated according to each technology's <*Investment Priority*> and the <*Desired Capacity's Investment Cost*>. The

<Investment Priority> variable was driven by three factors, namely: 1) *<Remaining Resource Ratio>*; 2) *<Effect of Generation Profit>*; and 3) *<Policy: Boost Infrastructure Investment>*. The first two would be discussed in this section while the last component would be discussed in further detail in **Section 3.2.10**.

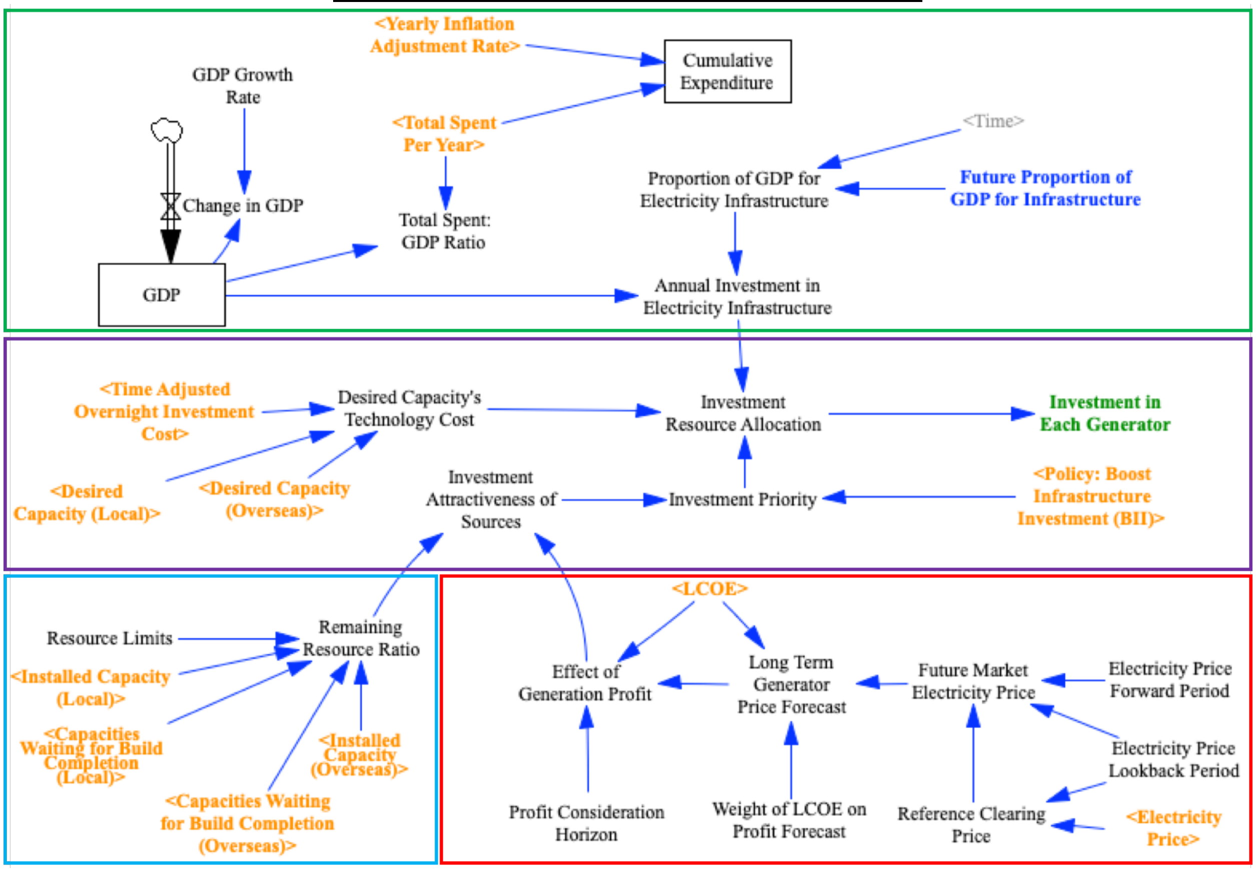
Resource Limitations. This was modelled based on the interactions represented in the blue box region of **Figure 3.5**. Investment in generation capacities could only occur when there are physical resources available to be invested in. As it was not expected for Singapore to be able to use a significant proportion of its neighbors' available renewable resources, the available limit was set at 10% of the total estimated overseas renewable energy.[33,83] The geographical area of interest was bounded to Malaysia and the state of Sumatra, which is a major state of Indonesia that is nearest to Singapore. The nuclear energy limit was currently estimated at 5,000MW as Singapore has limited offshore positions or underground[2] options. A feasible design of offshore floating nuclear power plants have been currently scoped at up to 1,100MW per unit and it was assumed that there could be up to five such sites in and around Singapore.[84] The local natural gas fired and waste to energy limit was bounded to 20% higher than the latest reported installed capacity of 2018 as it was not expected there would be significantly more land provided for power plants to build beyond what was already built. The Local Solar PV estimates was obtained from the Sustainable Energy Association of Singapore.[23] **Table 3.4** shows the summary of resource limits applied in this model.

[2] Technically feasible but have not been implemented anywhere yet.

Table 3-4: Estimated Resource Limits

Generator Type	Resource Limits (MW)	Generator Type	Resource Limits (MW)
Local Natural Gas Fired	16,000	Overseas Solar PV	14,400
Local Waste to Energy	310	Overseas Hydro	4,500
Local Solar PV	6,000	Overseas Geothermal	1,300
Overseas Nuclear	5,000	Overseas Onshore Wind	360

Figure 3.5: Infrastructure Investment Sub-Model



Profitability Outlook. The profitability assessment for each technology was calculated based on the model shown in the red rectangular region of **Figure 3.5**. Centrally, profitability was assumed to be dependent on the both the future electricity price and the cost of the generation technology. The *<Future Market Electricity Price>* performed forecasts of electricity prices. The *<Long-Term Generator Price Forecast>*, shown in **Equation 7**, was determined based on a weighted average between the future electricity price and the lowest LCOE amongst all the technologies.[56,58] From there, the final output variable *<Effect of Generation Profit>*, shown in **Equation 8**, was calculated based on the consideration of each technology, the <*Long-Term Generator Price Forecast*>, and a <*Profit Consideration Horizon*>.[56,57]

Equation 7: Long-Term Generator Price Forecast

$$Long\_Term\ Generation\ Price\ Forecast\ = FP \times (1 - Wt_{LCOE}) + Min(LCOE) \times (Wt_{LCOE}),$$

where FP = Future Market Electricity Price,
Wt_{LCOE} = Weight of LCOE on Profit Forecast = 0.25 (Ref: Vogstad 2004),
Min(LCOE) = Lowest LCOE amongst all generating technologies.

Equation 8: Effect of Generation Profit

$$Effect\ of\ Generation\ Profit = \ exp^{\frac{SMOOTH[(LG_{Price}), Horizon_{Profit}]}{SMOOTH[(LCOE), Horizon_{Profit}]}},$$

where LG_{Price} = Long Term Generation Price Forecast,
$Horizon_{Profit}$ = Profit Consideration Horizon = 4 years.

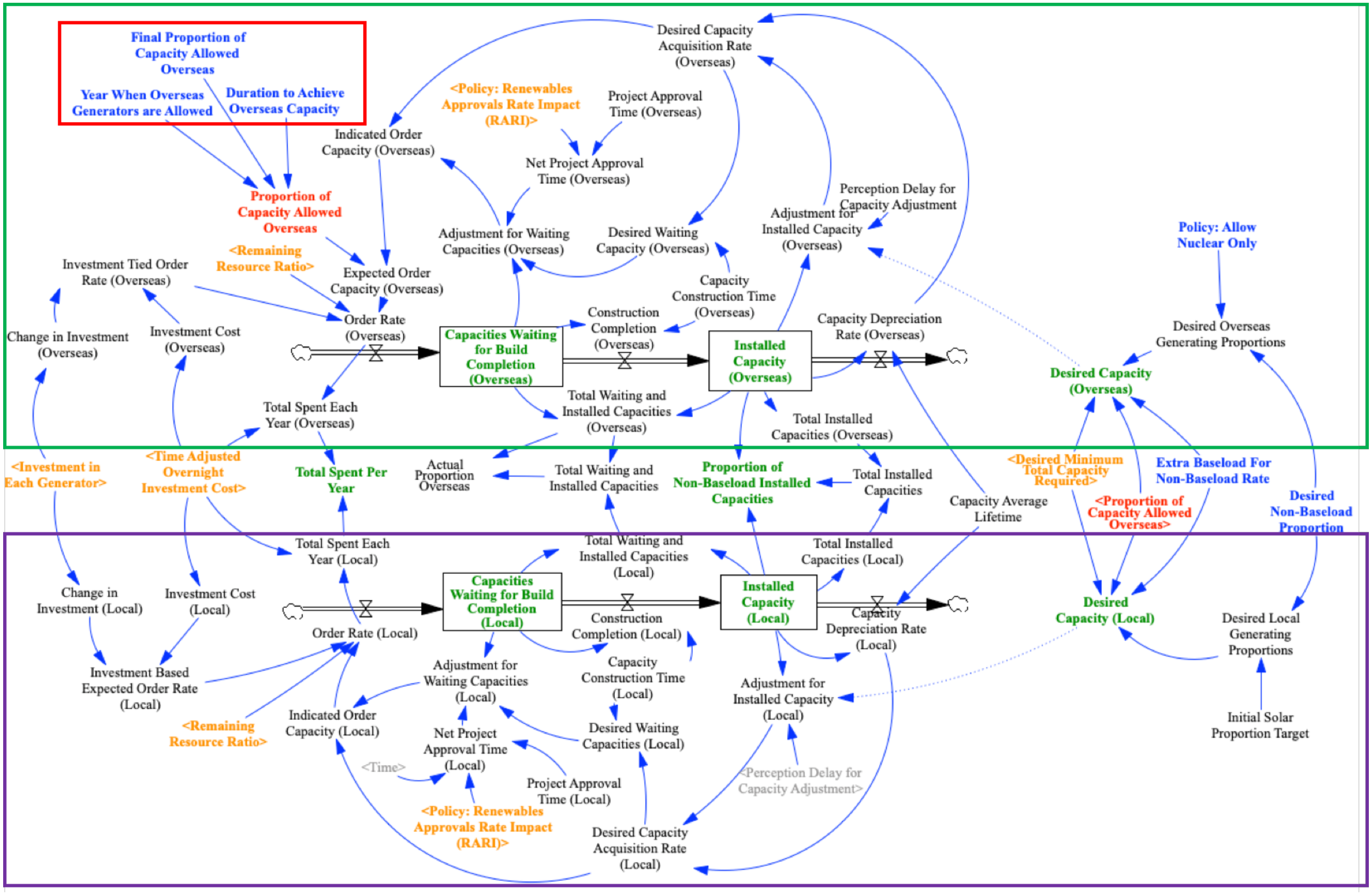
GDP Estimation and Proportion of GDP for Infrastructure Investment. The GDP projection and electricity infrastructure investment amount were calculated based on the model shown in the green rectangular region of **Figure 3.5** The initial GDP data for Singapore was obtained from the World Bank and the final estimated growth rate per year (2.58%) was obtained through the median value of year-on-year GDP growth rate from 2000 to 2018[85], which was then adjusted down based on the inflation rate. The <*Annual Investment in Electricity Infrastructure*> was calculated based on the GDP and the <*Proportion of GDP for Electricity Infrastructure*>. The proportion variable was estimated at 0.5% for 2010 to 2019, as reported by Global Infrastructure Outlook[86], and an adjustable input (*Future Proportion of GDP for Electricity Infrastructure*) for 2020 onwards to observe policy changes when different amounts were used.

3.2.4: Local and Overseas Capacity

Stock Management Structure. The buildup and retirement of generating capacities are modelled based upon the stock management structure, shown in **Figure 3.6**, which have been commonly used in SD to describe supply lines.[53] The stock management structure allowed the differentiation between capacities that are being built and capacities that are already built and providing supplies. Expired capacities with other key drivers would then drive the future acquisition of new capacities over time. The stock management structure for the local and overseas capacities have the same overall structure but they were built separately within **Figure 3.6** to allow the differences in assumptions and policy mechanisms between them to be shown more easily. The key components in **Figure 3.6** would be described starting from the top left corner.

Allowing Electricity Import. The alternative scenarios explored in this thesis were based on the notion of allowing import of electricity generated from renewable or low carbon sources. We can expect that even if the government allows electricity import, there would be a limit to how much would be imported and that limit would adjust over time. That idea is represented by the red box in **Figure 3.6**. The <*Year When Overseas Generators are Allowed*> variable sets the starting year in which electricity could be imported and it could have a value between 2025 to 2100. The <*Final Proportion of Capacity Allowed Overseas*> variable was assumed to be 0.5, indicating an upper limit of 50% for electricity import. The limit is adjusted on a linear basis based on the *Duration to Achieve Overseas Capacity* variable, which is assumed at 20 years. Using a specific example, the <*Proportion of Capacity Allowed Overseas*> (indicated in red in **Figure 3.6**) linearly increases from 0 to 0.5 between 2025 to 2045 if electricity import is allowed from 2025 onwards (2.5% in the first year, 5% in the second, and so on until 50% by 2045).

Figure 3.6: Local and Overseas Capacity Sub-Model



Project Approval Time. Before generating capacities can start construction, the project must first be approved by the government. The related project approval time variables are indicated by the <*Project Approval Time (Local/Overseas)*> variables. The project approval waiting time for local projects was assumed at 1 year, based on the information provided by the Energy Market Authority of Singapore.[87] The project approval time for overseas projects was assumed to be longer than the local rate and set at three years.[88] The final approval times were modelled to be adjustable according to the social pressure, based on the concept that with sufficient pressure from social needs, project approvals could be expedited up to a certain limit. The adjusted project approval times were represented by the <*Net Project Approval Time (Local/Overseas)*>.

Order Rates. The approval time just discussed would be used to then convert the difference between <*Desired Waiting Capacities (Local/Overseas)*> and the stock of capacities undergoing construction <*Capacities Waiting for Build Completion (Local/Overseas)*> into a rate, forming the <*Indicated Order Capacity (Local/Overseas)*>. This formulation could be viewed similarly to an anchor-and-adjustment mechanism.[53] The <Indicated Order Capacity (Local/Overseas)> and the <*Investment Based Expected Order Rate*> is summed to form the <*Order Rate <(Local/Overseas)*>.

The <*Investment in Each Generator*> variable from **Section 3.2.3**, variable represented the amount of money that might be spent on each technology based on the allocation and it so it was converted to a MW form in the <*Investment Based Expected Order Rate*> variable.

Construction Time. Construction times were represented by <*Capacity Construction Time (Local/Oversea)*> variables and the data were from the IPCC WG-III's report and the Energy Market Authority.[76,87] Grid-scale solar PV construction time in the IPCC WG-III's report was assumed at zero years to complete, which was assessed to be infeasible and thus was assumed to be at 3 years, which is the maximum time the EMA expects generating companies to take for construction of any grid-scale power plants within Singapore.[76,87] The stock variables, *<Local Capacities Waiting for Build Completion>* and *<Overseas Capacities Waiting for Build Completion>* would be divided by the correspond construction times for the various technologies, to form the in-flow to the stocks, *<Installed Capacity (Local/Overseas>.*

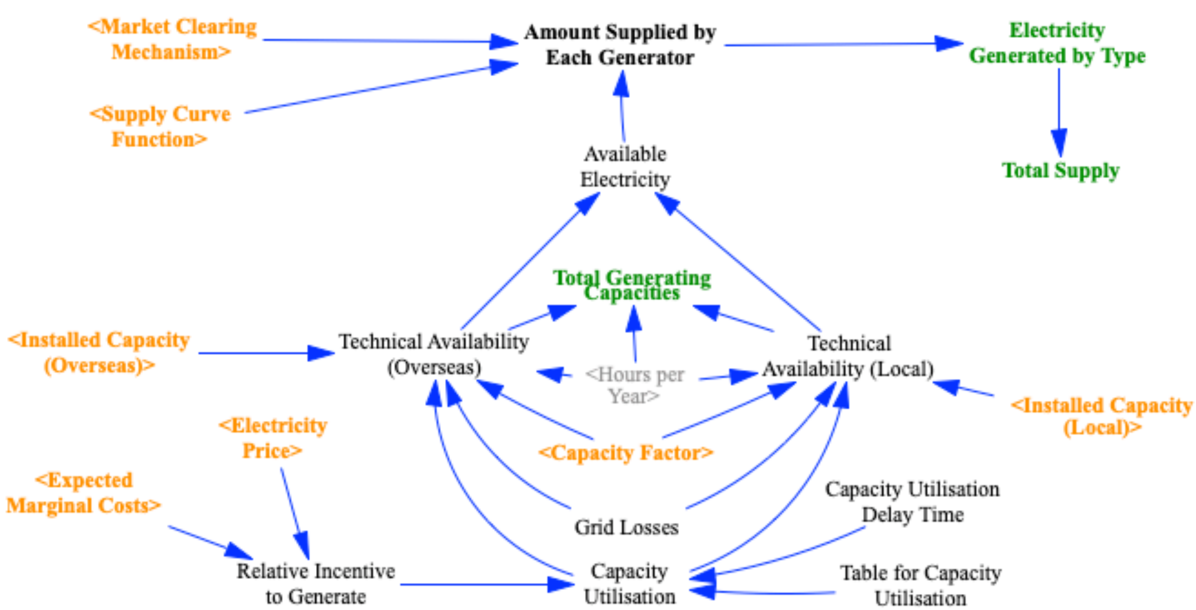
Desired Capacities. The desired capacities for the local and overseas generators are dependent upon the <*Desired Minimum Total Capacity Required*> (from **Section 3.2.1**), <*Proportion of Capacity Allowed Overseas>,* and <*Extra Baseload Due to Non-Baseload*>. As solar and wind were considered non-baseload technologies that have low availability (0.15 and 0.32)[89], any high loading of grid scale wind and solar may cause disruption to the overall grid if there are extended periods of insufficient wind or solar (i.e. monsoon season). The total capacity available may not be representative of its capability to provide power into the grid consistently. Thus, a policy that requires extra power from baseload technologies to make up for the intermittent technologies was introduced. For example, for every MW of solar PV or onshore wind built, there is a need for 0.5 times of that capacity divided across the desired capacities of other baseload technologies (geothermal, nuclear, hydro, natural gas fired).

Policy: Allow Nuclear Only. One of the scenarios that would be explored in **Chapter 4** included a case where instead of importing electricity generated via renewable resources with Malaysia and Indonesia, it was envisioned that Singapore developed floating or underground nuclear power plants that can also provide electricity to its neighbors as a form of co-development and resource sharing. The <*Policy: Allow Nuclear Only*> functions as a switch mechanism that allows only for the nuclear development within the overseas stock management structure to capture this idea.

3.2.5: Electricity Generation

Available Electricity. After the generating capacities were calculated, there is need to then determine how much actual electricity (*Available Electricity)* would be produced. Factors such as the capacity factor, grid losses, and capacity utilization would then have to be considered. The capacity utilization is dependent on the <*Relative Incentive to Generate*>, which is the ratio between <*Electricity Price*> and <*Expected Marginal Cost*>. A nonlinear function mechanism was used to determine the actual <*Capacity Utilization*> as some technologies may still be producing even when the market price condition might not be favorable as there could be high start-up costs or long durations to shut-down that does not favor shutting down just because the short-term incentive to produce is not present.[59]

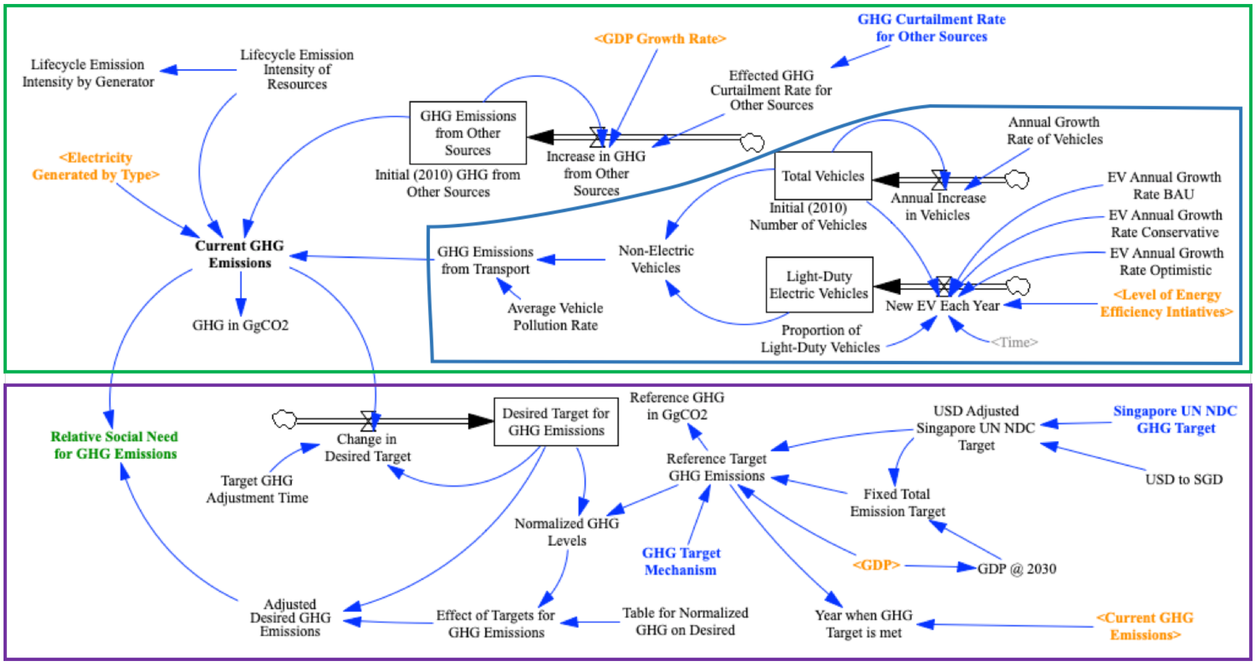
Figure 3.7: Generation Sub-model



3.2.6: Emissions Level

Calculating Total Emissions. According to the National Environment Agency (NEA), the greenhouse gas (GHG) emissions from the electricity generation sector only accounted for 41 to 43% of the total GHG emissions in Singapore in 2010 to 2014.[90] The emissions by other GHG emitting sectors were included in this stock-and-flow model to better indicate what the total emissions of the future might be and to have a clearer estimate when would the INDC target be met. In the green rectangle area shown in model of **Figure 3.8**, emissions from the Industry, Commercial, and Household sectors used a simplified model where the growth in their emissions was based on the GDP growth rate, assuming that there would be an increase in emissions from increased economic activities. The transport sector GHG emission is based on the emissions from the vehicles and thus the model included a separate growth model for vehicles, shown in the blue rectangle region in **Figure 3.8**. This has allowed for the light vehicle EV penetration that was initially discussed in **Section 3.2.1** to be properly estimated and modelled accordingly. The <*Annual Growth Rate of Vehicles*> was 0.6%.[68] The <*Average Vehicle Pollution Rate*> was calculated from the NEA report and the Land Transport Authority (LTA)'s vehicle data and estimated at 7,309kgCO2/(Vehicle*Year).[90,91] Data for the <*Lifecycle Emission Intensity of Resources*> was obtained from the IPCC Working Group-III report for all technologies, except waste-to-energy as it was not included and was obtained from Kuo et. al. (2011) instead.[76,92]

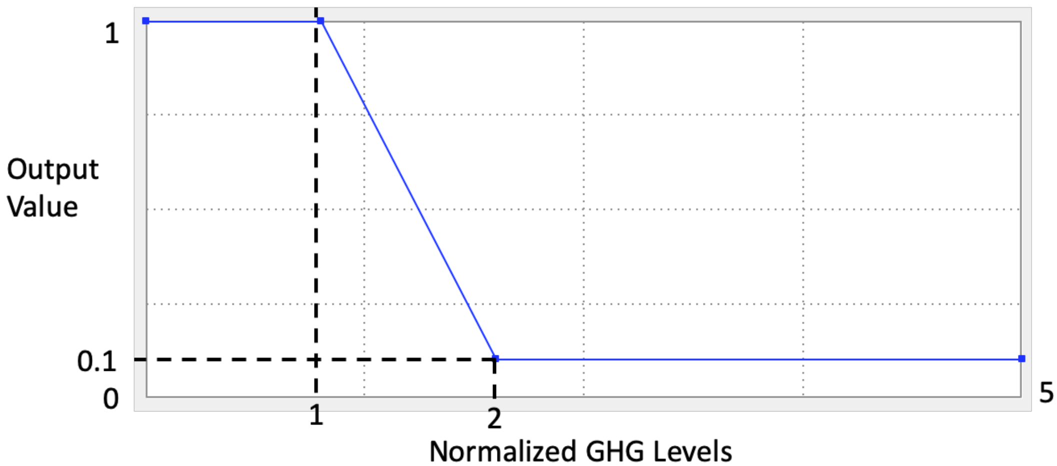
Figure 3.8: Emissions Sub-model



Calculating Emissions Related Needs. Similar to how the social need for demand-supply balance was determined, a floating goal mechanism was used for setting the GHG emissions related social need.[53,56] This is shown in the purple rectangle area of **Figure 3.8**. The <*Target GHG Emissions*> could take on either one of two target mechanism in this model. One approach is to have the target fixed based on a constant emission intensity in GDP dollars, such as the target that Singapore used in the INDC, which was based on a per GDP dollars (2010's value) and was set at 0.113 $kgCO_2eqv/S\$$.[15] The other mechanism is based on holding yearly emissions constant as a target. The model allows for switching between the two types of mechanism to study how the different targets might have different outcomes. The <*Desired Target for GHG Emissions*> variable was converted to a normalized form by dividing it against the <*Reference Target GHG Emissions*>. The <*Normalized GHG levels*>applied through a nonlinear function to determine the adjustment factor to apply back to the Desired Target to form the Adjusted *Desired GHG Emissions*. The nonlinear function graph, <*Table for Normalized GHG on Desired*>*,* is shown in

Figure 3.9. As an example, if the desired target is lower than the INDC target, this signifies that the state of the system has surpassed the INDC target and thus there is no need to lower the desired state so the adjustment factor stays at 1. If the desired GHG emissions is higher than the target, it signifies that there should be more done to lower the desired GHG emissions and thus an adjustment value < 1 is applied to the desired target.

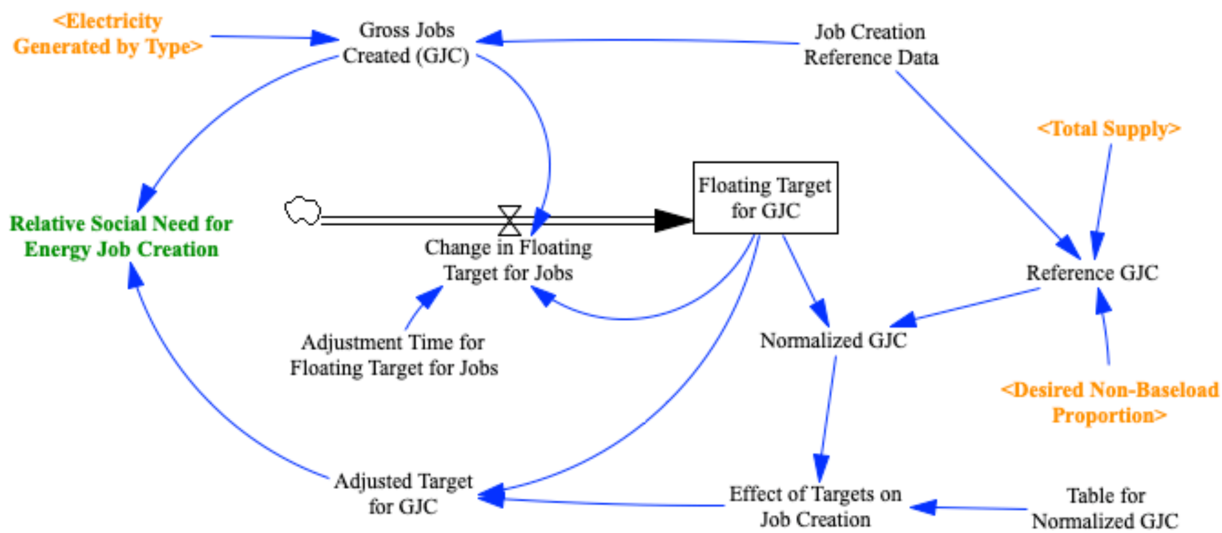
Figure 3.9: Nonlinear Function of Normalized GHG for Adjusted Desired GHG Emissions



3.2.7: Energy Related Jobs

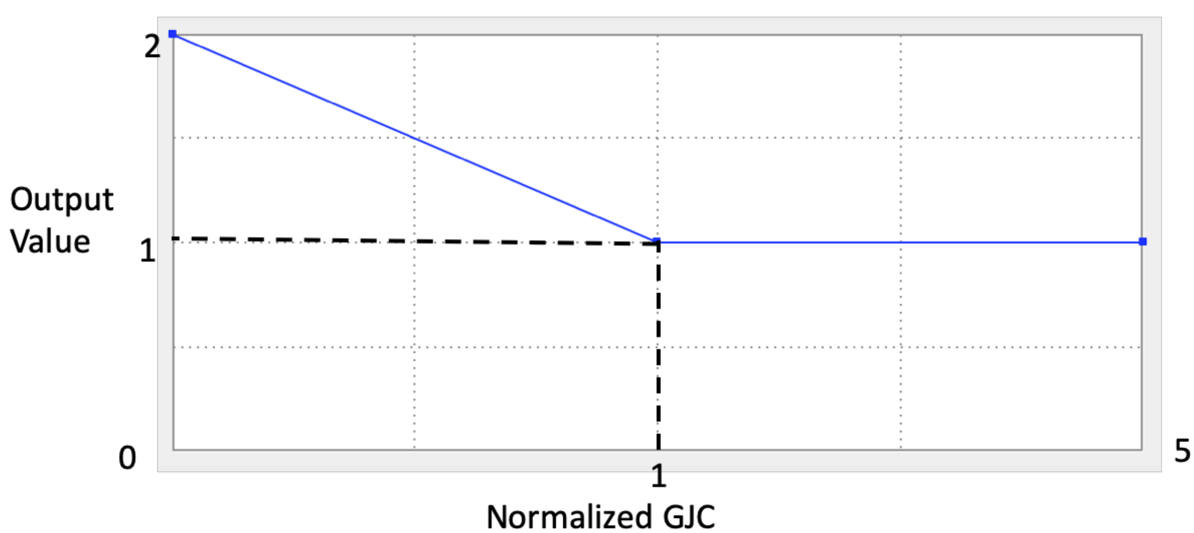
Modelling Job Creation. The job market segment modelling here was based on the total jobs created through each technology type's electricity generation. The reference data was obtained through reports for the UK and the US, where the gross jobs data in jobs/GWh was extracted. Jobs in the report refers to the full-time equivalent job over the lifetime of the electricity generating plant.[93,94] The <*Reference GJC*> data was then calculated based on the wish that the <*Total Supply*> was producing based on the highest possible job creation technology possible for the desired baseload and non-baseload proportions. The model for the job market sub-model is shown below in **Figure 3.10**.

Figure 3.10: Job Market Creation Sub-model



Job Market Social Need. Like the emissions model, a floating target mechanism was used. A normalization was applied to the floating target and passed through a nonlinear function to determine the adjustment factor. The nonlinear function is shown below in **Figure 3.11**. In the event that the *<Normalized GJC>* > 1, then there is no need for additional pressure to change the target. However, when the converse occurs, where *<Normalized GJC>* < 1, an adjustment factor to increase the target would be applied.

Figure 3.11: Nonlinear Function of Normalized GJC for Adjusted Target for GJC



3.2.8: Energy Security

Measuring Energy Security. The notion of energy security can take on many forms.[95] In Singapore's context, our electricity is not directly imported and instead it is the natural gas that provides for electricity that gets imported via PNG or LNG.[7] At its current state, we would not expect Singapore to be able to lower its reliance on imports. Thus, there would be value for Singapore to reduce risk through further diversification between energy types and not just between source countries for natural gas. This could help Singapore hedge against the economic risk cases where natural gas prices increase to levels where economic livelihood might be affected. In the model, shown below in **Figure 3.12**, the <*Current Energy Diversity Index*> variable is measured using the Herfindahl-Hirschman Index (HHI) method (**Equation 4**). The index shows a measure of energy type diversity. The index can take on a value up to 10000 (100 x 100), which is the case of complete monopoly by a single energy type.

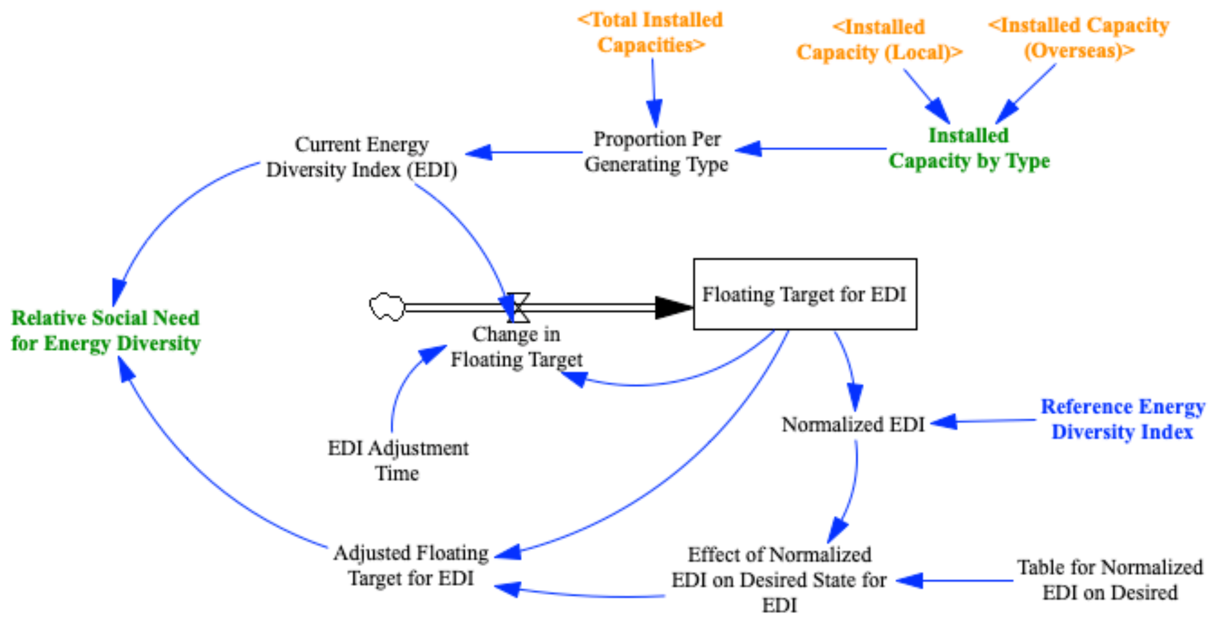
Equation 9: Herfindahl-Hirschman Index for Energy Security Measure

$$HHI = \sum_i S_i^2,$$

where S_i = Share of installed capacity of technology type, in percent values (i.e. 50% = 50)

Calculating Energy Diversity Needs. A similar approach to the needs from GHG emission was applied here for energy diversity needs. The <*Reference Energy Diversity Index*> used here was set at 5000, which was based on the energy diversity values for the high diversity states listed by Ioannidis et.al.[96] A normalized diversity index was then obtained and transform through the same nonlinear function shown in **Figure 3.9** to obtain an adjustment value of the floating target and the ratio between the adjusted and the current then forms into the relative social need.

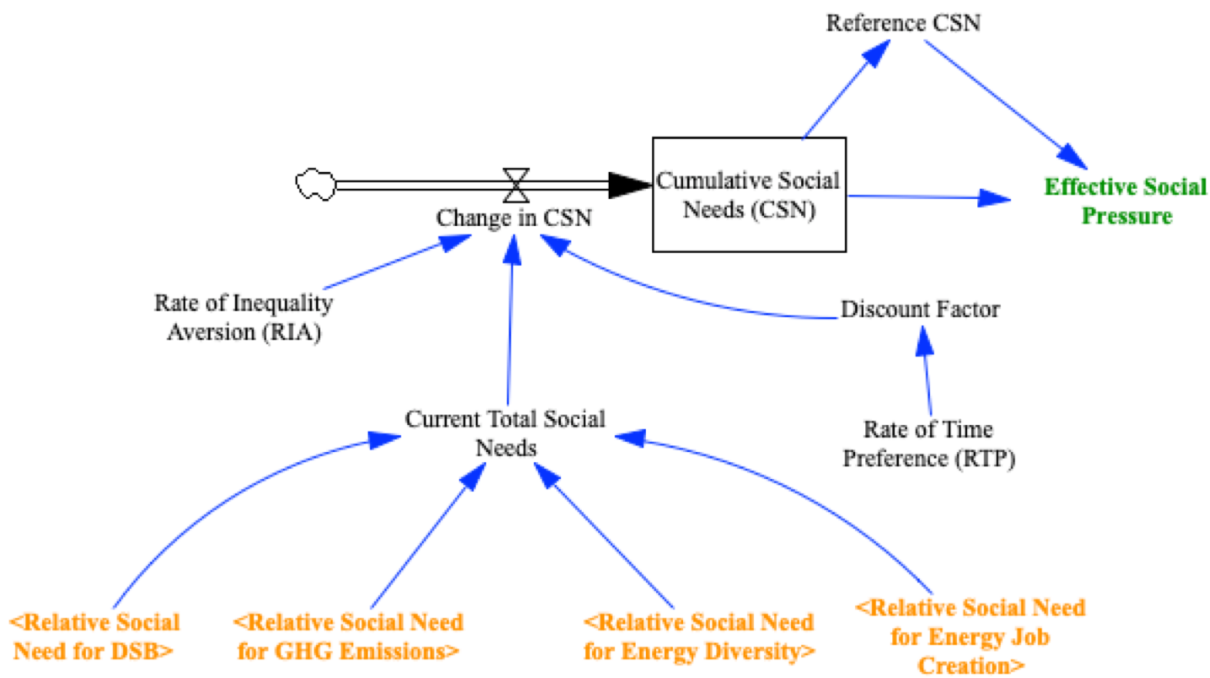
Figure 3.12: Energy Security Sub-model



3.2.9: Social Needs

Combining Needs. The social needs that were discussed previously come together in this sub-model (**Figure 3.13**) multiplicatively to form the <*Current Total Social Needs*> variable as it was assumed that the factors have influence on each other and were not strongly separable from each other.[53] The <*Current Total Social Needs*> was then converted to <*Cumulative Social Needs (CSN)*> through the use of a cumulative discount utility (CDU) function.[56,62] The CDU has a discount factor applied that through a <*Rate of Time Preference (RTP)*> that ranges between 0 to 0.3 and a <*Rate of Inequality Aversion* (RIA)> factor applied at a value of 2.5.[62] An RTP of 0 and a RIA of 2.5 signifies a situation where the welfare of all generations are weighted equally.[62] The <*Effective Social Pressure*> variable is built based a comparison between CSN and a smoothed CSN as a reference point, similar to a heuristic where recent changes have a higher impact than past changes.

Figure 3.13: Social Needs Sub-model



3.2.10: Policy

Overview. The broad model for the three endogenous policies modelled here take the form of a hill-climbing optimization, which could be considered as a variant of the floating goal mechanism discussed previously.[53] The policy models are shown in **Figure 3.14**. This approach is chosen as the optimum point was not known as the dynamics unfolds over time in the model. In essence, each policy model used the <*Effective Social Pressure*> as inputs into nonlinear functions for the three endogenous policy mechanisms studied here. The nonlinear functions' outputs set the adjustment effect on the existing policy rate to produce the desired rates.

Carbon Tax. The nonlinear equation for carbon tax policy that would be applied is shown in **Figure 3.15**. When the social pressure is low (< 1), there is no incentive to change the carbon tax from what it already is. However, when the social pressure is high, we can expect carbon tax to be adjusted upwards to incentivize generation from other segments. The carbon tax was set as part of the fuel cost component of the Pricing sub-model (**Section 3.2.2**). Formally, the carbon tax was introduced in Singapore starting in Sep 2019 at S$5/tonCO2eqv[97] and this was reflected in the model as well.

Figure 3.14: Policies Sub-models

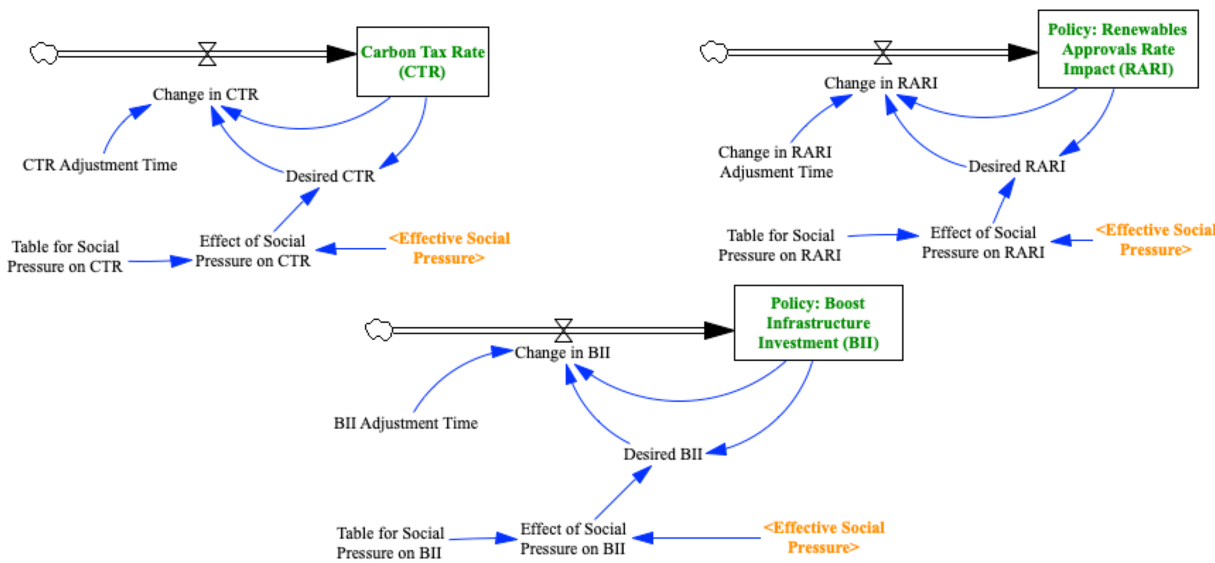
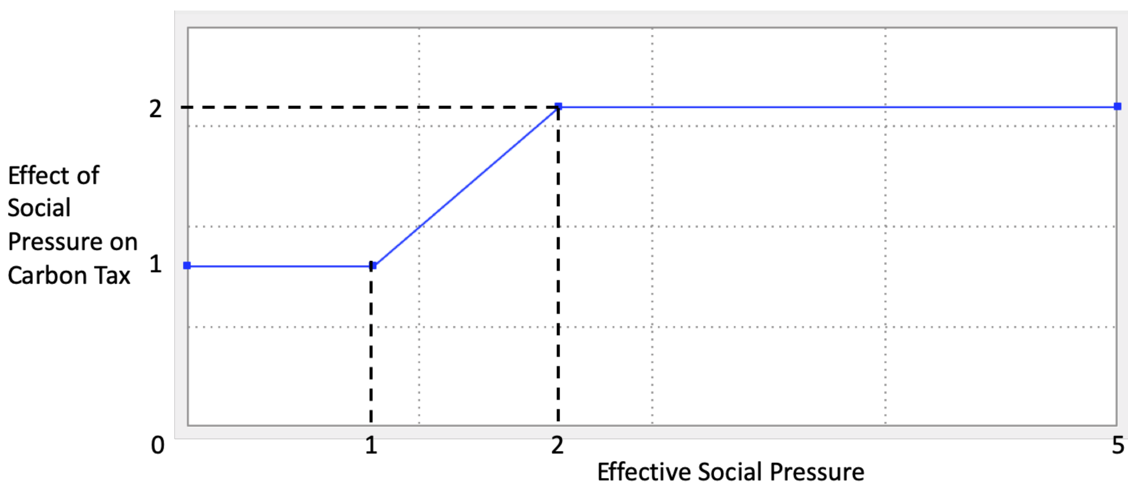


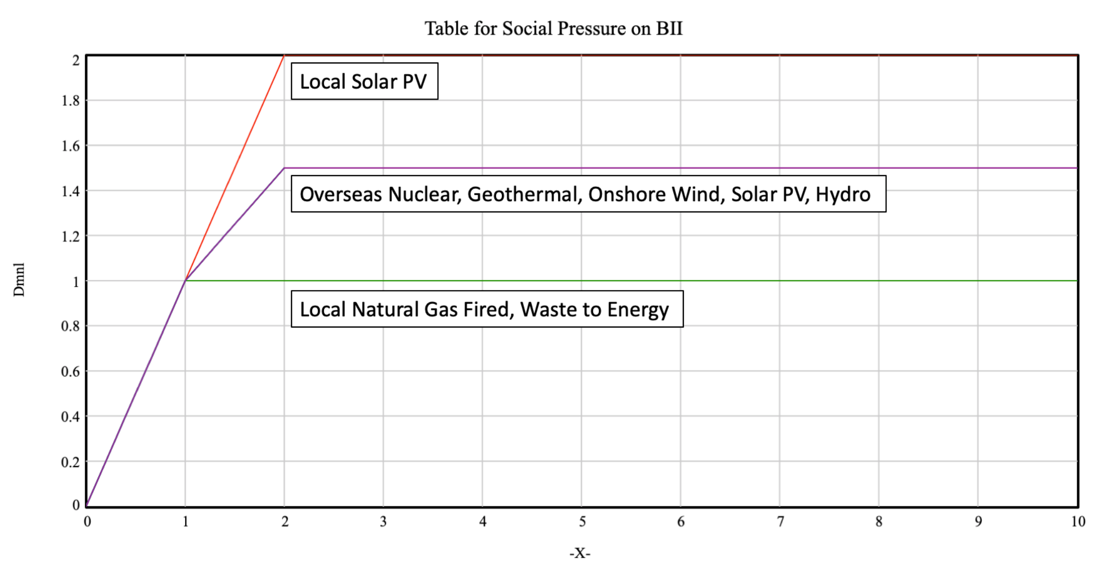
Figure 3.15: Nonlinear function for Carbon Tax



Renewables Approval Rate Impact. As the social pressure increases, we can expect that there would be changes in the approval times for different projects. This is based on the notion that with the right pressure, more effort would be put in by the government to approve relevant projects so that the it does not impede the overall process. However, there is also a limit set here where we expect the overall approval time would be shorten to at most half of what the original time taken was. This was previously discussed in **Section 3.2.4 Figure 3.6**. The nonlinear function used for this policy is the same as that of the Carbon Tax.

Boost Infrastructure Investment. The main concept of this policy's nonlinear function is to allocate a score for the different renewable or nuclear projects. Local solar project gets a higher score than overseas project. These output scores would then have an effect of creating a higher priority for renewables to non-renewable if all other effects (resource limits and generation incentive) are equal when the variables flow through Infrastructure Investment sub-model (**Section 3.2.3 Figure 3.4**). If social pressure is low (<1), then there would be less incentive to continue allocating resources to build generating capacities beyond the basic replacement rate and that applies to all technologies. The nonlinear equation for this policy is shown in **Figure 3.16**. This policy does not necessarily make one technology favoured over another at all times since there are the other effects such as the resource limitation and the effect of long term generation profitability.

Figure 3.16: Nonlinear Function for Boost Infrastructure Investment



3.2.11: Model Dashboard

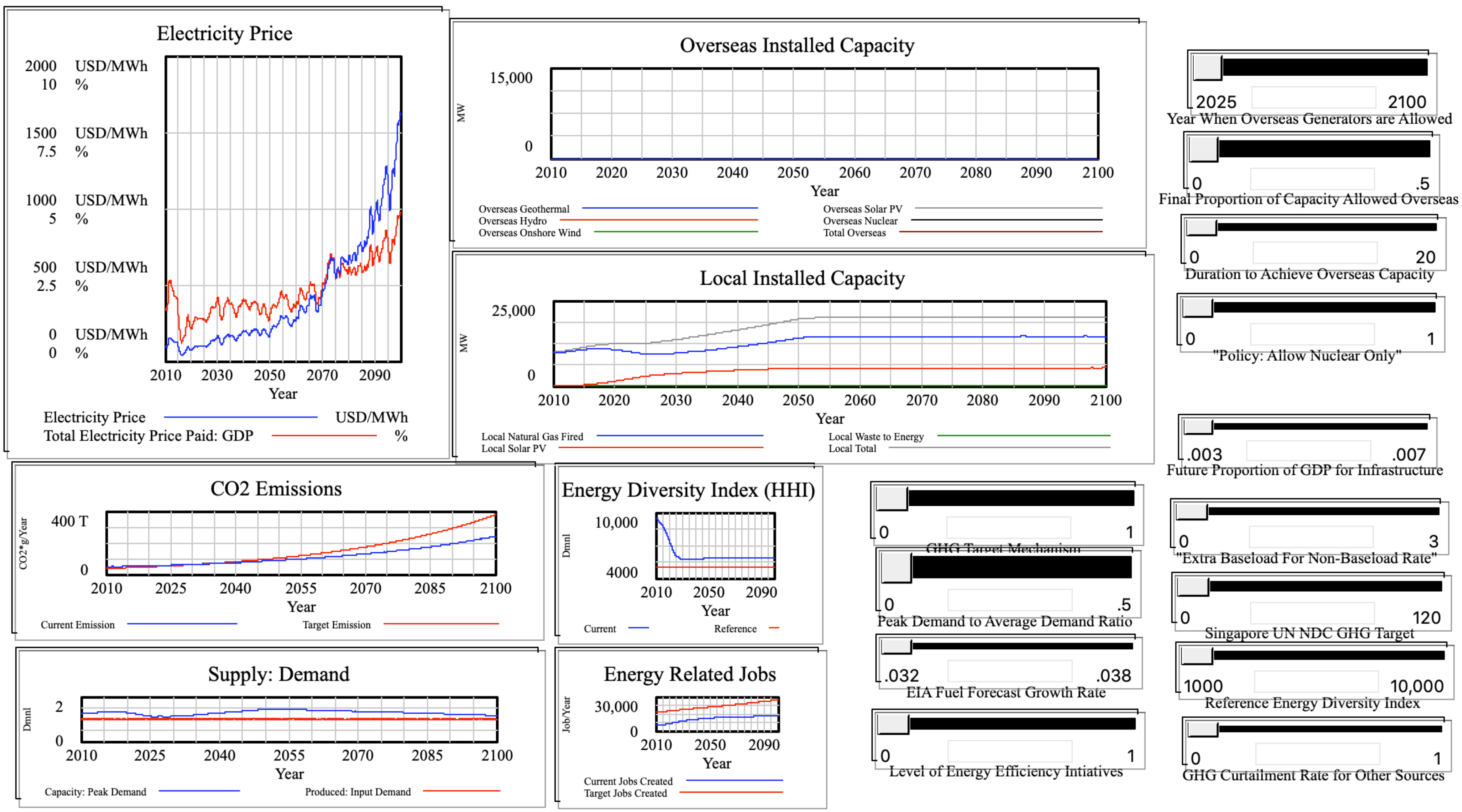
Viewing Model Outputs. A model dashboard that consist the views of key model output variables were all setup within one view page of the model file. The key outputs and parameters that can be adjusted on a slider bar during simulation mode in VensimDSS are listed in **Table 3-5**. The dashboard layout is shown in **Figure 3.17**.

Table 3-5: Adjustable Variables in Dashboard View

Variable Name	Units	Value Range	BAU Value
Peak Demand to Average Demand Ratio	Dmnl	0.24 – 0.45	**0.32**
Level of Energy Efficiency Initiatives	Dmnl	0, 0.5, 1	**0**
EIA Fuel Growth Rate	Dmnl	0.032 – 0.038	**0.035**
Future Proportion of GDP for Infrastructure	Dmnl	0.003 – 0.010	**0.005**
Year When Overseas Generators are Allowed	Year	2025 – 2100	**2100**
Final Proportion of Capacity Allowed Overseas	Dmnl	0 – 0.5	**0**
Duration to Achieve Overseas Capacity	Year	1 – 100	**100**
Policy: Allow Nuclear Only	Dmnl	0, 1	**0**
Extra Baseload for Non-Baseload Rate	Dmnl	0 – 1	**0.5**
Desired Non-Baseload Proportion	Dmnl	0 – 1	**0.2**
GHG Target Mechanism	Dmnl	0, 1	**0**
Singapore UN NDC GHG Target	gCO2/SGD$	50 – 120	**113**
GHG Curtailment Rate for Other Sources	Dmnl	0 – 1	**0**
Reference Energy Diversity Index	Dmnl	100 – 9000	**5000**

Legend:	**Demand Supply**	**Pricing**	**Infrastructure Investment**	**Electricity Capacity**	**CO2 Emissions**	**Energy Security**

Figure 3.17: Sample Dashboard View (BAU)



Chapter 4 | Scenarios and Model Results

4.1 | Scenario Setup

Overview. To better understand how the electricity landscape dynamics might evolve in Singapore till 2100, there is a need to establish comparative scenarios. The scenarios are established through changing some of the parameter values listed in **Table 3-5**. First, three different supply scenarios were defined and the key outputs from the various runs were compared to develop an understanding of what the model can provide. A sensitivity analysis on the cost and demand factors was then performed to better understand the range of possibilities in key outcomes.

Parameters Values for Scenarios. The scenarios are based on variables according to **Table 4-1**.

Table 4-1: Parameter Changes for Supply Scenarios

Variable Name	Units	BAU Value	Add Nuclear	Add Renewables & Nuclear
Year When Overseas Generators are Allowed	Year	**2100**	**2025**	**2025**
Final Proportion of Capacity Allowed Overseas	Dmnl	**0**	**0.5**	**0.5**
Duration to Achieve Overseas Capacity	Year	**100**	**20**	**20**
Policy: Allow Nuclear Only	Dmnl	**0**	**1**	**0**
Variables held constant for baseline comparison				
Variable Name	**Units**	**Value Range**		**BAU Value**
Peak Demand to Average Demand Ratio	Dmnl	0.24 – 0.45		**0.32**
Level of Energy Efficiency Initiatives	Dmnl	0, 0.5, 1		**0**
EIA Fuel Growth Rate	Dmnl	0.032 – 0.038		**0.035**
Future Proportion of GDP for Infrastructure	Dmnl	0.003 – 0.010		**0.005**
Extra Baseload for Non-Baseload Rate	Dmnl	0 – 1		0.5
Desired Non-Baseload Proportion	Dmnl	0 – 1		0.2
GHG Target Mechanism	Dmnl	0, 1		0
Singapore UN NDC GHG Target	gCO2/SGD	50 – 120		113
GHG Curtailment Rate for Other Sources	Dmnl	0 – 1		0
Reference Energy Diversity Index	Dmnl	100 – 9000		5000

Legend:	Demand Supply	Pricing	Infrastructure Investment	Electricity Capacity	CO2 Emissions	Energy Security

4.2 |Results

4.2.1. Capacities

Figure 4.1 to Figure 4.3 shows how the local, overseas, and total capacities would change over time under the different scenarios respectively. Nuclear power plants were classified as overseas as it was assumed that offshore technologies were employed. The other overseas technologies were based on the renewable energy technologies in Malaysia and Sarawak, Indonesia.

In the BAU case, we observe a gradual increase in solar capacity peaking eventually at about 5,400MW while natural gas plants would stabilize after a period of initial growth and peak at around 14,500MW. This shows the limit of local diversification with a renewable energy penetration rate of about 26.5%.

In the Add Nuclear scenario, the capacity of natural gas power plants declined in the initial decades after nuclear is introduced before gradually picking up in installation again and reaching a maximum similar to BAU. In terms of total capacities installed, we observe that the eventual total capacities were higher than the BAU. Construction times for nuclear power plants was longer so while the construction was ongoing, more projects was being loaded into natural gas capacity construction and that led into a higher total capacity that were installed eventually.

In the Add Renewable and Nuclear scenario, we observed that local natural gas power plant capacity declines for a longer period to a bottom of 5,000 MW while overseas renewable capacities increase gradually before reaching peak installed capacities near their resource limit, except overseas solar which has a significantly higher expected resource limit than the other renewable technologies. The total installed capacities from this scenario was lower than BAU between 2025 onwards to 2065 before continually growing beyond 2100.

From the changes in capacities that differ with each scenario, we now have a better understanding on how these changes might impact other factors such as the demand-supply balance, electricity prices, CO2 emissions, diversity index, and the job market changes.

Figure 4.1: Local Installed Capacities in the Three Scenarios

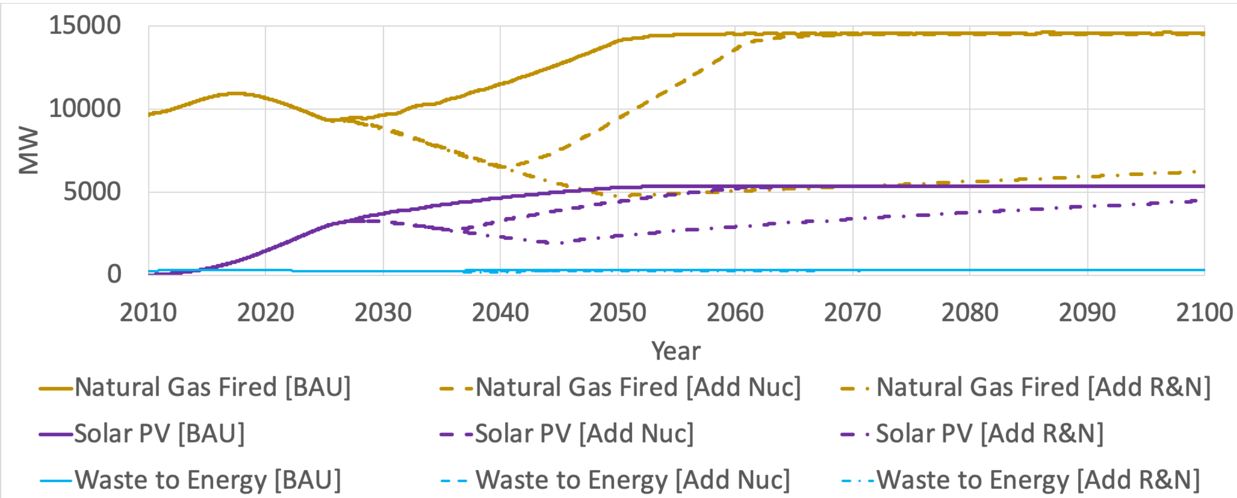


Figure 4.2: Overseas Installed Capacities in the Three Scenarios

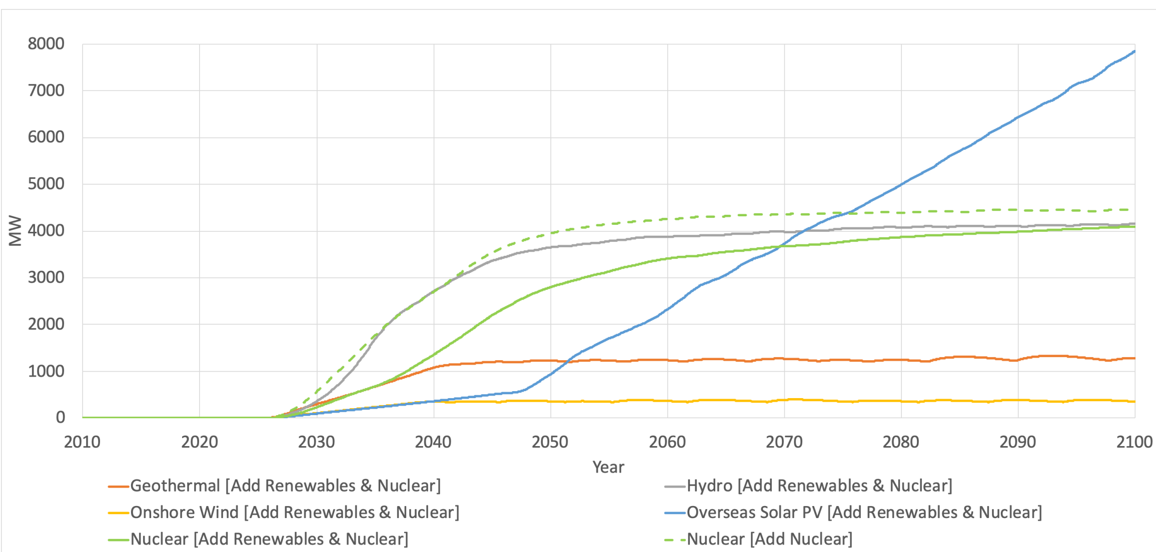
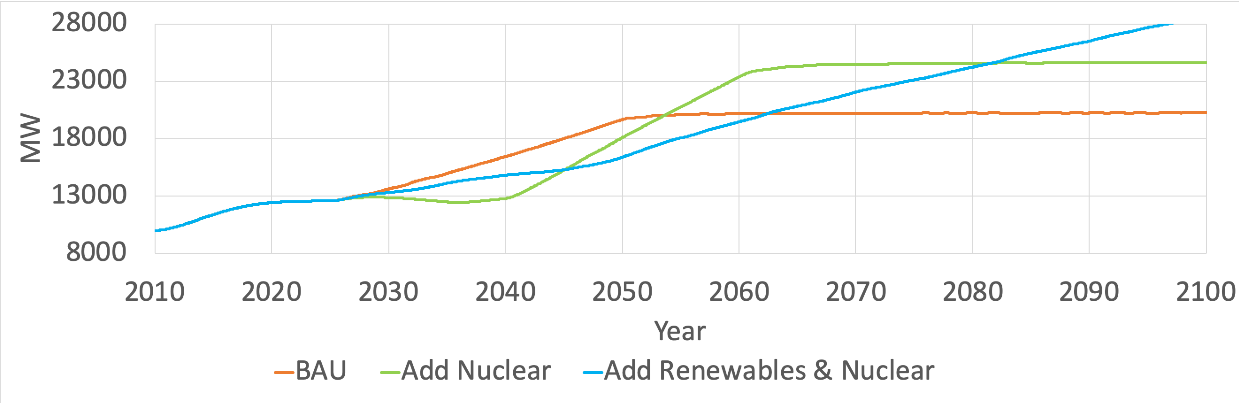


Figure 4.3: Total Installed Capacities



4.2.2. Price

Figure 4.4 shows how the electricity price would change over time and **Figure 4.5** how that price translates into social cost. The social cost of electricity here is represented through the proportion of total electricity price paid (*Input Demand* x *Energy Price*) relative to GDP. Across the scenarios, an increasing trend for the social cost of electricity was observed, signifying that electricity for consumers take up a higher portion of expenditure in the future than their past self. The increase goes from 1.6% to a range between 3.9% to 4.9%, which is a significant increase over the decades. Comparing within the electricity prices, prices are higher in the initial stages (2030s to 2050s) when the capacities from the alternative scenarios were lower than the BAU during that period. Electricity prices for the Add Nuclear scenario showed an eventual decline and it stayed consistently lower than the BAU scenario while electricity prices in the Add Renewables & Nuclear scenario were consistently higher but not by a large margin or close usually goes close to the BAU scenario.

Figure 4.4: Electricity Prices

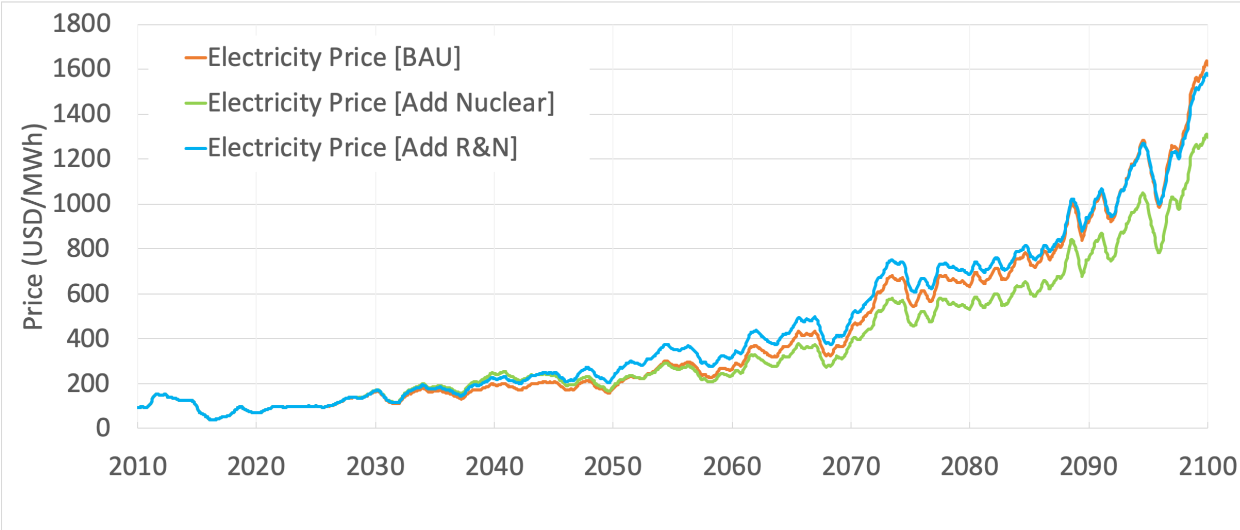
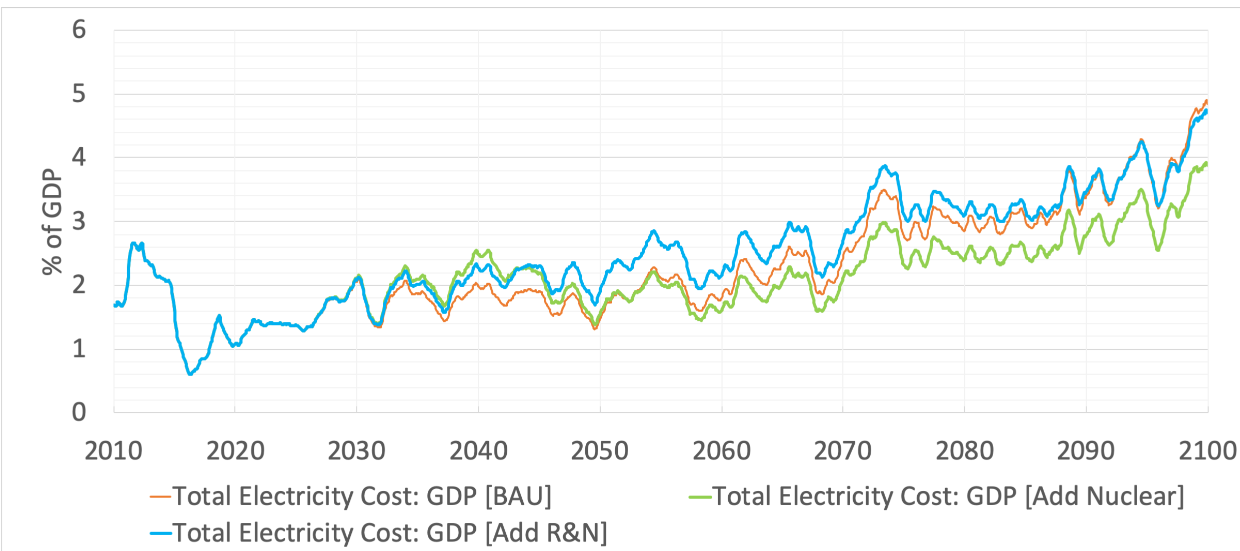


Figure 4.5: Cost of Electricity to Society



4.2.3. Demand Supply Balance

Figure 4.6 shows the ratio between the generating supply over peak demand over time. Generating supply in this case refers to installed capacities factored with grid losses, capacity factors, and capacity utilization. If the ratio presented is less than 1, it signifies that there may insufficient generating supply for peak periods which may then lead into blackouts.

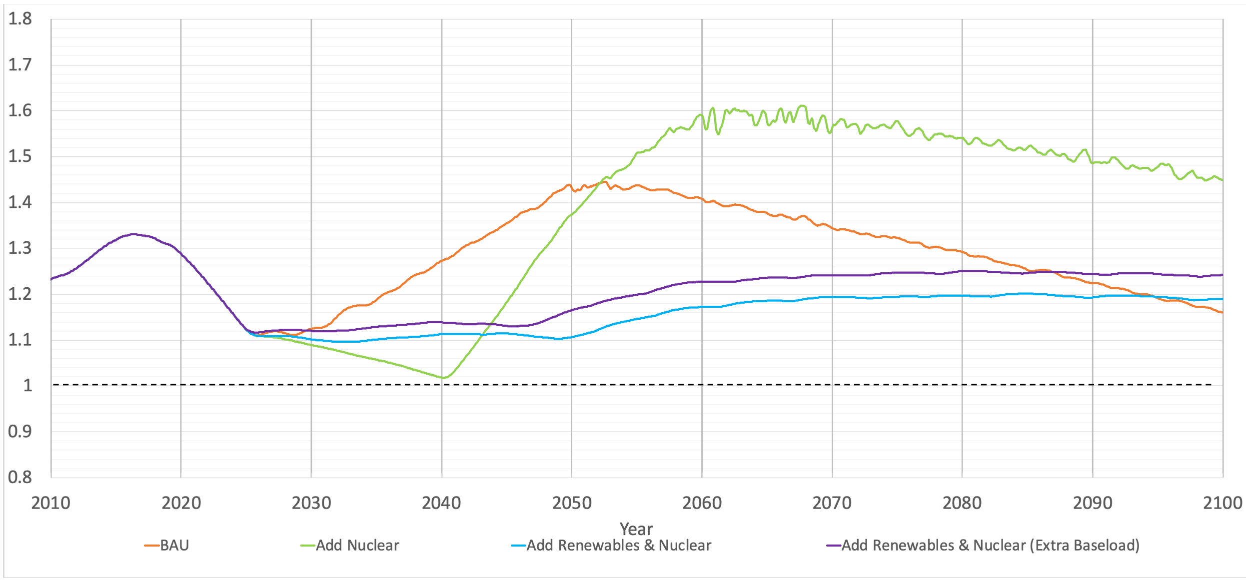
In all scenarios, the ratio increased to about 1.33 in the early decade before declining to 1.1 in the 2025. The BAU scenario reached a peak of 1.44 by 2050 before gradually declining over the remaining time in the simulation as demand outpaced capacity growth as we see the capacity stopped growing due to the resource limits by 2050 (BAU in **Figure 4.3**)

In the Add Nuclear scenario, the ratio declined to a low of 1.02 in the late 2030s before exceeding the BAU scenario by 2050 and peaking at 1.6 from late 2060s to 2070s. Installed capacity peaked by the 2060s (Add Nuclear in **Figure 4.3**) and as demand increased, the ratio would start to decline overtime, reaching about 1.45 by the time the simulation ended.

The Add Renewable and Nuclear scenario showed a consistently lower ratio that kept between 1.1 to 1.2 from 2025 on. Cross referenced with the total installed capacity data in **Figure 4.3**, this showed that continual investments to build up more renewable resources adds more installed capacity but it was only able to keep pace with the increasing demand and does not outpace demand significantly. This can be expected as the investment in capacities from renewable resources included non-baseload technologies (wind and solar) which increased physical capacity but the net generating capacity would not be increasing that quickly. An extra scenario was tested here where the *<Extra Baseload for Non-Baseload Rate>* variable was raised from 0.5 to 1, which increased the amount of desired baseload technologies as non-baseload technologies increases.

This Add Renewables & Nuclear (Extra Baseload) scenario increased the ratio slightly, exceeding 1.2 from 2050s onwards and peaked at 1.25 until the end of the simulation (shown in purple in **Figure 4.6**).

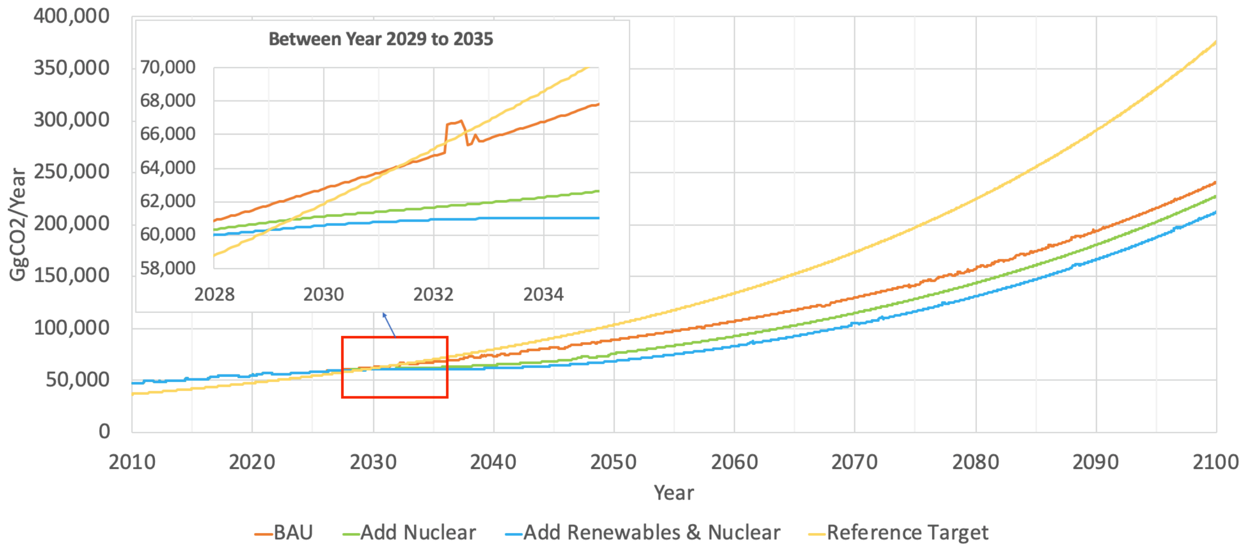
Figure 4.6: Current Peak Demand: Generating Supply Ratio



4.2.4. Emissions

Figure 4.7 shows the CO_2 emissions for the various scenarios. The data in the BAU scenario suggested that the 2030 emission intensity target would be achieved between 2031 to 2032. The alternative scenarios showed that the targets were achieved by 2029 to 2030, as seen in the inset graph in **Figure 4.7**. While the time to achieve the 2030 emission target were not significantly different from one another, the effects of the alternative scenarios have a longer-term impact on the carbon emissions, where the difference in emissions between BAU and the alternative scenarios increased over time.

Figure 4.7: CO2 Emissions from the Three Scenarios



Coupling Energy Efficiency Initiatives with the Supply Scenarios. The effects of the different energy efficiency (EE) initiatives were considered and modelled together with the three supply scenarios discussed thus far. The two extreme conditions (BAU-EE and Optimistic-EE) were tested and the results are shown in **Figure 4.8 to Figure 4.11**, for peak demand, generating capacity: peak demand ratio, energy prices, and CO2 emissions respectively. In the initial years up till about 2045, demand in the Optimistic-EE scenario was lower than the BAU-EE scenario. However, electricity demand increased beyond the BAU-EE after 2045 due to the increase penetration of EVs in the Optimistic EE scenario. The increase in EV led to higher electricity demand while lowering the total CO2 emissions. With increased electricity demand, energy prices expectedly increased (**Figure 4.10**).

In terms of meeting peak demand requirements (**Figure 4.9**), all supply scenarios had lower ratios in their corresponding Optimistic-EE scenarios. Optimistic-EE: BAU-Supply showed a decline over time that was almost 1 by the end of the simulation run. The Optimistic-EE: Add Renewable & Nuclear scenario's ratio hovered around 1.1 from 2050 onwards.

The inset table in **Figure 4.10** shows how much the energy price increased from 2095 to 2100 for each supply scenario between their corresponding Optimistic-EE and BAU-EE. The BAU-supply scenario showed the highest relative increase in energy price, at a range of 12.28% to 14.17% while the Add Renewable & Nuclear scenario had the lowest relative increase in energy price, with a range of 7.60 to 8.08%.

The total CO2 emissions were lower in the Optimistic EE than the BAU EE scenario as the EVs that had a lower carbon footprint than internal combustion engine vehicles. Shown in **Figure 4.11**, the scenarios of Add Nuclear and Add Renewables and Nuclear scenarios were thus able to meet the Singapore's INDC target by 2030 while the BAU scenario reached the target by 2031.

Figure 4.8: Peak Demand Changes between BAU and Optimistic Energy Efficiency Measures

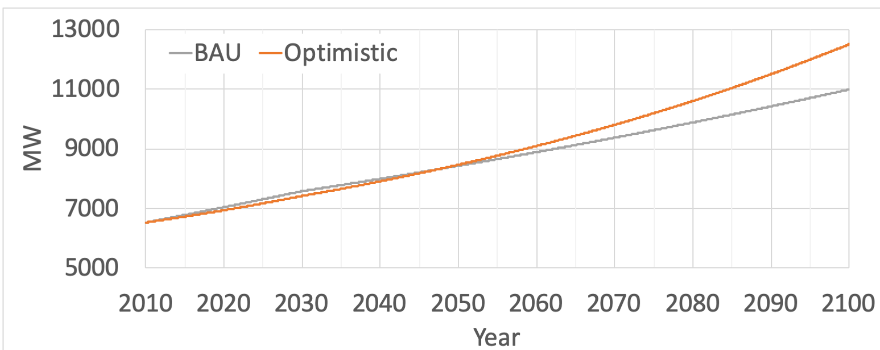


Figure 4.9: Generating Supplies: Peak Demand Ratio

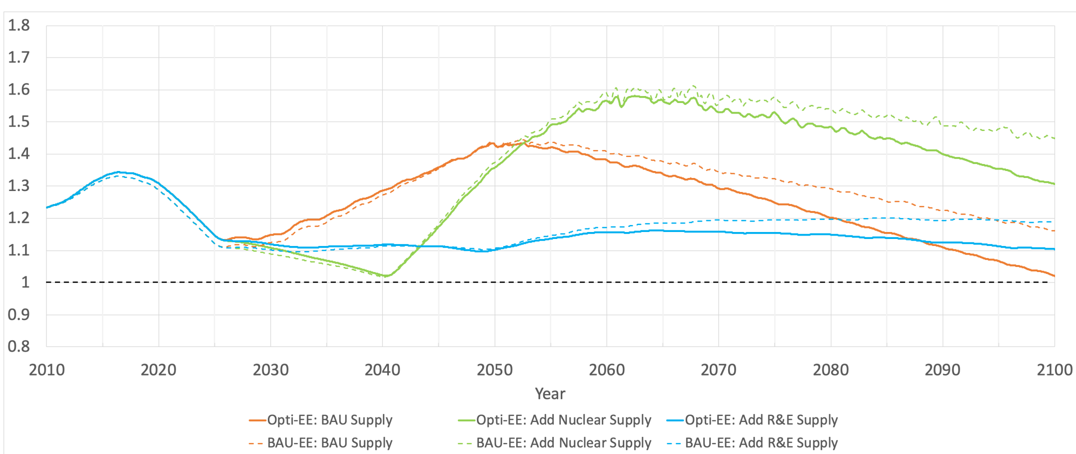
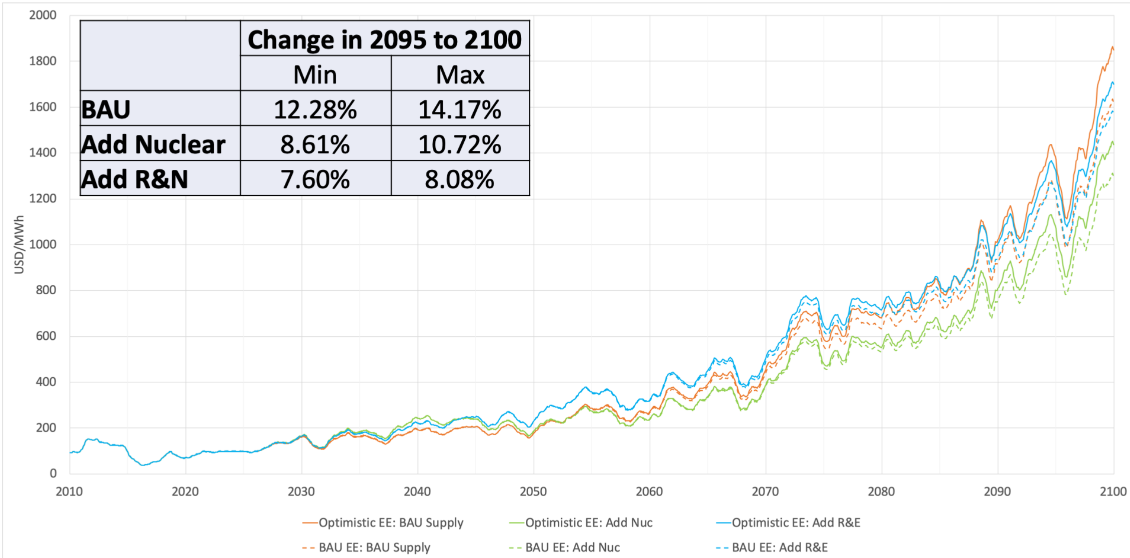
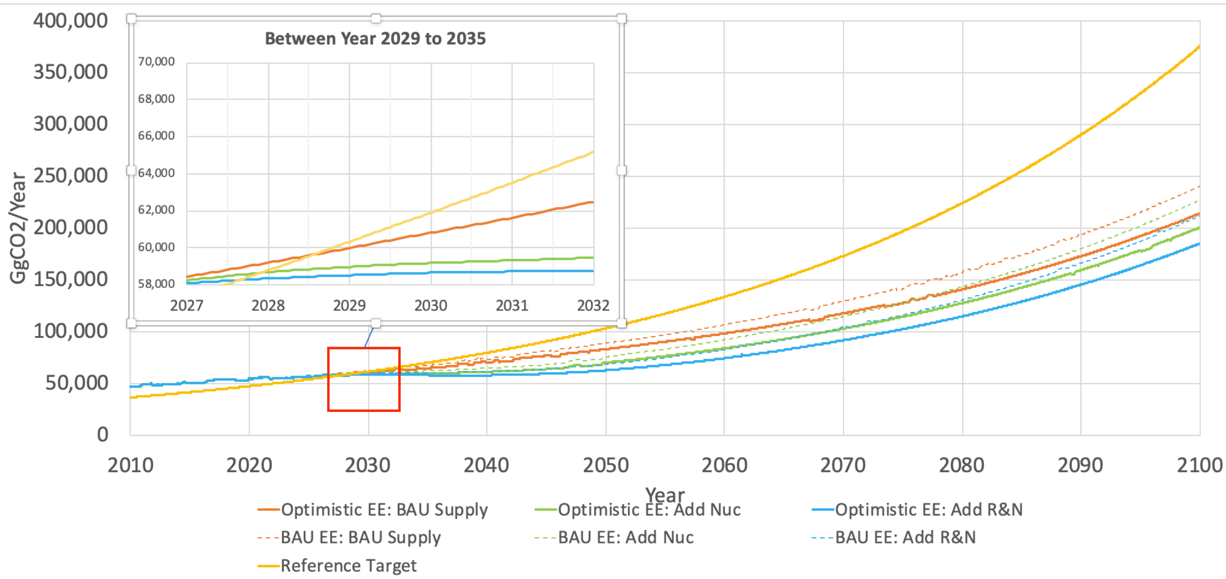


Figure 4.10: Changes in Energy Prices Under Different Energy Efficiency Scenarios



	Change in 2095 to 2100	
	Min	Max
BAU	12.28%	14.17%
Add Nuclear	8.61%	10.72%
Add R&N	7.60%	8.08%

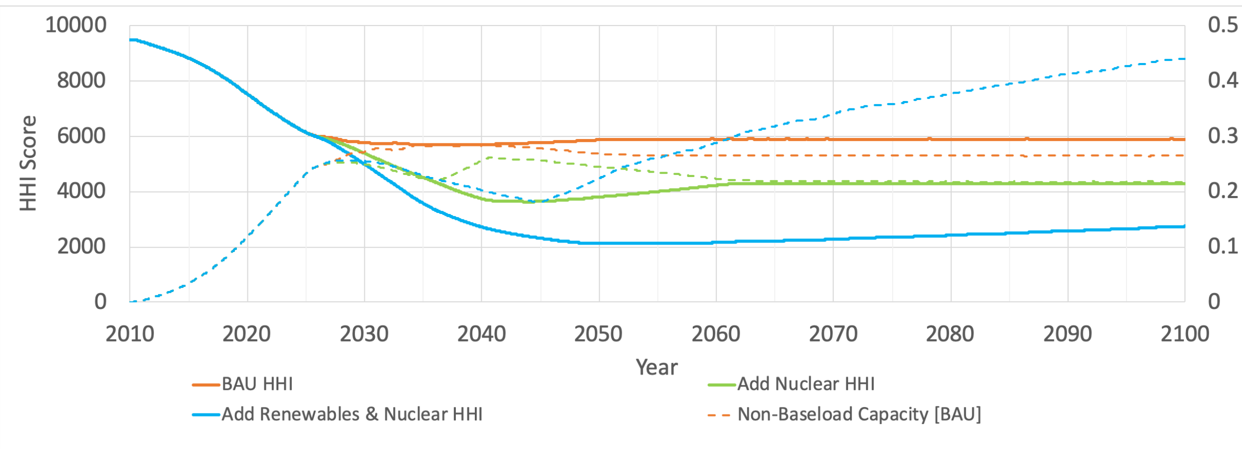
Figure 4.11: CO2 Emissions Under Different Energy Efficiency Scenarios



4.2.5. Energy Security

Figure 4.12 shows the Herfindahl-Hirschman Index (HHI) over time for the three different scenarios and the dotted lines show the proportion of installed non-baseload generation capacities (wind & solar), with the scale on the right. In terms of the diversity index, it was within expectations that the Add Renewables & Nuclear scenario would be the most diverse and BAU being the least diverse. The Add Nuclear scenario shows the lowest proportion of non-baseload technology compared to the other scenarios, implying that the grid under the Add Nuclear scenario might be more stable in terms of supply consistency during potential extended periods where non-baseload capacities are unable to perform during times of low sunshine and wind.

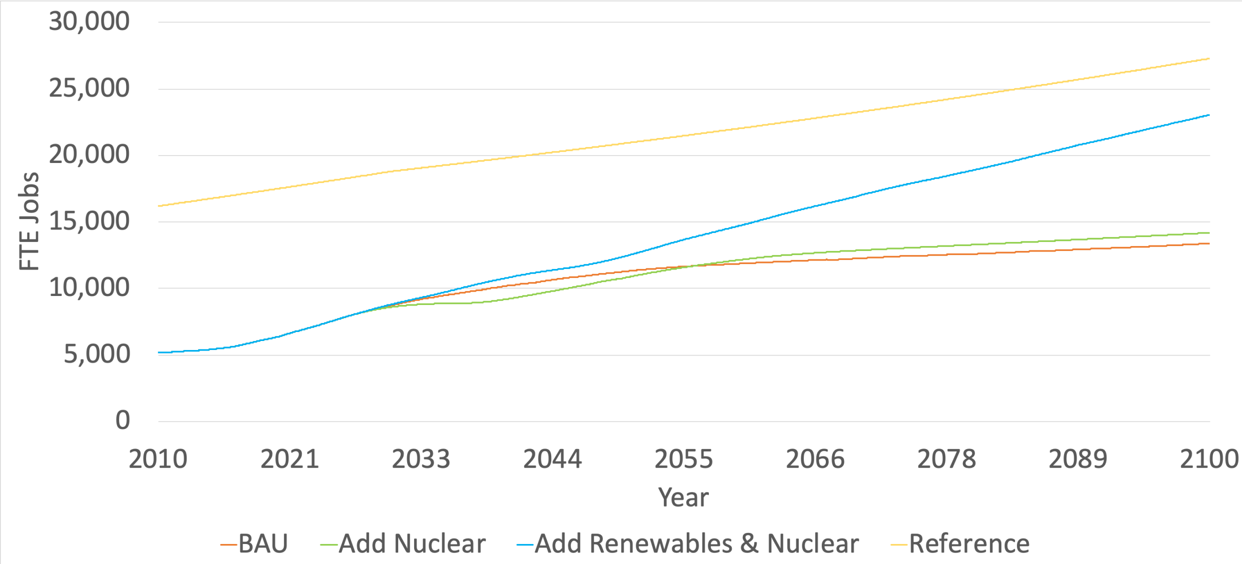
Figure 4.12: Herfindahl-Hirschman Index and Proportion of Non-Baseload for the Three Scenarios



4.2.6. Job Prospects in Energy Market

Figure 4.13 shows the expected full-time equivalent (FTE) jobs that the different scenarios created over time. While the total installed capacities of the Add Renewables & Nuclear scenario were consistently lower than the other scenarios (**Figure 4.3**), the Add Renewable & Nuclear scenario was able to generate more FTE jobs for than the other two scenarios.

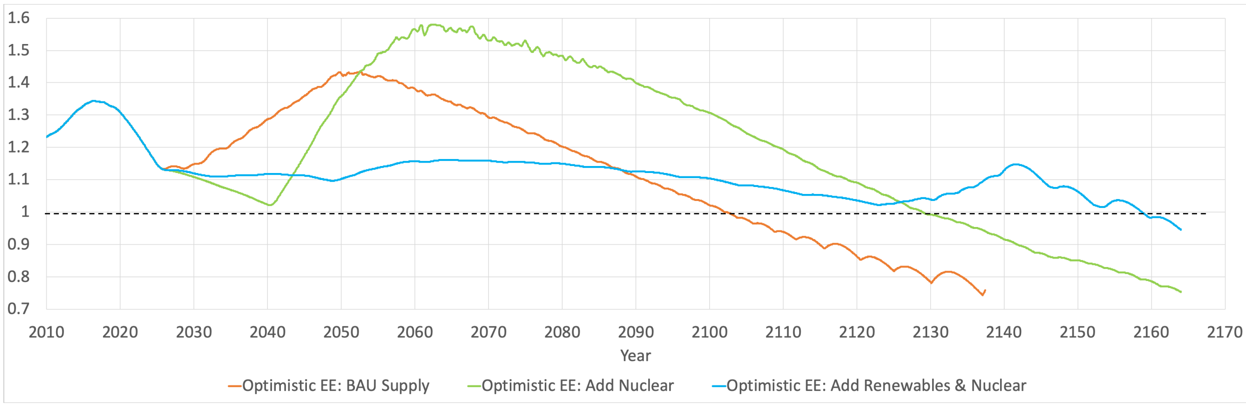
Figure 4.13: Job Market Potential of the Three Scenarios



4.2.7. Extended Runs & Resource Limits

The resource limits set forth in the scenarios may seem to suggest that Singapore should be able to cope with rising electricity needs up till 2100. However, we do see trends where the electricity needs might not be properly fulfilled beyond 2100. Extending the simulations till 2200 while assuming the optimistic level of energy efficiency and continued growth in population, shows that all scenarios was unable to cope with the increasing demands eventually by 2160. The BAU scenario showed the earliest time to be unable to cope near 2100 while the Add Nuclear scenario got up to 2130 and Add Renewables & Nuclear scenario got up to 2060 (**Figure 4.14**). Fundamentally, this seemed to suggest that the current plan where Singapore does not import electricity while focusing on energy efficiency measures may not be viable beyond the current and next generation.

Figure 4.14: Demand Supply Balance for Extended Runs for the Three Scenarios



4.2.8. Sensitivity Analysis

Setup. To determine if the key values generated from the scenarios suggested were sensible, a multivariant sensitivity analysis was performed. The variables to be randomized were the cost factors for all technologies (Overnight Capital Cost, Variable O&M, Fixed O&M, emission intensity), peak demand to average demand ratio, EIA fuel cost growth rate, and demand growth rate[69,71,76,79,81,92]. All variables were assumed to have a normal distribution around the median values used. The standard deviation was not provided by the corresponding source data and was estimated based on the methodology proposed by Hozo et. al. (2005).[98]

Energy efficiency initiatives were set at the optimistic level. 1000 multivariant Monte Carlo simulation runs were then done for each of the three scenarios. The setup was done within the Sensitivity Analysis feature in the Vensim software. Data was then exported to Microsoft Excel to determine the 10th, 50th, and 90th percentile runs at each time step for graph drawing of the bounds of the key outputs and they are shown in **Figure 4.15 to Figure 4.20**.

Figure 4.15: Demand Supply Balance with Percentiles

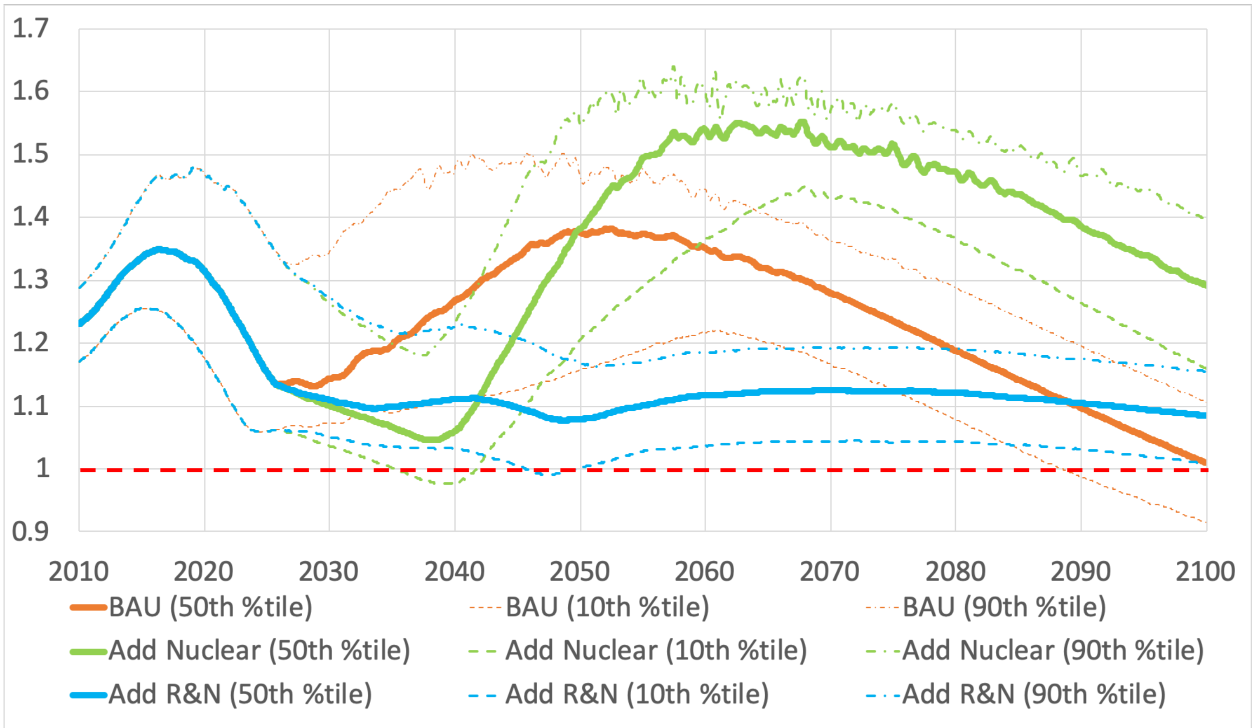


Figure 4.16: Electricity Price with Percentiles

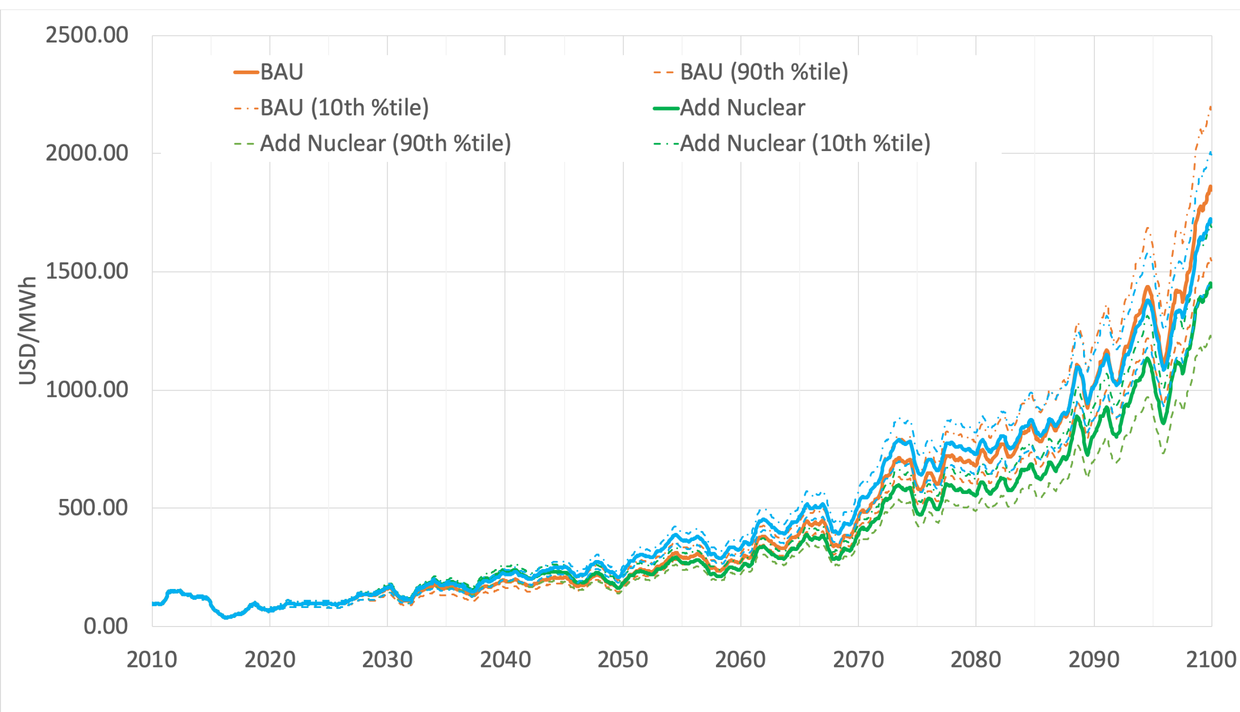


Figure 4.17: Total Electricity Price Paid: GDP with Percentiles

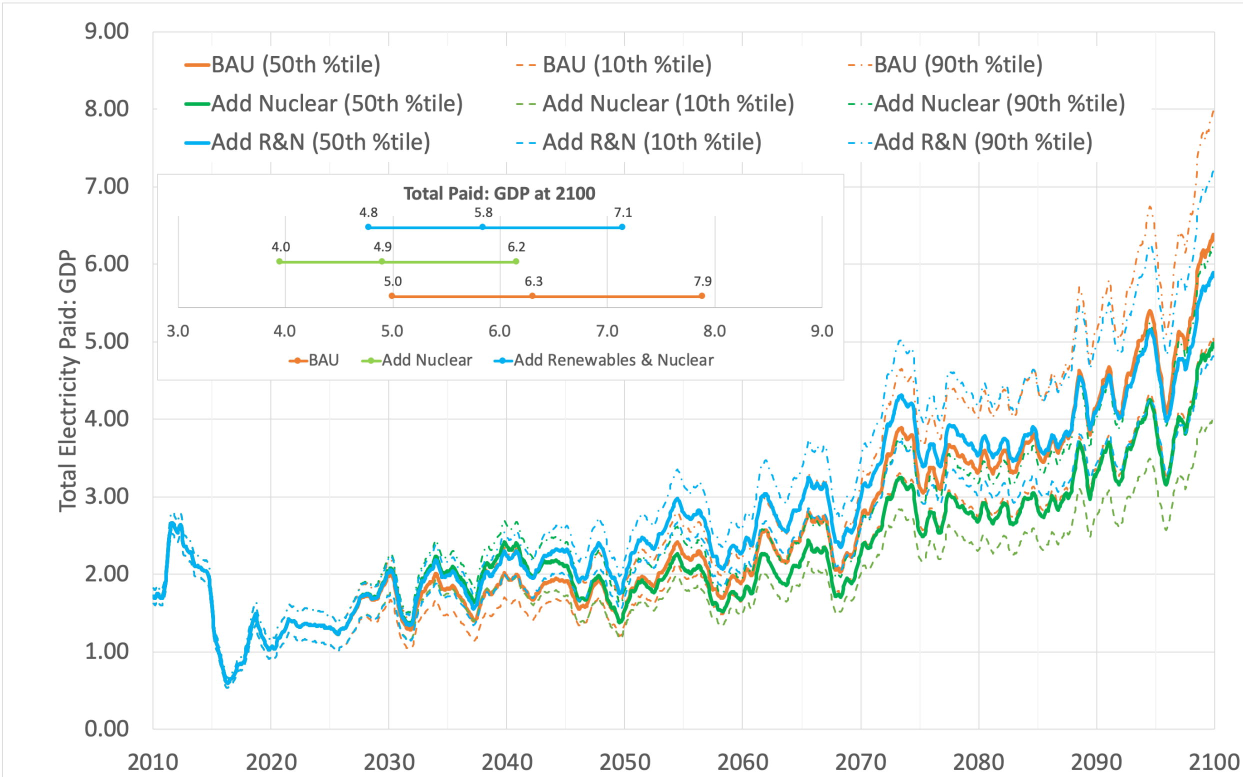


Figure 4.18: Cumulative Expenditure in USD (2010) with Percentiles

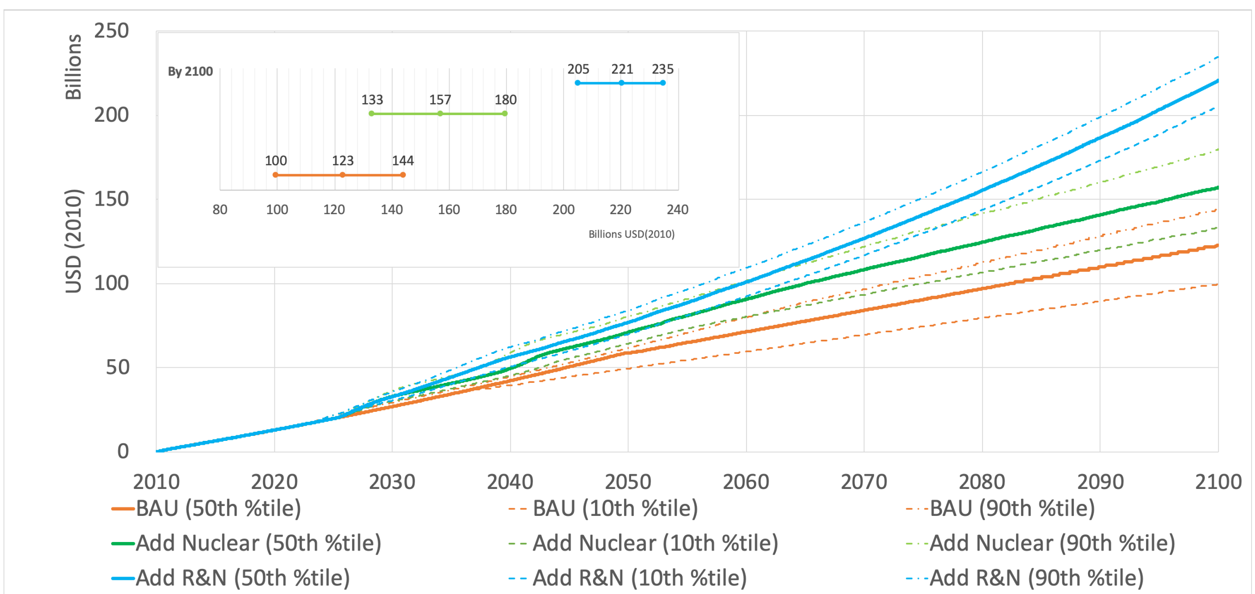


Figure 4.19: GHG Emissions with Percentiles

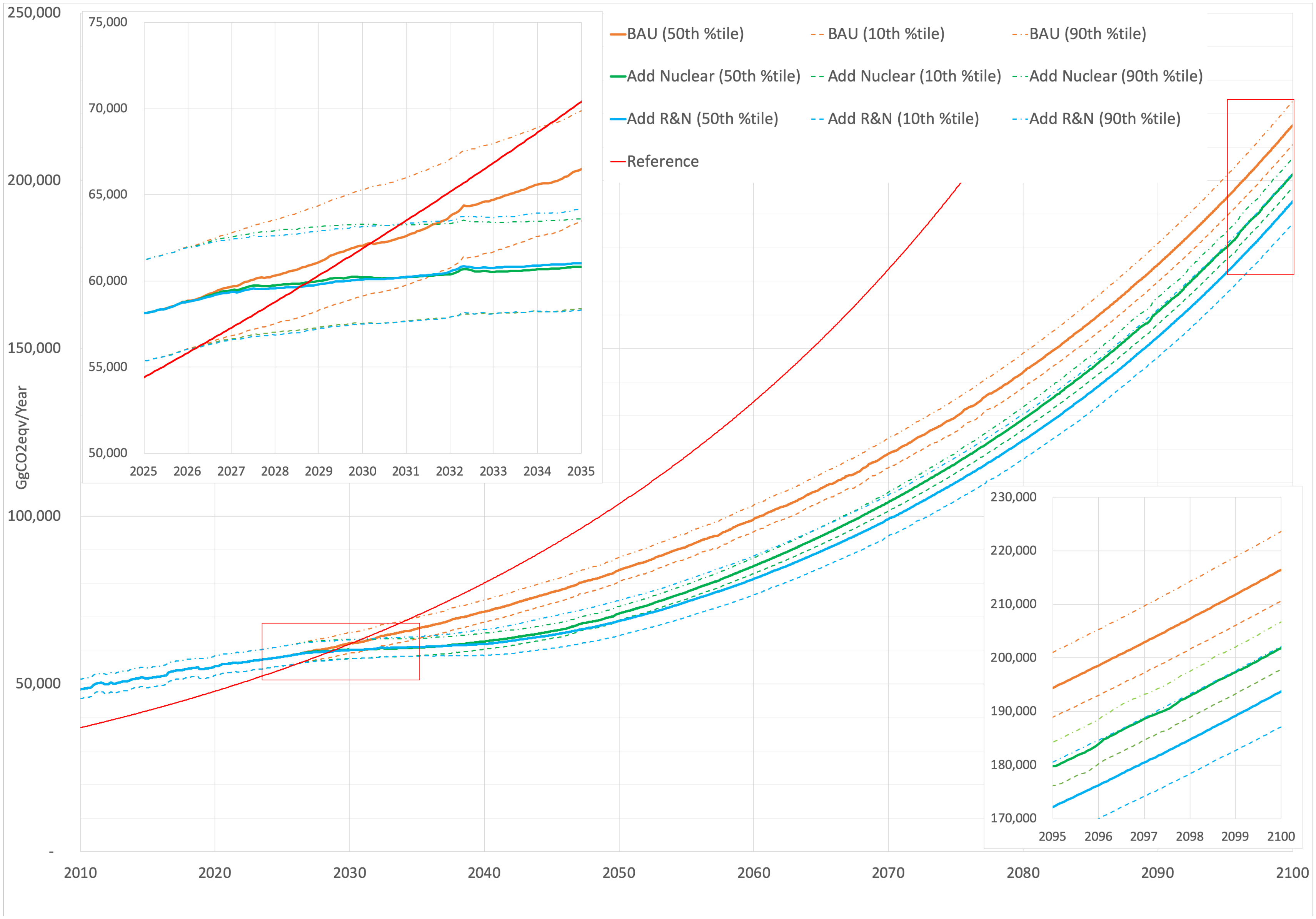
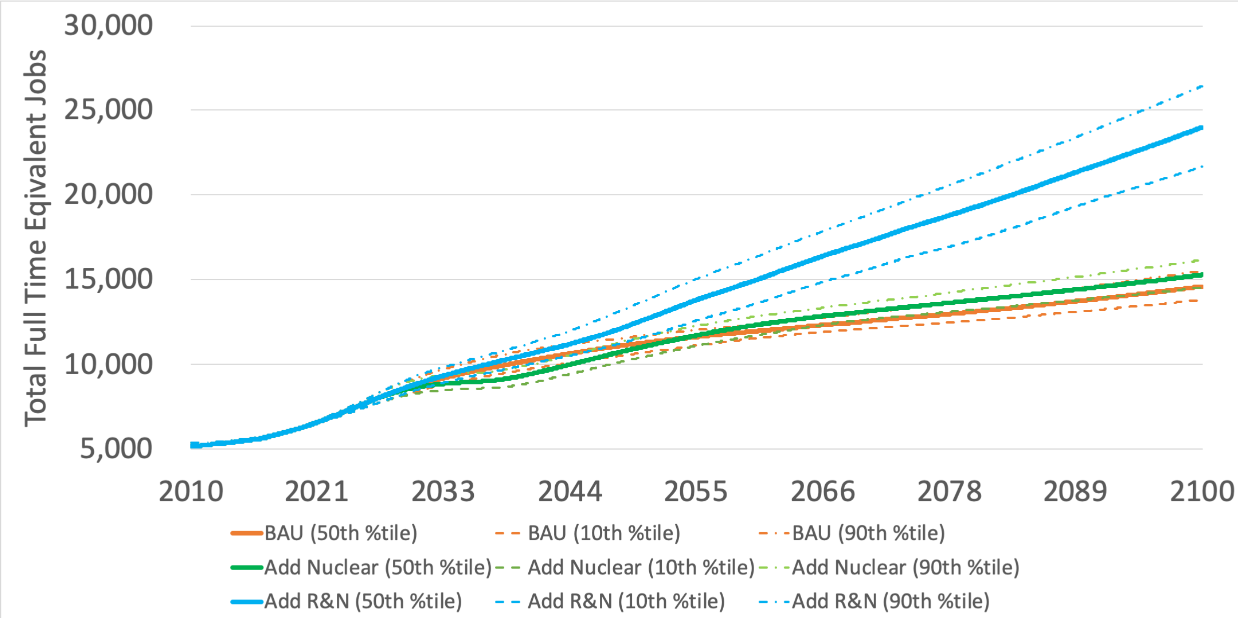


Figure 4.20: Job Market Data with Percentiles



Demand Supply Balance. From the demand-supply balance curves in **Figure 4.15**, it is observed that the Add Nuclear and Add Renewables and Nuclear options are generally able to keep up with the demand over time, at least until 2100. There are some scenarios in the lower percentiles of the alternative scenarios that had a ratio less than 1 at the early stages of transition, where capacities were still being built up. In the BAU scenario, it was observed that where ~40% of the scenarios where generating supply might not be able to keep up with the demand towards the end of the simulation.

Electricity Price and Cost to Society. The energy price related curves in **Figure 4.16** and **Figure 4.17** showed that there were overlaps in price outcomes across all three scenarios. The number lines shown in the inset graph in **Figure 4.17** showed that the 10th to 50th percentile data at year 2100 for the Add Nuclear scenario was cheaper for the society compared to the 10th percentile data from the BAU scenario. This would suggest that switching to the alternative scenarios, especially the Add Nuclear scenario, might not be that costly to the users eventually.

Cumulative Expenditure. While the proportion of GDP set for infrastructure investment was at 0.05%, the actual expenditure was dependent on the other factors such as resource limits, allocation, depreciated assets within the model. **Figure 4.18** shows the estimated cumulative expenditure in electricity infrastructure for all three scenarios in 2010 dollars. Generally speaking, the expenditure by the alternative scenarios were higher than the BAU, with a segment of overlap between the Add Nuclear and the BAU.

Emissions. The emissions estimate in **Figure 4.19** showed that all three scenarios in which the UN INDC target were able to achieve the UN INDC target between 2026 to 2034. This might suggest that the focusing on energy efficiency initiatives would be sufficient for Singapore to meet its goal. However, a change in perspective might also suggest that the original target set forth was too lenient. Looking at the inset graph on the right in **Figure 4.19**, it is observed that the 10^{th} to 90^{th} percentile of possible outcomes in the BAU scenario do not overlap with the 10^{th} to 90^{th} percentile of the alternative scenarios. In other words, the data suggests that it might be worthwhile for Singapore to switch to the alternative scenarios to achieve significantly lower emissions than the BAU scenario in the long run.

Job Market. In terms of providing for jobs, as seen in **Figure 4.18**, the Add Renewables & Nuclear scenario consistently outperforms the other scenarios in terms of total number of jobs provided from 2060 onwards, as the 10^{th} to 90^{th} percentile of runs do not overlap with the BAU and Add Nuclear scenario.

Chapter Summary. The results thus far have shown how Singapore's electricity landscape might transform based on the model proposed. Through the different scenarios tested under varying conditions, it is observed that there are no clear and consistent winners amongst all three scenarios. Each scenario has its own benefits and what is clear is that adding electricity import may be a worthwhile consideration as the economic outcomes are not fundamentally detrimental and there are multiple potential upsides that can be gained from such an endeavour. The next chapter will conclude all the findings and discuss the potentials and impacts from externalities beyond the current model boundary.

Chapter 5 | Conclusion

5.1 | Is There A Best Option?

Comparing Options. The key findings from **Chapter 4** is summarized in **Table 5-1** below.

Table 5-1: Summary of Findings Between Options

Scenario / Key Outcomes	BAU	Allow Nuclear	Allow Renewables & Nuclear
A: Total Electricity Price paid (% by 2100)	Highest & Widest Range (5% to 7.9%)	Lowest and Shortest (4.0% to 6.2%)	Mid-range (4.8% to 7.1%)
B: Expenditure to build-up infrastructure (USD(2010) by 2100)	Lowest (100B$ to 144B$)	Mid-range (133B$ to 180B$) **(+25% to 33% of BAU)**	Highest (205B$ to 235B$) **(+63 to 105% of BAU)**
C1: Fulfilling Peak Demand till 2050 (current generation)	Consistently highest. 10^{th} to 90^{th} % Range: 1.05 to 1.5	Able to fulfil but lower than BAU 10^{th} to 90^{th} % Range: 0.98 to 1.4.	Able to fulfil but consistently lower. 10^{th} to 90^{th} % Range: 0.99 to 1.25.
C2: Fulfilling Peak Demand at 2100	50^{th} to 90^{th} percentile able to fulfil.	10^{th} to 90^{th} percentile able to fulfil.	10^{th} to 90^{th} percentile able to fulfil.
D1: Achieve emissions targets by 2030	10^{th} to 48^{th} percentile able to do so.	10^{th} to 75^{th} percentile able to do so.	10^{th} to 77th percentile able to do so.
D2: Emissions range in 2100	Highest range of values that exceeded other scenarios.	Mid-range. Completely outperforms the 10^{th} to 90^{th} % BAU range.	Best performing. Completely outperforms the 10^{th} to 90^{th} % BAU range.
E: Job Prospect	Lowest number of jobs generated	Mid-range.	Highest number of jobs generated.

The results shows that the BAU scenario with current policy focus on energy efficiency would be considered a sound strategy in the near term. However, its downsides in fulfilling needs, managing price growth, and emissions in the longer term. The Add Nuclear option would be the most economic option in the long run, and it would be able to fulfil needs better than in the long run compared to the BAU. The Add Renewable & Nuclear option would provide the most environmental benefits and most prospect in terms of job numbers but its main downsides shown here is in the high cost.

Recommended Option. After considering all that has been discussed thus far, **the recommended policy approach would be based on the Add Nuclear scenario**. The current policy focus on energy efficiency without allowing electricity import was a good short-term strategy but a poor long-term strategy. For a 33% increase in expenditure compared to BAU, adding nuclear to the electricity mix would centrally address the thesis question put forth.

The nuclear option increases baseload capacity more so than the Add Renewables and Nuclear option. It can thus change Singapore's position from an energy importer to a potential energy exporter to Malaysia and Indonesia with the excess baseload. Providing nuclear based electricity allows for increased regional cooperation further for economic development and decrease the carbon footprint of the region. In the scenario tested, natural gas fired plants remained a mainstay for locally generated electricity and thus Singapore would still require natural gas. However, the overall needs have decreased and thus Singapore may be able to export any excess piped natural gas to other countries beyond the immediate region for its neighbors thereby increasing the natural gas's position on the value chain. The alternative scenario would also help drive Singapore's knowledge-based economy further and allow the country to become a regional leader in nuclear technology if it establishes the technology first. The Add Nuclear option proposed were based on floating barges and platform solutions that could leverage upon Singapore's strong maritime technology foundations. Using floating platforms would have less environmental damage compared to building up renewable energy technologies which would affect the livelihood of locals in Malaysia and Indonesia (e.g. hydro damming + land clearing for solar/ wind) living near the identified resource areas.

Incentivizing Cooperation. Based on the data provided by the Observatory of Economic Complexity from 2007 to 2017, natural gas exports account for 9-25% of Indonesia's exports and 1-2.3% of Malaysia's exports to Singapore.[6] To maintain and possibly improve economic cooperation while Singapore lowers its reliance on piped natural gas for electricity, Singapore could re-export the piped natural gas by converting it to liquefied natural gas (LNG) or other products for industrial use. If the Add Renewable and Nuclear scenario was pursued instead, Singapore could also improve the bilateral trust by co-developing the renewable energy based power plants at scale that might bring about economic growth for the region.

Improving Public Awareness and Allaying Concerns. The negative sentiments towards nuclear by the public should be addressed to improve the awareness and acceptance. A Whole-of-Government (WoG) effort would be required to follow through on the long implementation journey, where the correct information must be shared and sufficient safety and security measures must be implemented to allay the public concerns.

5.2 | Model Limitations

The stock-and-flow model built for this thesis has certain limitations due to model assumptions and simplification.

Demand Model. Firstly, the demand model was built as an exogenous factor based centrally on population growth and the level of energy efficiency used for each simulation run. This might not be fully representative as changing electricity prices may in fact change behavior to peak load behavior and demand per capita may also change over time. The population growth model was not based on a Total Fertility Rate growth model but was instead simplified to a Compound Annual Growth Rate model and there was no population limit set.

Differing Marginal Cost. In terms of electricity production, it was assumed that the marginal cost within each technology was the same, i.e. all companies using the same technology had the same marginal cost. This may not be true as different companies within one technology would probably have differing marginal costs dependent on the time they obtained the technology and the corresponding fuel.

Non-Electricity Sector GHG Emissions Modelling. GHG emission from other sectors such as transport, industry, commercial, and residential used an exogenous change model and do not fully capture how increased electrification may lower their emissions. What was captured in the model was mainly these sectors' change in electricity needs through the energy efficiency levels. The average vehicle pollution rate and electricity demand per electric vehicle were assumed to be constant but they may vary as technology changes.

Impact of Non-Baseload Intermittency. As the model's time dimension was in years and not in months or days, the notion of intermittency from renewable technologies such as solar and wind was simplified through the capacity factors but that is not a complete reflection of the intermittency issues faced by these technologies on a day to day basis.

5.3 | Possible Future Research

It is my hope that the system dynamics model developed, the findings, and the limitations discussed can help improving the electricity market and sustainability efforts in Singapore and the ASEAN region. I have listed a few research areas that could be relevant to this thesis's findings.

Design and Implementation Studies for Offshore Floating Nuclear Power (OFNP) Plants. Based on the central recommendation of adding nuclear to the energy mix, it would be helpful to study the detailed design and implementation requirements of OFNP suitable for the regional waters. This could include how OFNP could be co-developed and utilized by Singapore and its neighbors where there might be a stronger case for economics of scale development and greater economic outcomes for all.

Demand Management and Grid Scale Storage. Current additional requirements of 30% beyond peak capacity may have inadvertently created excess capacity that challenges the profitability of many power companies.[99] Dynamic demand side management and grid-scale energy storage could play important roles in lowering overall peak capacity requirement and allow any excess capacity to be traded with other countries.

Encouraging Public Transport or Electric Vehicle Uptake to Lower Emissions. Carbon tax was recently introduced in Singapore for industrial facilities while carbon tax for vehicle emissions have a different form.[97] There could be changes to how carbon tax is charged for vehicles to incentivize utilization of the public metro network and EV conversion, which would thus increase electricity demand, helping with the excess capacity problem, and lower the transport sector's GHG emissions.

Enabling Electricity Trading and Regional Investment. The ASEAN Power Grid (APG) remains central in enabling regional electricity trading. To achieve greater penetration of renewable energy or nuclear energy development in Singapore and its neighbors, there can be more studies on changes in policy and investment mechanisms to enable greater realization of the APG.

Preparing for Future Possibilities. If nuclear fission energy options remain an unacceptable option, then there should be more talent development in other potential baseload technologies that could be suitable for Singapore, the region, and many areas of the world, such as nuclear fusion, which has made promising advancement in the recent years.[100–102] Rather than rushing to acquire it with other nations when the technology becomes mature, more can be done to leverage upon the highly educated population to better prepare Singapore for it.

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Style guide used: Nature style guide updated on 10/10/2019 in Zotero.

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Appendix I: Equations of the Singapore Electricity Landscape Transformation Model

All equations generated using the Document function in VensimDSS, alphabetically ordered. **Appendix 2** would list the variables in order of appearance in Chapter 3 and there would be a brief description of each variable.

(001) Actual Proportion Overseas=
"Total Waiting and Installed Capacities (Overseas)"/Total Waiting and Installed Capacities
Units: Dmnl

(002) Adjusted Desired GHG Emissions=
Desired Target for GHG Emissions*Effect of Targets for GHG Emissions
Units: CO2*g/Year

(003) Adjusted Floating Target for EDI=
Floating Target for EDI*Effect of Normalized EDI on Desired State for EDI
Units: Dmnl

(004) Adjusted Price for Each Technology[Generator]=
Expected Price*"Effect of Short-Term Demand-Supply Balance on Price"*Effect of Marginal Cost on Price[Generator
]
Units: USD/(MW*h)

(005) Adjusted Target for GJC=
Floating Target for GJC*Effect of Policy Targets on Job Creation
Units: Job/Year

(006) "Adjustment for Installed Capacity (Local)"[Local Generator]=
("Desired Capacity (Local)"[Local Generator]-"Installed Capacity (Local)"[Local Generator])/Perception Delay for Capacity Adjustment
Units: MW/Year

(007) "Adjustment for Installed Capacity (Overseas)"[Overseas Generator]=
("Desired Capacity (Overseas)"[Overseas Generator]-"Installed Capacity (Overseas)"[Overseas Generator])/Perception Delay for Capacity Adjustment
Units: MW/Year

(008) "Adjustment for Waiting Capacities (Local)"[Local Generator]=
("Desired Waiting Capacities (Local)"[Local Generator]-"Capacities Waiting for Build Completion (Local)"[Local Generator])/"Net Project Approval Time (Local)"
Units: MW/Year

(009) "Adjustment for Waiting Capacities (Overseas)"[Overseas Generator]=
("Desired Waiting Capacity (Overseas)"[Overseas Generator]-"Capacities Waiting for Build Completion (Overseas)"[Overseas Generator])/"Net Project Approval Time (Overseas)"
Units: MW/Year

(010) Adjustment Time for Floating Target for Jobs=
5
Units: Year

(011) Amount Supplied by Each Generator[Generator]=
SUPPLY AT PRICE(Available Electricity[Generator] , Supply Curve Function[Generator,ptype] , Market Clearing Mechanism
)
Units: MW*h/Year

(012) Annual Growth Rate of Vehicles=
0.006
Units: Dmnl/Year

(013) Annual Increase in Vehicles=
Total Vehicles*Annual Growth Rate of Vehicles
Units: Vehicle/Year

(014) Annual Investment in Electricity Infrastructure=
Proportion of GDP for Electricity Infrastructure*GDP
Units: USD/Year

(015) Available Electricity[Local Generator]=
"Technical Availability (Local)"[Local Generator]
Available Electricity[Overseas Generator]=
"Technical Availability (Overseas)"[Overseas Generator]
Units: MW*h/Year

(016) Average Demand Per EV=
4000
Units: kW*h/(Year*Vehicle)

(017) Average Vehicle Pollution Rate=
0.007309*1e+09

Units: CO2*g/(Vehicle*Year)

(018) Baseline Electricity Demand by Sectors[Demand Type]=
Demand Sector Baseline Proportion[Demand Type]*Population Based Electricity Demand
Units: kW*h/Year

(019) BII Adjustment Time=
4
Units: Year

(020) Building Demand Savings Rate=
IF THEN ELSE(Level of Energy Efficiency Intiatives = 0, Building Demand Savings Rate BAU(Time/Year Unit),IF THEN ELSE(Level of Energy Efficiency Intiatives
=0.5,Building Demand Savings Rates Conservative(Time/Year Unit),Building Demand Savings Rate Optimistic(Time/Year Unit)))
Units: Dmnl

(021) Building Demand Savings Rate BAU(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.03),(2050,0.06),(2100,0.135))
Units: Dmnl

(022) Building Demand Savings Rate Optimistic(
[(2010,0)-(2100,30)],(2010,0),(2030,0.12),(2050,0.15),(2100,0.225))
Units: Dmnl

(023) Building Demand Savings Rates Conservative(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.06),(2050,0.075),(2100,0.1125))
Units: Dmnl

(024) "Capacities Waiting for Build Completion (Local)"[Local Natural Gas Fired]= INTEG (
"Order Rate (Local)"[Local Natural Gas Fired]-"Construction Completion (Local)"[Local Natural Gas Fired],
("Installed Capacity (Local)"[Local Natural Gas Fired]*Population Growth Rate+"Installed Capacity (Local)"[Local Natural Gas Fired
]/Capacity Average Lifetime[Local Natural Gas Fired])*(EXP(Population Growth Rate*("Capacity Construction Time (Local)"+"Net Project Approval Time (Local)"
))-1)/Population Growth Rate)
"Capacities Waiting for Build Completion (Local)"[Local Waste to Energy]= INTEG (
"Order Rate (Local)"[Local Waste to Energy]-"Construction Completion (Local)"[Local Waste to Energy],
0)
"Capacities Waiting for Build Completion (Local)"[Local Solar PV]= INTEG (

"Order Rate (Local)"[Local Solar PV]-"Construction Completion (Local)"[Local Solar PV],
0)
Units: MW

(025) "Capacities Waiting for Build Completion (Overseas)"[Overseas Onshore Wind]= INTEG (
"Order Rate (Overseas)"[Overseas Onshore Wind]-"Construction Completion (Overseas)"[Overseas Onshore Wind],
0)
"Capacities Waiting for Build Completion (Overseas)"[Overseas Geothermal]= INTEG (
"Order Rate (Overseas)"[Overseas Geothermal]-"Construction Completion (Overseas)"[Overseas Geothermal],
0)
"Capacities Waiting for Build Completion (Overseas)"[Overseas Hydro]= INTEG (
"Order Rate (Overseas)"[Overseas Hydro]-"Construction Completion (Overseas)"[Overseas Hydro],
0)
"Capacities Waiting for Build Completion (Overseas)"[Overseas Solar PV]= INTEG (
"Order Rate (Overseas)"[Overseas Solar PV]-"Construction Completion (Overseas)"[Overseas Solar PV],
0)
"Capacities Waiting for Build Completion (Overseas)"[Overseas Nuclear]= INTEG (
"Order Rate (Overseas)"[Overseas Nuclear]-"Construction Completion (Overseas)"[Overseas Nuclear],
0)
Units: MW

(026) Capacity Average Lifetime[Local Natural Gas Fired]=
30
Capacity Average Lifetime[Local Waste to Energy]=
30
Capacity Average Lifetime[Local Solar PV]=
25
Capacity Average Lifetime[Overseas Onshore Wind]=
25
Capacity Average Lifetime[Overseas Hydro]=
50
Capacity Average Lifetime[Overseas Geothermal]=
30
Capacity Average Lifetime[Overseas Solar PV]=
25
Capacity Average Lifetime[Overseas Nuclear]=
60
Units: Year

(027) "Capacity Construction Time (Local)"=
3
Units: Year

(028) "Capacity Construction Time (Overseas)"[Overseas Geothermal]=
3
"Capacity Construction Time (Overseas)"[Overseas Hydro]=
5
"Capacity Construction Time (Overseas)"[Overseas Onshore Wind]=
1.5
"Capacity Construction Time (Overseas)"[Overseas Solar PV]=
3
"Capacity Construction Time (Overseas)"[Overseas Nuclear]=
9
Units: Year

(029) Capacity Coverage=
SMOOTH(Current Capacity to Peak Demand Ratio, Year Unit/4)
Units: Dmnl

(030) "Capacity Depreciation Rate (Local)"[Local Generator]=
"Installed Capacity (Local)"[Local Generator]/Capacity Average Lifetime[Local Generator]
Units: MW/Year

(031) "Capacity Depreciation Rate (Overseas)"[Overseas Generator]=
"Installed Capacity (Overseas)"[Overseas Generator]/Capacity Average Lifetime[Overseas Generator]
Units: MW/Year

(032) Capacity Factor[Local Natural Gas Fired]=
0.9
Capacity Factor[Local Waste to Energy]=
0.91
Capacity Factor[Local Solar PV]=
0.15
Capacity Factor[Overseas Onshore Wind]=
0.32
Capacity Factor[Overseas Hydro]=
0.46
Capacity Factor[Overseas Geothermal]=
0.84
Capacity Factor[Overseas Solar PV]=

0.15
Capacity Factor[Overseas Nuclear]=
0.9
Units: Dmnl

(033) Capacity Utilisation[Generator]= ACTIVE INITIAL (
SMOOTH(Table for Capacity Utilisation[Generator](Relative Incentive to Generate[Generator]) , Capacity Utilisation Delay Time),
1)
Units: Dmnl

(034) Capacity Utilisation Delay Time=
0.25
Units: Year

(035) Capital Recovery Factor[Generator]=
(Weight Average Cost of Capital*(1+Weight Average Cost of Capital)^(Capacity Average Lifetime[Generator]/Year Unit
))/(((1+Weight Average Cost of Capital)^(Capacity Average Lifetime[Generator]/Year Unit))-1)
Units: Dmnl

(036) Carbon Tax Payable[Generator]=
Lifecycle Emission Intensity by Generator[Generator]*"Carbon Tax Rate (CTR)"*kg to g/kW to MW
Units: USD/(MW*h)

(037) "Carbon Tax Rate (CTR)"= INTEG (
Change in CTR,
0.0037)
Units: USD/(kg*CO2)

(038) Change in BII[Generator]=
(Desired BII[Generator]-"Policy: Boost Infrastructure Investment (BII)"[Generator])/BII Adjustment Time
Units: Dmnl/Year

(039) Change in CSN=
(Current Total Social Needs^(1-"Rate of Inequality Aversion (RIA)")-1)/((1-"Rate of Inequality Aversion (RIA)")*Year Unit)*Discount Factor
Units: Dmnl/Year

(040) Change in CTR=
(Desired CTR-"Carbon Tax Rate (CTR)")/CTR Adjustment Time

Units: USD/(Year*kg*CO2)

(041) Change in Desired Target=
(Current GHG Emissions-Desired Target for GHG Emissions)/Target GHG Adjustment Time
Units: CO2*g/(Year*Year)

(042) Change in FGDSB=
(Current Capacity to Peak Demand Ratio-"Floating Goal for Demand Supply Balance (FGDSB)")/Change in FGDSB Adjustment Time
Units: Dmnl/Year

(043) Change in FGDSB Adjustment Time=
4
Units: Year

(044) Change in Floating Target=
("Current Energy Diversity Index (EDI)"-Floating Target for EDI)/EDI Adjustment Time
Units: 1/Year

(045) Change in Floating Target for Jobs=
("Gross Jobs Created (GJC)"-Floating Target for GJC)/Adjustment Time for Floating Target for Jobs
Units: Job/(Year*Year)

(046) Change in GDP=
GDP*GDP Growth Rate
Units: USD/Year

(047) "Change in Investment (Local)"[Local Generator]=
Investment in Each Generator[Local Generator]
Units: USD/Year

(048) "Change in Investment (Overseas)"[Overseas Generator]=
Investment in Each Generator[Overseas Generator]
Units: USD/Year

(049) Change in Population=
Population*Population Growth Rate
Units: People/Year

(050) Change in RARI=

(Desired RARI-"Policy: Renewables Approvals Rate Impact (RARI)")/Change in RARI Adjusment Time
Units: Dmnl/Year

(051) Change in RARI Adjusment Time=
4
Units: Year

(052) Changes to Expected Price=
(Indicated Price-Expected Price)/Time to Adjust Expected Price
Units: USD/(MW*h*Year)

(053) "Construction Completion (Local)"[Local Generator]=
"Capacities Waiting for Build Completion (Local)"[Local Generator]/"Capacity Construction Time (Local)"
Units: MW/Year

(054) "Construction Completion (Overseas)"[Overseas Generator]=
"Capacities Waiting for Build Completion (Overseas)"[Overseas Generator]/"Capacity Construction Time (Overseas)"[Overseas Generator]
Units: MW/Year

(055) CTR Adjustment Time=
4
Units: Year

(056) Cumulative Expenditure= INTEG (
Total Spent Per Year/Yearly Inflation Adjustment Rate,
0)
Units: USD

(057) "Cumulative Social Needs (CSN)"= INTEG (
Change in CSN,
Current Total Social Needs)
Units: Dmnl

(058) Current Capacity to Peak Demand Ratio=
Total Generating Capacities/Peak Demand in MW
Units: Dmnl

(059) "Current Energy Diversity Index (EDI)"=
SUM(Proportion Per Generating Type[Energy Source Type!]^2)
Units: Dmnl

(060) Current GHG Emissions=
SUM(Electricity Generated by Type[Energy Source Type!]*Lifecycle Emission Intensity of Resources[Energy Source Type!])/
kW to MW+SUM(GHG Emissions from Other Sources[Other GHG Sources!])+GHG Emissions from Transport
Units: CO2*g/Year

(061) Current Total Social Needs=
Relative Social Need for Energy Diversity*Relative Social Need for Energy Job Creation*Relative Social Need for DSB*Relative Social Need for GHG Emissions
Units: Dmnl

(062) Demand After Changes[Industry]=
Baseline Electricity Demand by Sectors[Industry]*(1-Industry Demand Savings Rate)
Demand After Changes[Transport]=
Baseline Electricity Demand by Sectors[Transport]+Transport Sector Electricity Demand Growth
Demand After Changes[Buildings]=
Baseline Electricity Demand by Sectors[Buildings]*(1-Building Demand Savings Rate)
Demand After Changes[Household]=
Baseline Electricity Demand by Sectors[Household]*(1-Household Demand Savings Rate)
Demand After Changes[Others]=
Baseline Electricity Demand by Sectors[Others]
Units: kW*h/Year

(063) Demand Cruve pType=
1
Units: Dmnl

(064) Demand Cruve pWidth=
1
Units: Dmnl

(065) Demand Curve Function[Demand for Market Clearing,ptype]=
Demand Cruve pType
Demand Curve Function[Demand for Market Clearing,ppriority]=
VMAX(Supply Curve Price[Generator!])+1
Demand Curve Function[Demand for Market Clearing,pwidth]=
Demand Cruve pWidth
Demand Curve Function[Demand for Market Clearing,pextra]=
Demand Curve pExtra

Units: Dmnl

(066) Demand Curve pExtra=
0
Units: Dmnl

(067) Demand for Market Clearing:
Total Demand

(068) Demand Sector Baseline Proportion[Industry]=
0.43
Demand Sector Baseline Proportion[Buildings]=
0.31
Demand Sector Baseline Proportion[Transport]=
0.05
Demand Sector Baseline Proportion[Household]=
0.18
Demand Sector Baseline Proportion[Others]=
0.03
Units: Dmnl

(069) Demand Type:
Industry,Transport,Buildings,Household,Others

(070) Depreciated Investment Cost DIC[Generator]=
Time Adjusted Overnight Investment Cost[Generator]*Capital Recovery Factor[Generator]
Units: USD/(MW*Year)

(071) Desired BII[Generator]=
"Policy: Boost Infrastructure Investment (BII)"[Generator]*Effect of Social Pressure on BII[Generator]
Units: Dmnl

(072) "Desired Capacity (Local)"[Local Natural Gas Fired]=
Desired Minimum Total Capacity Required*(1-Proportion of Capacity Allowed Overseas)*Desired Local Generating Proportions[Local Natural Gas Fired]+"Extra Baseload For Non-Baseload Rate"
*"Desired Capacity (Local)"[Local Solar PV]
"Desired Capacity (Local)"[Local Solar PV]=
Desired Minimum Total Capacity Required*(1-Proportion of Capacity Allowed Overseas)*Desired Local Generating Proportions[Local Solar PV]
"Desired Capacity (Local)"[Local Waste to Energy]=

Desired Minimum Total Capacity Required*(1-Proportion of Capacity Allowed Overseas)*Desired Local Generating Proportions[Local Waste to Energy]
Units: MW

(073) "Desired Capacity (Overseas)"[Overseas Geothermal]=
Desired Minimum Total Capacity Required*Proportion of Capacity Allowed Overseas*Desired Overseas Generating Proportions[Overseas Geothermal]+("Desired Capacity (Overseas)"
[Overseas Solar PV]+"Desired Capacity (Overseas)"[Overseas Onshore Wind])*"Extra Baseload For Non-Baseload Rate"/3
"Desired Capacity (Overseas)"[Overseas Hydro]=
Desired Minimum Total Capacity Required*Proportion of Capacity Allowed Overseas*Desired Overseas Generating Proportions[Overseas Hydro]+("Desired Capacity (Overseas)"
[Overseas Solar PV]+"Desired Capacity (Overseas)"[Overseas Onshore Wind])*"Extra Baseload For Non-Baseload Rate"/3
"Desired Capacity (Overseas)"[Overseas Onshore Wind]=
Desired Minimum Total Capacity Required*Proportion of Capacity Allowed Overseas*Desired Overseas Generating Proportions[Overseas Onshore Wind
]
"Desired Capacity (Overseas)"[Overseas Solar PV]=
Desired Minimum Total Capacity Required*Proportion of Capacity Allowed Overseas*Desired Overseas Generating Proportions[Overseas Solar PV
]
"Desired Capacity (Overseas)"[Overseas Nuclear]=
Desired Minimum Total Capacity Required*Proportion of Capacity Allowed Overseas*Desired Overseas Generating Proportions[Overseas Nuclear]+("Desired Capacity (Overseas)"
[Overseas Solar PV]+"Desired Capacity (Overseas)"[Overseas Onshore Wind])*"Extra Baseload For Non-Baseload Rate"/3
Units: MW

(074) "Desired Capacity Acquisition Rate (Local)"[Local Generator]=
Max(0, "Adjustment for Installed Capacity (Local)"[Local Generator]+"Capacity Depreciation Rate (Local)"[Local Generator])
Units: MW/Year

(075) "Desired Capacity Acquisition Rate (Overseas)"[Overseas Generator]=
Max(0,"Adjustment for Installed Capacity (Overseas)"[Overseas Generator]+"Capacity Depreciation Rate (Overseas)"[Overseas Generator])
Units: MW/Year

(076) Desired Capacity's Technology Cost[Local Natural Gas Fired]=

"Desired Capacity (Local)"[Local Natural Gas Fired]*Time Adjusted Overnight Investment Cost[Local Natural Gas Fired]

Desired Capacity's Technology Cost[Local Solar PV]=

"Desired Capacity (Local)"[Local Solar PV]*Time Adjusted Overnight Investment Cost[Local Solar PV]

Desired Capacity's Technology Cost[Local Waste to Energy]=

"Desired Capacity (Local)"[Local Waste to Energy]*Time Adjusted Overnight Investment Cost[Local Waste to Energy]

Desired Capacity's Technology Cost[Overseas Geothermal]=

"Desired Capacity (Overseas)"[Overseas Geothermal]*Time Adjusted Overnight Investment Cost[Overseas Geothermal]

Desired Capacity's Technology Cost[Overseas Hydro]=

"Desired Capacity (Overseas)"[Overseas Hydro]*Time Adjusted Overnight Investment Cost[Overseas Hydro]

Desired Capacity's Technology Cost[Overseas Onshore Wind]=

"Desired Capacity (Overseas)"[Overseas Onshore Wind]*Time Adjusted Overnight Investment Cost[Overseas Onshore Wind]

Desired Capacity's Technology Cost[Overseas Solar PV]=

"Desired Capacity (Overseas)"[Overseas Solar PV]*Time Adjusted Overnight Investment Cost[Overseas Solar PV]

Desired Capacity's Technology Cost[Overseas Nuclear]=

"Desired Capacity (Overseas)"[Overseas Nuclear]*Time Adjusted Overnight Investment Cost[Overseas Nuclear]

Units: USD/Year

(077) Desired CTR=

"Carbon Tax Rate (CTR)"*Effect of Social Pressure on CTR

Units: USD/(kg*CO2)

(078) Desired Local Generating Proportions[Local Natural Gas Fired]=

1-Desired Local Generating Proportions[Local Solar PV]-Desired Local Generating Proportions[Local Waste to Energy]

Desired Local Generating Proportions[Local Solar PV]=

Initial Solar Proportion Target+RAMP(("Desired Non-Baseload Proportion"-Initial Solar Proportion Target

)/(40*Year Unit) , 2010 , 2050)

Desired Local Generating Proportions[Local Waste to Energy]=

0.02

Units: Dmnl

(079) Desired Minimum Total Capacity Required=

Peak Demand in MW*Reserve Capacity Requirements

Units: MW

(080) "Desired Non-Baseload Proportion"=
0.2
Units: Dmnl

(081) Desired Overseas Generating Proportions[Overseas Geothermal]=
IF THEN ELSE("Policy: Allow Nuclear Only" = 1, 0, (1-"Desired Non-Baseload Proportion")/3)
Desired Overseas Generating Proportions[Overseas Hydro]=
IF THEN ELSE("Policy: Allow Nuclear Only" = 1, 0, (1-"Desired Non-Baseload Proportion")/3)
Desired Overseas Generating Proportions[Overseas Onshore Wind]=
IF THEN ELSE("Policy: Allow Nuclear Only" = 1, 0, ("Desired Non-Baseload Proportion")/2)
Desired Overseas Generating Proportions[Overseas Solar PV]=
IF THEN ELSE("Policy: Allow Nuclear Only" = 1, 0, ("Desired Non-Baseload Proportion")/2)
Desired Overseas Generating Proportions[Overseas Nuclear]=
IF THEN ELSE("Policy: Allow Nuclear Only" = 1, (1-"Desired Non-Baseload Proportion"), (1-"Desired Non-Baseload Proportion")/3)
Units: Dmnl

(082) Desired RARI=
"Policy: Renewables Approvals Rate Impact (RARI)"*Effect of Social Pressure on RARI
Units: Dmnl

(083) Desired State for Demand Supply Balance=
IF THEN ELSE(Max(Reserve Capacity Requirements,"Floating Goal for Demand Supply Balance (FGDSB)") > Maximum Excess Supply Proportion, Maximum Excess Supply Proportion
, Max(Reserve Capacity Requirements,"Floating Goal for Demand Supply Balance (FGDSB)"))
Units: Dmnl

(084) Desired Target for GHG Emissions= INTEG (
Change in Desired Target,
Current GHG Emissions)
Units: CO2*g/Year

(085) "Desired Waiting Capacities (Local)"[Local Generator]=
"Capacity Construction Time (Local)"*"Desired Capacity Acquisition Rate (Local)"[Local Generator]
Units: MW

(086) "Desired Waiting Capacity (Overseas)"[Overseas Generator]=
"Capacity Construction Time (Overseas)"[Overseas Geothermal]*"Desired Capacity Acquisition Rate (Overseas)"[Overseas Generator]
Units: MW

(087) Discount Factor=
EXP((-"Rate of Time Preference (RTP)")*(Time-INITIAL TIME))
Units: Dmnl

(088) Duration to Achieve Overseas Capacity=
20
Units: Year

(089) EDI Adjustment Time=
5
Units: Year

(090) Effect of Generation Profit[Generator]=
EXP(SMOOTH(Long Term Generator Price Forecast,Profit Consideration Horizon)/SMOOTH(LCOE[Generator],Profit Consideration Horizon))
Units: Dmnl

(091) Effect of Marginal Cost on Price[Generator]=
IF THEN ELSE(Expected Marginal Costs[Generator]< 0, 1, 1+Sensitivity of Price to Marginal Cost*(Expected Marginal Costs[Generator]/Expected Price-1)
)
Units: Dmnl

(092) Effect of Normalized EDI on Desired State for EDI=
Table for Normalized EDI on Desired(Normalized EDI)
Units: Dmnl

(093) Effect of Policy Targets on Job Creation=
Table for Normalized GJC(Normalized GJC)
Units: Dmnl

(094) "Effect of Short-Term Demand-Supply Balance on Price"=
(Capacity Coverage/Reserve Capacity Requirements)^"Sensitivity of Price to Demand-Supply Balance"
Units: Dmnl

(095) Effect of Social Pressure on BII[Generator]=
Table for Social Pressure on BII[Generator](Effective Social Pressure)
Units: Dmnl

(096) Effect of Social Pressure on CTR=
Table for Social Pressure on CTR(Effective Social Pressure)
Units: Dmnl

(097) Effect of Social Pressure on RARI=
Table for Social Pressure on RARI(Effective Social Pressure)
Units: Dmnl

(098) Effect of Targets for GHG Emissions=
Table for Normalized GHG on Desired(Normalized GHG levels)
Units: Dmnl

(099) Effected GHG Curtailment Rate for Other Sources=
IF THEN ELSE(Time > 2020, GHG Curtailment Rate for Other Sources, 0)
Units: Dmnl

(100) Effective Social Pressure=
"Cumulative Social Needs (CSN)"/Reference CSN
Units: Dmnl

(101) EIA Fuel Forecast Growth Rate=
0.035
Units: Dmnl

(102) Electricity Demand Per Capita=
8587.78
Units: kW*h/(People*Year)

(103) Electricity Generated by Type[Natural Gas Fired]=
Amount Supplied by Each Generator[Local Natural Gas Fired]
Electricity Generated by Type[Waste to Energy]=
Amount Supplied by Each Generator[Local Waste to Energy]
Electricity Generated by Type[Solar PV]=
Amount Supplied by Each Generator[Local Solar PV]+Amount Supplied by Each Generator[Overseas Solar PV]
Electricity Generated by Type[Onshore Wind]=
Amount Supplied by Each Generator[Overseas Onshore Wind]
Electricity Generated by Type[Geothermal]=
Amount Supplied by Each Generator[Overseas Geothermal]
Electricity Generated by Type[Hydro]=
Amount Supplied by Each Generator[Overseas Hydro]
Electricity Generated by Type[Nuclear]=
Amount Supplied by Each Generator[Overseas Nuclear]

Units: MW*h/Year

(104) Electricity Price=
Market Clearing Mechanism*Unit Price
Units: USD/(MW*h)

(105) Electricity Price Forward Period=
3
Units: Year

(106) Electricity Price Lookback Period=
2
Units: Year

(107) Energy Source Type:
Natural Gas Fired,Waste to Energy,Solar PV,Hydro,Geothermal,Onshore Wind, Nuclear

(108) EV Annual Growth Rate BAU(
[(2010,0)-(2100,0.1)],(2010,0),(2030,0),(2050,0),(2100,0))
Units: Dmnl/Year

(109) EV Annual Growth Rate Conservative(
[(2010,0)-(2100,0.04)],(2010,0),(2030,0),(2050,0.01),(2100,0.035))
Units: Dmnl/Year

(110) EV Annual Growth Rate Optimistic(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.03),(2050,0.05),(2100,0.1))
Units: Dmnl/Year

(111) Expected Carbon Tax[Generator]=
IF THEN ELSE(Time > 2019.75, Carbon Tax Payable[Generator] , 0)
Units: USD/(MW*h)

(112) Expected Fuel Price[Generator]=
FORECAST("Fuel Price (with Noise)"[Generator], Fuel Price Lookback Period , Fuel Price Forward Period)
Units: USD/MBtu

(113) Expected Marginal Costs[Generator]=
SMOOTH("Time Adjusted Fixed O&M Cost"[Generator]/(Hours per Year*Capacity Factor[Generator])+"Time Adjusted Variable O&M Cost"
[Generator]+Fuel Cost in USD per MWh[Generator] , Year Unit/2)
Units: USD/(h*MW)

(114) "Expected Order Capacity (Overseas)"[Overseas Generator]=
IF THEN ELSE(Proportion of Capacity Allowed Overseas>0, ("Investment Tied Order Rate (Overseas)"[Overseas Generator]+Max(0,"Indicated Order Capacity (Overseas)"[Overseas Generator])) , 0)
Units: MW/Year

(115) Expected Price= INTEG (
Changes to Expected Price,
125.59)
Units: USD/(MW*h)

(116) "Extra Baseload For Non-Baseload Rate"=
0.5
Units: Dmnl

(117) Extra Value for Waste to Energy=
26
Units: USD/(h*MW)

(118) Final Proportion of Capacity Allowed Overseas=
0.5
Units: Dmnl

(119) FINAL TIME = 2100
Units: Year

(120) Fixed Total Emission Target=
USD Adjusted Singapore UN NDC Target*"GDP @ 2030"/Year Unit
Units: CO2*g/Year

(121) "Floating Goal for Demand Supply Balance (FGDSB)"= INTEG (
Change in FGDSB,
Current Capacity to Peak Demand Ratio)
Units: Dmnl

(122) Floating Target for EDI= INTEG (
Change in Floating Target,
"Current Energy Diversity Index (EDI)")
Units: Dmnl

(123) Floating Target for GJC= INTEG (
Change in Floating Target for Jobs,
"Gross Jobs Created (GJC)")

Units: Job/Year

(124) Fuel at Last Database Time=
11.38
Units: USD/MBtu

(125) Fuel Cost in USD per MWh[Local Natural Gas Fired]=
Expected Fuel Price[Local Natural Gas Fired]*Heat Rate[Local Natural Gas Fired]*MBtu to Btu+Expected Carbon Tax[Local Natural Gas Fired
]
Fuel Cost in USD per MWh[Local Waste to Energy]=
Expected Carbon Tax[Local Waste to Energy]-Extra Value for Waste to Energy*Yearly Inflation Adjustment Rate
Fuel Cost in USD per MWh[Local Solar PV]=
Expected Carbon Tax[Local Solar PV]
Fuel Cost in USD per MWh[Overseas Onshore Wind]=
Expected Carbon Tax[Overseas Onshore Wind]
Fuel Cost in USD per MWh[Overseas Hydro]=
Expected Carbon Tax[Overseas Hydro]
Fuel Cost in USD per MWh[Overseas Geothermal]=
Expected Carbon Tax[Overseas Geothermal]
Fuel Cost in USD per MWh[Overseas Solar PV]=
Expected Carbon Tax[Overseas Solar PV]
Fuel Cost in USD per MWh[Overseas Nuclear]=
Expected Fuel Price[Overseas Nuclear]*Heat Rate[Overseas Nuclear]*MBtu to Btu+Expected Carbon Tax[Overseas Nuclear]
Units: USD/(MW*h)

(126) "Fuel Price (with Noise)"[Local Natural Gas Fired]=
IF THEN ELSE(Time > 2018.9, Pink Noise Maker*Fuel at Last Database Time*Yearly Fuel Increase Adjustment Rate,Fuel Price Database[Local Natural Gas Fired
])
"Fuel Price (with Noise)"[Local Solar PV]=
Fuel Price Database[Local Solar PV]*Yearly Inflation Adjustment Rate
"Fuel Price (with Noise)"[Local Waste to Energy]=
Fuel Price Database[Local Waste to Energy]*Yearly Inflation Adjustment Rate
"Fuel Price (with Noise)"[Overseas Geothermal]=
Fuel Price Database[Overseas Geothermal]*Yearly Inflation Adjustment Rate
"Fuel Price (with Noise)"[Overseas Hydro]=
Fuel Price Database[Overseas Hydro]*Yearly Inflation Adjustment Rate
"Fuel Price (with Noise)"[Overseas Onshore Wind]=
Fuel Price Database[Overseas Onshore Wind]*Yearly Inflation Adjustment Rate
"Fuel Price (with Noise)"[Overseas Solar PV]=
Fuel Price Database[Overseas Solar PV]*Yearly Inflation Adjustment Rate

"Fuel Price (with Noise)"[Overseas Nuclear]=
Max(Fuel Price Database[Overseas Nuclear]*Yearly Fuel Increase Adjustment Rate*Pink Noise Maker,0)
Units: USD/MBtu

(127) Fuel Price Database[Local Natural Gas Fired]:INTERPOLATE::=
GET XLS DATA('Brent Price Data.xlsx', 'Fuel Price' , '1' , 'B2')
Fuel Price Database[Local Waste to Energy]=
0
Fuel Price Database[Local Solar PV]=
0
Fuel Price Database[Overseas Onshore Wind]=
0
Fuel Price Database[Overseas Hydro]=
0
Fuel Price Database[Overseas Geothermal]=
0
Fuel Price Database[Overseas Solar PV]=
0
Fuel Price Database[Overseas Nuclear]=
0.805/1.05587
Units: USD/MBtu

(128) Fuel Price Forward Period=
1
Units: Year

(129) Fuel Price Lookback Period=
1
Units: Year

(130) Future Market Electricity Price=
FORECAST(Reference Clearing Price , Electricity Price Lookback Period , Electricity Price Forward Period)
Units: USD/(MW*h)

(131) Future Proportion of GDP for Infrastructure=
0.005
Units: Dmnl/Year

(132) GDP= INTEG (
Change in GDP,
2.39809e+11)
Units: USD

(133) "GDP @ 2030"=SAMPLE IF TRUE(
Time=2030, GDP,GDP)
Units: USD

(134) GDP Growth Rate=
0.0258
Units: Dmnl/Year

(135) Generator:
Local Natural Gas Fired,Local Solar PV,Local Waste to Energy,Overseas Geothermal,Overseas Hydro,Overseas Onshore Wind,Overseas Solar PV, Overseas Nuclear

(136) GHG Curtailment Rate for Other Sources=
0
Units: Dmnl

(137) GHG Emissions from Other Sources[Other GHG Sources]= INTEG (
Increase in GHG from Other Sources[Other GHG Sources],
"Initial (2010) GHG from Other Sources"[Other GHG Sources])
Units: CO2*g/Year

(138) GHG Emissions from Transport=
"Non-Electric Vehicles"*Average Vehicle Pollution Rate
Units: CO2*g/Year

(139) GHG in GgCO2=
Current GHG Emissions/1e+09
Units: CO2*g/Year

(140) GHG Target Mechanism=
0
Units: Dmnl

(141) Grid Losses=
0.1
Units: Dmnl

(142) "Gross Jobs Created (GJC)"=
SMOOTH(SUM(Electricity Generated by Type[Energy Source Type!]*Job Creation Reference Data[Energy Source Type!])*MW to GW,3*Year Unit)
Units: Job/Year

(143) Heat Rate[Local Natural Gas Fired]=

6.35e+06
Heat Rate[Local Waste to Energy]=
1.35e+07
Heat Rate[Local Solar PV]=
0
Heat Rate[Overseas Onshore Wind]=
0
Heat Rate[Overseas Hydro]=
0
Heat Rate[Overseas Geothermal]=
0
Heat Rate[Overseas Solar PV]=
0
Heat Rate[Overseas Nuclear]=
1.0461e+07
Units: Btu/(MW*h)

(144) Hours per Year=
8760
Units: h/Year

(145) Household Demand Savings Rate=
IF THEN ELSE(Level of Energy Efficiency Intiatives = 0, Household Demand Savings Rate BAU(Time/Year Unit),IF THEN ELSE(Level of Energy Efficiency Intiatives =0.5,Household Demand Savings Rate Conservative(Time/Year Unit),Household Demand Savings Rate Optimistic(Time/Year Unit)))
Units: Dmnl

(146) Household Demand Savings Rate BAU(
[(2010,0)-(2100,0.03)],(2010,0),(2030,0.005),(2050,0.01),(2100,0.0225))
Units: Dmnl

(147) Household Demand Savings Rate Conservative(
[(2010,0)-(2100,0.05)],(2010,0),(2030,0.01),(2050,0.02),(2100,0.045))
Units: Dmnl

(148) Household Demand Savings Rate Optimistic(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.025),(2050,0.05),(2100,0.1125))
Units: Dmnl

(149) Increase in GHG from Other Sources[Industry GHG]=
GHG Emissions from Other Sources[Industry GHG]*GDP Growth Rate*(1-Effected GHG Curtailment Rate for Other Sources)
Increase in GHG from Other Sources[Commercial GHG]=

GHG Emissions from Other Sources[Commercial GHG]*GDP Growth Rate*(1-Effected GHG Curtailment Rate for Other Sources)
Increase in GHG from Other Sources[Residential GHG]=
GHG Emissions from Other Sources[Residential GHG]*GDP Growth Rate*(1-Effected GHG Curtailment Rate for Other Sources)
Units: CO2*g/(Year*Year)

(150) "Indicated Order Capacity (Local)"[Local Generator]=
("Investment Based Expected Order Rate (Local)"[Local Generator]+Max(0,"Desired Capacity Acquisition Rate (Local)"[Local Generator]+"Adjustment for Waiting Capacities (Local)"
[Local Generator]))
Units: MW/Year

(151) "Indicated Order Capacity (Overseas)"[Overseas Generator]=
"Desired Capacity Acquisition Rate (Overseas)"[Overseas Generator]+"Adjustment for Waiting Capacities (Overseas)"[Overseas Generator]
Units: MW/Year

(152) Indicated Price=
Max(Electricity Price, VMIN(Expected Marginal Costs[Generator!]))
Units: USD/(MW*h)

(153) Industry Demand Savings Rate=
IF THEN ELSE(Level of Energy Efficiency Intiatives = 0, Industry Demand Savings Rate BAU(Time/Year Unit),IF THEN ELSE(Level of Energy Efficiency Intiatives
=0.5,Industry Demand Savings Rate Conservative(Time/Year Unit),Industry Demand Savings Rate Optimistic(Time/Year Unit)))
Units: Dmnl

(154) Industry Demand Savings Rate BAU(
[(2010,0)-(2100,0.08)],(2010,0),(2030,0.01),(2050,0.03),(2100,0.08))
Units: Dmnl

(155) Industry Demand Savings Rate Conservative(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.015),(2050,0.05),(2100,0.1375))
Units: Dmnl

(156) Industry Demand Savings Rate Optimistic(
[(2010,0)-(2100,0.2)],(2010,0),(2030,0.025),(2050,0.07),(2100,0.1875))
Units: Dmnl

(157) Inflation Rate=
0.016

Units: Dmnl

(158) "Initial (2010) GHG from Other Sources"[Industry GHG]=
18614.3*1e+09
"Initial (2010) GHG from Other Sources"[Commercial GHG]=
455.1*1e+09
"Initial (2010) GHG from Other Sources"[Residential GHG]=
209.1*1e+09
Units: CO2*g/Year

(159) "Initial (2010) Number of Vehicles"=
945829
Units: Vehicle

(160) Initial Population=
5.043e+06
Units: People

(161) Initial Solar Proportion Target=
0.005
Units: Dmnl

(162) INITIAL TIME = 2010
Units: Year

(163) Input Demand=
SUM(Demand After Changes[Demand Type!])
Units: kW*h/Year

(164) Input Demand in MWh[Demand for Market Clearing]=
Input Demand*kW to MW
Units: MW*h/Year

(165) "Installed Capacity (Local)"[Local Natural Gas Fired]= INTEG (
"Construction Completion (Local)"[Local Natural Gas Fired]-"Capacity Depreciation Rate (Local)"[Local Natural Gas Fired],
9671.6)
"Installed Capacity (Local)"[Local Waste to Energy]= INTEG (
"Construction Completion (Local)"[Local Waste to Energy]-"Capacity Depreciation Rate (Local)"[Local Waste to Energy],
256.8)
"Installed Capacity (Local)"[Local Solar PV]= INTEG (
"Construction Completion (Local)"[Local Solar PV]-"Capacity Depreciation Rate (Local)"[Local Solar PV],

2.9)
Units: MW

(166) "Installed Capacity (Overseas)"[Overseas Onshore Wind]= INTEG (
"Construction Completion (Overseas)"[Overseas Onshore Wind]-"Capacity Depreciation Rate (Overseas)"[Overseas Onshore Wind],
0)
"Installed Capacity (Overseas)"[Overseas Geothermal]= INTEG (
"Construction Completion (Overseas)"[Overseas Geothermal]-"Capacity Depreciation Rate (Overseas)"[Overseas Geothermal],
0)
"Installed Capacity (Overseas)"[Overseas Hydro]= INTEG (
"Construction Completion (Overseas)"[Overseas Hydro]-"Capacity Depreciation Rate (Overseas)"[Overseas Hydro],
0)
"Installed Capacity (Overseas)"[Overseas Solar PV]= INTEG (
"Construction Completion (Overseas)"[Overseas Solar PV]-"Capacity Depreciation Rate (Overseas)"[Overseas Solar PV],
0)
"Installed Capacity (Overseas)"[Overseas Nuclear]= INTEG (
"Construction Completion (Overseas)"[Overseas Nuclear]-"Capacity Depreciation Rate (Overseas)"[Overseas Nuclear],
0)
Units: MW

(167) Installed Capacity by Type[Natural Gas Fired]=
"Installed Capacity (Local)"[Local Natural Gas Fired]
Installed Capacity by Type[Waste to Energy]=
"Installed Capacity (Local)"[Local Waste to Energy]
Installed Capacity by Type[Solar PV]=
"Installed Capacity (Local)"[Local Solar PV]+"Installed Capacity (Overseas)"[Overseas Solar PV]
Installed Capacity by Type[Hydro]=
"Installed Capacity (Overseas)"[Overseas Hydro]
Installed Capacity by Type[Onshore Wind]=
"Installed Capacity (Overseas)"[Overseas Onshore Wind]
Installed Capacity by Type[Geothermal]=
"Installed Capacity (Overseas)"[Overseas Geothermal]
Installed Capacity by Type[Nuclear]=
"Installed Capacity (Overseas)"[Overseas Nuclear]
Units: MW

(168) Investment Attractiveness of Sources[Generator]=
Effect of Generation Profit[Generator]*Remaining Resource Ratio[Generator]

Units: Dmnl

(169) "Investment Based Expected Order Rate (Local)"[Local Generator]=
"Change in Investment (Local)"[Local Generator]/("Investment Cost (Local)"[Local Generator]*Year Unit)
Units: MW/Year

(170) "Investment Cost (Local)"[Local Generator]=
Time Adjusted Overnight Investment Cost[Local Generator]
Units: USD/(MW*Year)

(171) "Investment Cost (Overseas)"[Overseas Generator]=
Time Adjusted Overnight Investment Cost[Overseas Generator]
Units: USD/(MW*Year)

(172) Investment in Each Generator[Generator]=
Max(0, Investment Resource Allocation[Generator])
Units: USD/Year

(173) Investment Priority[Generator]=
IF THEN ELSE(Time > 2020, 10*Investment Attractiveness of Sources[Generator]*"Policy: Boost Infrastructure Investment (BII)"[Generator], 10*Investment Attractiveness of Sources
[Generator])
Units: Dmnl

(174) Investment Resource Allocation[Generator]=
ALLOCATE BY PRIORITY(Desired Capacity's Technology Cost[Generator], Investment Priority[Generator] , ELMCOUNT(Generator) , 1 , Annual Investment in Electricity Infrastructure
)
Units: USD/Year

(175) "Investment Tied Order Rate (Overseas)"[Overseas Generator]=
"Change in Investment (Overseas)"[Overseas Generator]/("Investment Cost (Overseas)"[Overseas Generator]*Year Unit
)
Units: MW/Year

(176) Job Creation Reference Data[Natural Gas Fired]=
0.12
Job Creation Reference Data[Waste to Energy]=
0.21
Job Creation Reference Data[Solar PV]=

0.87
Job Creation Reference Data[Onshore Wind]=
0.17
Job Creation Reference Data[Geothermal]=
0.25
Job Creation Reference Data[Hydro]=
0.27
Job Creation Reference Data[Nuclear]=
0.14
Units: Job/(GW*h)

(177) kg to g=
1/1000
Units: kg/g

(178) kW to MW=
0.001
Units: MW/kW

(179) LCOE[Generator]=
(Depreciated Investment Cost DIC[Generator]+"Time Adjusted Fixed O&M Cost"[Generator])/(Hours per Year*Capacity Factor[
Generator])+"Time Adjusted Variable O&M Cost"[Generator]+Fuel Cost in USD per MWh[Generator]
Units: USD/(MW*h)

(180) Level of Energy Efficiency Intiatives=
1
Units: Dmnl

(181) Lifecycle Emission Intensity by Generator[Local Natural Gas Fired]=
Lifecycle Emission Intensity of Resources[Natural Gas Fired]
Lifecycle Emission Intensity by Generator[Local Waste to Energy]=
Lifecycle Emission Intensity of Resources[Waste to Energy]
Lifecycle Emission Intensity by Generator[Local Solar PV]=
Lifecycle Emission Intensity of Resources[Solar PV]
Lifecycle Emission Intensity by Generator[Overseas Onshore Wind]=
Lifecycle Emission Intensity of Resources[Onshore Wind]
Lifecycle Emission Intensity by Generator[Overseas Geothermal]=
Lifecycle Emission Intensity of Resources[Geothermal]
Lifecycle Emission Intensity by Generator[Overseas Hydro]=
Lifecycle Emission Intensity of Resources[Hydro]
Lifecycle Emission Intensity by Generator[Overseas Solar PV]=
Lifecycle Emission Intensity of Resources[Solar PV]

Lifecycle Emission Intensity by Generator[Overseas Nuclear]=
Lifecycle Emission Intensity of Resources[Nuclear]
Units: CO2*g/(h*kW)

(182) Lifecycle Emission Intensity of Resources[Natural Gas Fired]=
490
Lifecycle Emission Intensity of Resources[Waste to Energy]=
1340
Lifecycle Emission Intensity of Resources[Solar PV]=
48
Lifecycle Emission Intensity of Resources[Onshore Wind]=
11
Lifecycle Emission Intensity of Resources[Geothermal]=
38
Lifecycle Emission Intensity of Resources[Hydro]=
24
Lifecycle Emission Intensity of Resources[Nuclear]=
12
Units: (g*CO2)/(kW*h)

(183) "Light-Duty Electric Vehicles"= INTEG (
New EV Each Year,
1)
Units: Vehicle

(184) Local Generator:
Local Natural Gas Fired,Local Solar PV,Local Waste to Energy

(185) Long Term Generator Price Forecast=
Future Market Electricity Price*(1-Weight of LCOE on Profit Forecast)+VMIN(LCOE[Generator!])*Weight of LCOE on Profit Forecast
Units: USD/(MW*h)

(186) Market Clearing Mechanism=
FIND MARKET PRICE(Input Demand in MWh[Total Demand] , Demand Curve Function[Total Demand,ptype] , Available Electricity[Local Natural Gas Fired
] , Supply Curve Function[Local Natural Gas Fired,ptype])
Units: Dmnl

(187) Maximum Excess Supply Proportion=
2
Units: Dmnl

(188) MBtu to Btu=

1/1e+06
Units: MBtu/Btu

(189) MW to GW=
0.001
Units: GW/MW

(190) "Net Project Approval Time (Local)"=
IF THEN ELSE(Time > 2020, Max(0.5,"Project Approval Time (Local)"*(1-"Policy: Renewables Approvals Rate Impact (RARI)")),"Project Approval Time (Local)"
)
Units: Year

(191) "Net Project Approval Time (Overseas)"=
Max(1.5,"Project Approval Time (Overseas)"*(1-"Policy: Renewables Approvals Rate Impact (RARI)"))
Units: Year

(192) New EV Each Year=
IF THEN ELSE(Level of Energy Efficiency Intiatives = 0, EV Annual Growth Rate BAU(Time/Year Unit)
,IF THEN ELSE(Level of Energy Efficiency Intiatives
=0.5,EV Annual Growth Rate Conservative(Time/Year Unit),EV Annual Growth Rate Optimistic
(Time/Year Unit)))*Total Vehicles*"Proportion of Light-Duty Vehicles"
Units: Vehicle/Year

(193) "Non-Electric Vehicles"=
Total Vehicles-"Light-Duty Electric Vehicles"
Units: Vehicle

(194) Normalized EDI=
Floating Target for EDI/Reference Energy Diversity Index
Units: Dmnl

(195) Normalized GHG levels=
Desired Target for GHG Emissions/Reference Target GHG Emissions
Units: Dmnl

(196) Normalized GJC=
Floating Target for GJC/Reference GJC
Units: Dmnl

(197) "Order Rate (Local)"[Local Generator]=

IF THEN ELSE(Remaining Resource Ratio[Local Generator]=0, 0, ("Indicated Order Capacity (Local)"[Local Generator]))
Units: MW/Year

(198) "Order Rate (Overseas)"[Overseas Generator]=
IF THEN ELSE(Remaining Resource Ratio[Overseas Generator] = 0, 0, "Expected Order Capacity (Overseas)"[Overseas Generator
])
Units: MW/Year

(199) Other GHG Sources:
Industry GHG, Commercial GHG, Residential GHG

(200) Overnight Investment Cost[Local Natural Gas Fired]=
1.1e+06
Overnight Investment Cost[Local Waste to Energy]=
5.6e+06
Overnight Investment Cost[Local Solar PV]=
3.2e+06
Overnight Investment Cost[Overseas Onshore Wind]=
2.3e+06
Overnight Investment Cost[Overseas Hydro]=
2.1e+06
Overnight Investment Cost[Overseas Geothermal]=
5.2e+06
Overnight Investment Cost[Overseas Solar PV]=
3.4e+06
Overnight Investment Cost[Overseas Nuclear]=
4.5e+06
Units: USD/(MW*Year)

(201) Overseas Generator:
Overseas Geothermal,Overseas Hydro,Overseas Onshore Wind,Overseas Solar PV,Overseas Nuclear

(202) Peak Demand in MW=
Input Demand/Hours per Year*(1+Peak Demand to Average Demand Ratio)*kW to MW
Units: MW

(203) Peak Demand to Average Demand Ratio=
0.32
Units: Dmnl

(204) Perception Delay for Capacity Adjustment=
1
Units: Year

(205) Pink Noise Maker=
RANDOM PINK NOISE(1, 0.1, 1, 1234)
Units: Dmnl

(206) "Policy: Allow Nuclear Only"=
0
Units: Dmnl

(207) "Policy: Boost Infrastructure Investment (BII)"[Generator]= INTEG (
Change in BII[Generator],
1)
Units: Dmnl

(208) "Policy: Renewables Approvals Rate Impact (RARI)"= INTEG (
Change in RARI,
0.05)
Units: Dmnl

(209) Population= INTEG (
Change in Population,
Initial Population)
Units: People

(210) Population Based Electricity Demand=
Population*Electricity Demand Per Capita
Units: kW*h/Year

(211) Population Growth Rate=
0.006462
Units: Dmnl/Year

(212) pprofile:
ptype, ppriority, pwidth, pextra

(213) Profit Consideration Horizon=
4
Units: Year

(214) "Project Approval Time (Local)"=
1

Units: Year

(215) "Project Approval Time (Overseas)"=
3
Units: Year

(216) Proportion of Capacity Allowed Overseas=
RAMP(Final Proportion of Capacity Allowed Overseas/Duration to Achieve Overseas Capacity , Year When Overseas Generators are Allowed , Year When Overseas Generators are Allowed
+Duration to Achieve Overseas Capacity)
Units: Dmnl

(217) Proportion of GDP for Electricity Infrastructure=
IF THEN ELSE(Time < 2020, 0.005, Future Proportion of GDP for Infrastructure)
Units: Dmnl/Year

(218) "Proportion of Light-Duty Vehicles"=
0.65
Units: Dmnl

(219) "Proportion of Non-Baseload Installed Capacities"=
("Installed Capacity (Local)"[Local Solar PV]+"Installed Capacity (Overseas)"[Overseas Solar PV]+"Installed Capacity (Overseas)"[Overseas Onshore Wind
])/Total Installed Capacities
Units: Dmnl

(220) Proportion Per Generating Type[Energy Source Type]=
(Installed Capacity by Type[Energy Source Type]/Total Installed Capacities)*100
Units: Dmnl

(221) Public Transport Demand Growth BAU(
[(2010,0)-
(2100,2e+09)],(2010,0),(2030,1.74e+09),(2050,1.74e+09),(2100,1.74e+09))
Units: h*kW/Year

(222) Public Transport Demand Growth Conservative(
[(2010,0)-
(2100,2e+09)],(2010,0),(2030,1.7415e+09),(2050,1.743e+09),(2100,1.74675e+09))
Units: h*kW/Year

(223) Public Transport Demand Growth Optimistic(
[(2010,0)-
(2100,2e+09)],(2010,0),(2030,1.745e+09),(2050,1.76e+09),(2100,1.76e+09))

Units: kW*h/Year

(224) "Rate of Inequality Aversion (RIA)"=
2.5
Units: Dmnl

(225) "Rate of Time Preference (RTP)"=
0
Units: 1/Year

(226) Ref Year for EIA AEO Forecast=
2018
Units: Year

(227) Ref Year for Inflation Normalization=
2010
Units: Year

(228) Reference Clearing Price=
SMOOTH(Electricity Price , Electricity Price Lookback Period)
Units: USD/(MW*h)

(229) Reference CSN=
SMOOTH("Cumulative Social Needs (CSN)" , 5*Year Unit)
Units: Dmnl

(230) Reference Energy Diversity Index=
5000
Units: Dmnl

(231) "Reference Fixed O&M Cost"[Local Natural Gas Fired]=
7000
"Reference Fixed O&M Cost"[Local Waste to Energy]=
101000
"Reference Fixed O&M Cost"[Local Solar PV]=
20000
"Reference Fixed O&M Cost"[Overseas Onshore Wind]=
0
"Reference Fixed O&M Cost"[Overseas Hydro]=
35000
"Reference Fixed O&M Cost"[Overseas Geothermal]=
0
"Reference Fixed O&M Cost"[Overseas Solar PV]=
20000

"Reference Fixed O&M Cost"[Overseas Nuclear]=
0
Units: USD/(MW*Year)

(232) Reference GHG in GgCO2=
Reference Target GHG Emissions/1e+09
Units: CO2*g/Year

(233) Reference GJC=
Total Supply*(Job Creation Reference Data[Solar PV]*"Desired Non-Baseload Proportion" + (1-"Desired Non-Baseload Proportion")*Job Creation Reference Data [Geothermal])*MW to GW
Units: Job/Year

(234) Reference Target GHG Emissions=
IF THEN ELSE(GHG Target Mechanism = 0, USD Adjusted Singapore UN NDC Target*GDP/Year Unit, IF THEN ELSE(Time >=2030, Fixed Total Emission Target, USD Adjusted Singapore UN NDC Target *GDP/Year Unit))
Units: CO2*g/Year

(235) "Reference Variable O&M Cost"[Local Natural Gas Fired]=
3.2
"Reference Variable O&M Cost"[Local Waste to Energy]=
0
"Reference Variable O&M Cost"[Local Solar PV]=
0
"Reference Variable O&M Cost"[Overseas Onshore Wind]=
14
"Reference Variable O&M Cost"[Overseas Hydro]=
0
"Reference Variable O&M Cost"[Overseas Geothermal]=
11
"Reference Variable O&M Cost"[Overseas Solar PV]=
0
"Reference Variable O&M Cost"[Overseas Nuclear]=
13
Units: USD/(MW*h)

(236) Relative Incentive to Generate[Generator]=
ZIDZ(Electricity Price,IF THEN ELSE(Expected Marginal Costs[Generator]<0,0,Expected Marginal Costs[Generator]))
Units: Dmnl

(237) Relative Social Need for DSB=
Desired State for Demand Supply Balance/Current Capacity to Peak Demand Ratio
Units: Dmnl

(238) Relative Social Need for Energy Diversity=
ZIDZ("Current Energy Diversity Index (EDI)",Adjusted Floating Target for EDI)
Units: Dmnl

(239) Relative Social Need for Energy Job Creation=
ZIDZ(Adjusted Target for GJC,"Gross Jobs Created (GJC)")
Units: Dmnl

(240) Relative Social Need for GHG Emissions=
ZIDZ(Current GHG Emissions,Adjusted Desired GHG Emissions)
Units: Dmnl

(241) Remaining Resource Ratio[Local Generator]=
Max(0,SMOOTH(ZIDZ((Resource Limits[Local Generator]-"Installed Capacity (Local)"[Local Generator]-"Capacities Waiting for Build Completion (Local)"
[Local Generator]),Resource Limits[Local Generator]), Year Unit))
Remaining Resource Ratio[Overseas Generator]=
Max(0,SMOOTH(ZIDZ((Resource Limits[Overseas Generator]-"Installed Capacity (Overseas)"[Overseas Generator]-"Capacities Waiting for Build Completion (Overseas)"
[Overseas Generator]),Resource Limits[Overseas Generator]),Year Unit))
Units: Dmnl

(242) Reserve Capacity Requirements=
1.3
Units: Dmnl

(243) Resource Limits[Local Natural Gas Fired]=
16000
Resource Limits[Local Waste to Energy]=
310
Resource Limits[Local Solar PV]=
6000
Resource Limits[Overseas Onshore Wind]=
360
Resource Limits[Overseas Geothermal]=
1300
Resource Limits[Overseas Hydro]=
4500
Resource Limits[Overseas Solar PV]=
14400

Resource Limits[Overseas Nuclear]=
5000
Units: MW

(244) SAVEPER =
TIME STEP
Units: Year

(245) "Sensitivity of Price to Demand-Supply Balance"=
MIN(0, -(1-"Proportion of Non-Baseload Installed Capacities"))
Units: Dmnl

(246) Sensitivity of Price to Marginal Cost=
1-"Proportion of Non-Baseload Installed Capacities"
Units: Dmnl

(247) Singapore UN NDC GHG Target=
113
Units: CO2*g/SGD

(248) Supply Curve Function[Generator,ptype]=
Supply Curve pType
Supply Curve Function[Generator, ppriority]=
Supply Curve Price[Generator]
Supply Curve Function[Generator,pwidth]=
Supply Curve pWidth
Supply Curve Function[Generator,pextra]=
Supply Curve pExtra
Units: Dmnl

(249) Supply Curve pExtra=
1
Units: Dmnl

(250) Supply Curve Price[Generator]=
Adjusted Price for Each Technology[Generator]/Unit Price
Units: Dmnl

(251) Supply Curve pType=
1
Units: Dmnl

(252) Supply Curve pWidth=
1

Units: Dmnl

(253) Supply Sufficiency=
Total Supply/SUM(Input Demand in MWh[Demand for Market Clearing!])
Units: Dmnl

(254) Table for Capacity Utilisation[Local Natural Gas Fired](
[(0,0)-
(40,1)],(0,0),(0.1,0),(0.2,0),(0.3,0),(0.4,0),(0.5,0.0188),(0.6,0.117),(0.7,0.315),(0.822811,0.881517),(0.9,0.977),(1,1),(1.1,1),(2,1),(5,1),
(15,1),(40,1))
Table for Capacity Utilisation[Local Waste to Energy](
[(0,0)-(40,1)],(0,1),(40,1))
Table for Capacity Utilisation[Local Solar PV](
[(0,0)-(40,1)],(0,1),(2,1),(5,1),(40,1))
Table for Capacity Utilisation[Overseas Onshore Wind](
[(0,0)-(40,1)],(0,1),(2,1),(5,1),(40,1))
Table for Capacity Utilisation[Overseas Geothermal](
[(0,0)-
(40,1)],(0,0),(0.4,0.00952),(0.4,0),(0.5,0.0444),(0.6,0.127),(0.7,0.311),(0.8,0.454),(0.9,0.619),(1,0.902),(1.1,0.987),(1.2,1),(2,1),(40,1))
Table for Capacity Utilisation[Overseas Hydro](
[(0,0)-
(40,1)],(0,0),(0.1,0),(0.6,0),(0.7,0),(0.8,0.103),(0.9,0.493),(1,0.911),(1.1,0.981),(1.2,1),(1.3,1),(1.4,1),(1.5,1),(1.6,1),(1.7,1),(2,1),(5,
1),(40,1))
Table for Capacity Utilisation[Overseas Solar PV](
[(0,0)-(40,1)],(0,1),(2,1),(5,1),(40,1))
Table for Capacity Utilisation[Overseas Nuclear](
[(0,0.8)-
(40,1)],(0,0.85),(0.1,0.887),(0.2,0.915),(0.3,0.944),(0.4,0.967),(0.5,0.991),(0.6,1),(40,1))
Units: Dmnl

(255) Table for Normalized EDI on Desired(
[(0,0)-(5,1)],(0,1),(1,1),(2,0.1),(5,0.1))
Units: Dmnl

(256) Table for Normalized GHG on Desired(
[(0,0)-(5,1)],(0,1),(1,1),(2,0.1),(5,0.1))
Units: Dmnl

(257) Table for Normalized GJC(
[(0,0)-(2,2)],(0,2),(1,1),(2,1))
Units: Dmnl

(258) Table for Social Pressure on BII[Local Natural Gas Fired](
[(0,0)-(10,1)],(0,0),(1,1),(10,1))
Table for Social Pressure on BII[Local Waste to Energy](
[(0,0)-(10,1)],(0,0),(1,1),(10,1))
Table for Social Pressure on BII[Local Solar PV](
[(0,0)-(10,2)],(0,0),(1,1),(2,2),(10,2))
Table for Social Pressure on BII[Overseas Onshore Wind](
[(0,0)-(10,2)],(0,0),(1,1),(2,1.5),(10,1.5))
Table for Social Pressure on BII[Overseas Geothermal](
[(0,0)-(10,2)],(0,0),(1,1),(2,1.5),(10,1.5))
Table for Social Pressure on BII[Overseas Hydro](
[(0,0)-(10,2)],(0,0),(1,1),(2,1.5),(10,1.5))
Table for Social Pressure on BII[Overseas Solar PV](
[(0,0)-(10,2)],(0,0),(1,1),(2,1.5),(10,1.5))
Table for Social Pressure on BII[Overseas Nuclear](
[(0,0)-(10,2)],(0,0),(1,1),(2,1.5),(10,1.5))
Units: Dmnl

(259) Table for Social Pressure on CTR(
[(0,0)-(5,2.5)],(0,1),(1,1),(2,2),(5,2))
Units: Dmnl

(260) Table for Social Pressure on RARI(
[(0,0)-(5,2.5)],(0,1),(1,1),(2,2),(5,2))
Units: Dmnl

(261) Target GHG Adjustment Time=
5
Units: Year

(262) "Technical Availability (Local)"[Local Generator]=
("Installed Capacity (Local)"[Local Generator]*Capacity Factor[Local Generator])*(1-Grid Losses)*Hours per Year*Capacity Utilisation
[Local Generator]
Units: MW*h/Year

(263) "Technical Availability (Overseas)"[Overseas Generator]=
("Installed Capacity (Overseas)"[Overseas Generator]*Capacity Factor[Overseas Generator])*(1-Grid Losses)*Hours per Year
*Capacity Utilisation[Overseas Generator]
Units: MW*h/Year

(264) "Time Adjusted Fixed O&M Cost"[Generator]=

"Reference Fixed O&M Cost"[Generator]*Yearly Inflation Adjustment Rate
Units: USD/(MW*Year)

(265) Time Adjusted Overnight Investment Cost[Generator]=
Overnight Investment Cost[Generator]*Yearly Inflation Adjustment Rate
Units: USD/(MW*Year)

(266) "Time Adjusted Variable O&M Cost"[Generator]=
"Reference Variable O&M Cost"[Generator]*Yearly Inflation Adjustment Rate
Units: USD/(MW*h)

(267) TIME STEP = 0.0625
Units: Year

(268) Time to Adjust Expected Price=
0.25
Units: Year

(269) "Total Electricity Price Paid: GDP"=
Electricity Price*Input Demand*kW to MW*Year Unit/GDP*100
Units: Dmnl

(270) Total Generating Capacities=
SUM("Technical Availability (Local)"[Local Generator!]/Hours per Year)+SUM("Technical Availability (Overseas)"[Overseas Generator
!]/Hours per Year)
Units: MW

(271) Total Installed Capacities=
"Total Installed Capacities (Local)"+"Total Installed Capacities (Overseas)"
Units: MW

(272) "Total Installed Capacities (Local)"=
SUM("Installed Capacity (Local)"[Local Generator!])
Units: MW

(273) "Total Installed Capacities (Overseas)"=
SUM("Installed Capacity (Overseas)"[Overseas Generator!])
Units: MW

(274) "Total Spent Each Year (Local)"[Local Generator]=
Time Adjusted Overnight Investment Cost[Local Generator]*"Order Rate (Local)"[Local Generator]*Year Unit
Units: USD/Year

(275) "Total Spent Each Year (Overseas)"[Overseas Generator]=
Time Adjusted Overnight Investment Cost[Overseas Generator]*"Order Rate (Overseas)"[Overseas Generator]*Year Unit
Units: USD/Year

(276) Total Spent Per Year=
SUM("Total Spent Each Year (Local)"[Local Generator!])+SUM("Total Spent Each Year (Overseas)"[Overseas Generator!])
Units: USD/Year

(277) "Total Spent: GDP Ratio"=
Total Spent Per Year/GDP*Year Unit
Units: Dmnl

(278) Total Supply=
SUM(Electricity Generated by Type[Energy Source Type!])
Units: MW*h/Year

(279) Total Vehicles= INTEG (
Annual Increase in Vehicles,
"Initial (2010) Number of Vehicles")
Units: Vehicle

(280) Total Waiting and Installed Capacities=
"Total Waiting and Installed Capacities (Local)"+"Total Waiting and Installed Capacities (Overseas)"
Units: MW

(281) "Total Waiting and Installed Capacities (Local)"=
SUM("Capacities Waiting for Build Completion (Local)"[Local Generator!]+"Installed Capacity (Local)"[Local Generator!])
Units: MW

(282) "Total Waiting and Installed Capacities (Overseas)"=
SUM("Capacities Waiting for Build Completion (Overseas)"[Overseas Generator!]+"Installed Capacity (Overseas)"[Overseas Generator!])
Units: MW

(283) Transport Sector Electricity Demand Growth=
IF THEN ELSE(Level of Energy Efficiency Intiatives = 0, Public Transport Demand Growth BAU(Time/Year Unit),IF THEN ELSE(Level of Energy Efficiency Intiatives
=0.5,Public Transport Demand Growth Conservative(Time/Year Unit),Public Transport Demand Growth Optimistic

(Time/Year Unit)))+Average Demand Per EV*"Light-Duty Electric Vehicles"
Units: h*kW/Year

(284) Unit Price=
1
Units: USD/(MW*h)

(285) USD Adjusted Singapore UN NDC Target=
Singapore UN NDC GHG Target*USD to SGD
Units: CO2*g/USD

(286) USD to SGD=
1.364
Units: SGD/USD

(287) Weight Average Cost of Capital=
0.05
Units: Dmnl

(288) Weight of LCOE on Profit Forecast=
0.25
Units: Dmnl

(289) Year Unit=
1
Units: Year

(290) Year when GHG Target is met=
IF THEN ELSE(Current GHG Emissions-Reference Target GHG Emissions> 0,Current GHG Emissions-Reference Target GHG Emissions, 0)
Units: CO2*g/Year

(291) Year When Overseas Generators are Allowed=
2025
Units: Year

(292) Yearly Fuel Increase Adjustment Rate=
(1+EIA Fuel Forecast Growth Rate)^((Time-Ref Year for EIA AEO Forecast)/Year Unit)
Units: Dmnl

(293) Yearly Inflation Adjustment Rate=
(1+Inflation Rate)^((Time-Ref Year for Inflation Normalization)/Year Unit)
Units: Dmnl

Appendix II: Descriptive Tables for the Singapore Electricity Landscape Transformation Model

Variable names are tallied with Appendix 1 but Eq # may not be tallied with Appendix 1 as system variables and some subscript ranges changes the equation count when generated via VensimDSS.

Table II-1: Descriptions for Variables in [1] Demand-Supply Balance

Eq. #	Variable Name	Description
-16	Average Demand Per EV -	Estimated average electricity need of an electric vehicle in Singapore. Based on Nian 2015.
-18	Baseline Electricity Demand by Sectors -	Proportion of electricity expressed in kW*h/Year
-20	Building Demand Savings Rate -	Actual building demand savings rate to be used, dependent on which demand scenario is being considered.
-21	Building Demand Savings Rate BAU -	Demand savings from the building sector in BAU as estimated in Nian 2015.
-22	Building Demand Savings Rate Optimistic -	Demand savings from the building sector in Optimistic Scenario as estimated in Nian 2015.
-23	Building Demand Savings Rates Conservative -	Demand savings from the building sector in Conservative Scenario as estimated in Nian 2015
-42	Change in FGDSB -	Change in FGDSB that is based on the difference between the present demand supply balance and the floating target.
-43	Change in FGDSB Adjustment Time -	This is the estimated adjustment time for the floating target for demand-supply balance, which is based on the estimate from the Energy Market Authority which requests for 4 years of way ahead supply estimates information ahead for their planning purposes for the future.
-49	Change in Population -	Total population projection up till 2050 obtained from Lee and Ghee 2014. Population growth rate (births and deaths inclusive) estimated using CAGR formula. Three scenarios in the projection and used Mid CAGR for modelling. Low CAGR: 0.4843%; Mid CAGR: 0.6462%; High CAGR: 0.9307% https://lkyspp.nus.edu.sg/docs/default-source/ips/pos2050_web_final_3009141.pdf?sfvrsn=1cb99e0b_2.
-58	Current Capacity to Peak Demand Ratio -	Ratio between peak demand to total generating capacities that includes grid losses, capacity factors, and capacity utilisation.
-62	Demand After Changes -	This is the net demand after savings from the energy efficiency initiatives.

-68	Demand Sector Baseline Proportion -	Proportion of electricity demand categorised by sector and as defined by the NCCS of Singapore (Nian 2015). As Singapore is considered an advanced economy with stability in its economic structure, the proportion of electricity demand is expected to remain relatively constant over time (Nian 2015).
-79	Desired Minimum Total Capacity Required -	Desired Capacity developed based on the peak demand and reserve capacity requirements, adjusted for the weighted average of the capacity factors, considering that more capacity is required from low capacity systems.
-83	Desired State for Demand Supply Balance -	The desired state would be the the maximum between what is the internal target for demand supply and the mandated minimum excess supply for DSB.
-102	Electricity Demand Per Capita -	10 year average electricity consumption per capita data from 2004 to 2014 was estimate the electricity demand per capita of Singapore. Data obtained from: https://data.worldbank.org/indicator/EG.USE.ELEC.KH.PC?end=2014&locations=SG&start=2004
-121	Floating Goal for Demand Supply Balance (FGDSB) -	This is the target that is set for demand-supply balance based on the present gap between demand and supply. It is built largely based on the floating game mechanism described in section 13.2.10 of Sterman 2000. It is assumed that the initial value for FGDSBB is equal to the current peak demand: capacity ratio.
-145	Hours per Year -	Number of hours per year.
-146	Household Demand Savings Rate -	Actual household demand savings rate to be used, dependent on which demand scenario is being considered.
-147	Household Demand Savings Rate BAU -	Demand savings from the household sector for BAU as estimated in Nian 2015.
-148	Household Demand Savings Rate Conservative -	Demand savings from the household sector for Conservative Scenario as estimated in Nian 2015
-149	Household Demand Savings Rate Optimistic -	Demand savings from the household sector for Conservative Scenario as estimated in Nian 2015
-154	Industry Demand Savings Rate -	Actual industry demand savings rate to be used, dependent on which demand scenario is being considered.
-155	Industry Demand Savings Rate BAU -	Demand savings from the industry sector for BAU as estimated in Nian 2015.
-156	Industry Demand Savings Rate Conservative -	Demand savings from the industry sector for Conservative Scenario as estimated in Nian 2015

-157	Industry Demand Savings Rate Optimistic -	Demand savings from the industry sector for Optimistic Scenario as estimated in Nian 2015.
-161	Initial Population -	This refers to Singapore's total population in 2010, rounded to the nearest thousand. Total population data extracted from page 46 of Lee and Ghee 2014. https://lkyspp.nus.edu.sg/docs/default-source/ips/pos2050_web_final_3009141.pdf?sfvrsn=1cb99e0b_2.
-164	Input Demand -	This is the total demand in kWh.
-165	Input Demand in MWh -	Input demand is converted to a subscripted version and converted to a MWh/Year format.
-179	kW to MW -	Converts kW to MW.
-181	Level of Energy Efficiency Intiatives -	Signifies the relative level of energy effiency initiatives where: 0 = BAU condition; 0.5 = Conservative; 1 = Optimistic
-184	Light-Duty Electric Vehicles -	Total number of light-duty electric vehicle. Formulation setup according to description listed in Nian 2015.
-188	Maximum Excess Supply Proportion -	Supply is planned to be at most twice of peak demand forecast.
-203	Peak Demand in MW -	This is the short run expected Peak Demand forecast. This information is estimated to be used by generators for price setting in the near future.
-204	Peak Demand to Average Demand Ratio -	This is peak demand estimate as compared to average demand. Estimate required to determine future capacity requirements. Data is estimated from past information from the Energy Market Authority of Singapore where load centres' monthly maximum and averge demand are reported. https://www.ema.gov.sg/statistic.aspx?sta_sid=20140802AcuzD76syICf
-210	Population -	Total Population of Singapore. Data extracted from p46 of Yap and Ghee 2014. https://lkyspp.nus.edu.sg/docs/default-source/ips/pos2050_web_final_3009141.pdf?sfvrsn=1cb99e0b_2
-211	Population Based Electricity Demand -	Singapore is considered an advanced economy with no large change in electricity needs per capita. As such, a population growth electricity demand is used as suggested in Nian 2014.
-212	Population Growth Rate -	Population growth rate (births and deaths inclusive) estimated using CAGR formula and referencing the 2050 population growth values (p. 46, IPS). Three scenarios in the projection. Low CAGR: 0.4843%; Mid CAGR: 0.6462%; High CAGR: 0.9307% https://lkyspp.nus.edu.sg/docs/default-source/ips/pos2050_web_final_3009141.pdf?sfvrsn=1cb99e0b_2.

-222	Public Transport Demand Growth BAU -	Electricity demand growth from the public transport sector in the BAU scenario as estimated in Nian 2015.
-223	Public Transport Demand Growth Conservative -	Electricity demand growth from the public transport sector in the conservative scenario as estimated in Nian 2015.
-224	Public Transport Demand Growth Optimistic -	Electricity demand growth from the public transport sector in the conservative scenario as estimated in Nian 2015.
-239	Relative Social Need for DSB -	The current demand supply ratio is divided by the desired demand supply ratio to express the relative social need between. A number > 1 signifies that current demand/supply has a higher value than desired, implying insufficient capacity while a number < 1 signifies the current demand/supply has a lower than the desired state, implying excess current capacity.
-244	Reserve Capacity Requirements -	The Singapore Government has mandated for supply of at least 30% higher than peak annual demand. https://www.ema.gov.sg/cmsmedia/Singapore_Electricity_Market_Outlook_2018_Final_rev11Jan2019.pdf
-273	Total Generating Capacities -	Available capacity to produce electricity in MW, after factoring in capacity utilisation, seasonal factors and grid losses.
-274	Total Installed Capacities -	Total installed capacities available.
-286	Transport Sector Electricity Demand Growth -	Total additional electricity demand of the transport sector in Singapore.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.

Table II-2: Descriptions for Variables in [2] Pricing

Eq. #	Variable Name	Description
-4	Adjusted Price for Each Technology -	Adjusted price of each technology considering the effects of demand-supply and the effect of marginal cost.
-15	Available Electricity -	Combined variable to represent the various technologies available.
-26	Capacity Average Lifetime -	The average lifetime of technology for each source. Based on information from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf, https://www.ema.gov.sg/cmsmedia/Annex%202_Review%20of%20the%20Vesting%20Contract%20Technical%20Parameters_Final__.pdf
-29	Capacity Coverage -	Capacity Coverage refers to how much capacity is able to cover demand. Smoothed as it takes time for the information to be collected and reported. Howver, the time set is short as it is expected that all generators reported their plans early to the market regulator.
-32	Capacity Factor -	Refers to the ratio of maximal plant operating hours in a year. Generally high for baseload capabilities where it is expected to be operational for all times except for planned maintainance period. Low values for non-baseload technologies such as wind and solar. Average values from relevant reports regarding data from Singapore/ ASEAN are used when applicable. Gas Fired Plants: https://www.ema.gov.sg/cmsmedia/Annex%202_Review%20of%20the%20Vesting%20Contract%20Technical%20Parameters_Final__.pdf Local Waste to Energy: https://www.nrel.gov/docs/fy13osti/52829.pdf Local Solar PV, Wind, Overseas Hydro, Overseas Geothermal, Overseas Solar PV: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_Market_Southeast_Asia_2018.pdf. Overseas Nuclear assumed to be at same level of technical availability as baseload technologies like Natural Gas fired plants.
-35	Capital Recovery Factor -	The capital recovery factor is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). Formula based on equation listed in HOMER documentation. https://www.homerenergy.com/products/pro/docs/latest/capital_recovery_factor.html and also in

		https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf
-36	Carbon Tax Payable -	Amount of tax payable for using carbon emitting fuel sources.
-37	Carbon Tax Rate (CTR) -	Carbon tax was to be introduced in Singapore from Sep 2019 onwards at a rate of about 3.7USD per tonne of GHG emitted. https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/carbon-tax.
-52	Changes to Expected Price -	This is the rate by which the Energy Price is getting adjusted gradually using a Hill-Climbing Optimization approach.
-58	Current Capacity to Peak Demand Ratio -	Ratio between short term peak demand to total installed capacities.
-63	Demand Cruve pType -	Demand cruve type. 1: Rectangular.
-64	Demand Cruve pWidth -	Demand curve width. Same order of magnitude as Supply curve width.
-65	Demand Curve Function -	Demand Curve of input demand. Type use: Rectangular as electricity demand is assumed to be inelastic. ppriority set to be at values slightly higher than the priority curves of supply to allow all types to be accepted.
-66	Demand Curve pExtra -	Demand curve pextra. Not required for pType 1.
-70	Depreciated Investment Cost DIC -	DIC is the time-valued investment cost of each source, distributed over the lifetime of installed capacity.
-91	Effect of Marginal Cost on Price -	The effect of variable cost on price is built based on equation 20-50 in Sterman (2000). If sensitivity = 0, then there is no effect of marginal cost.
-94	Effect of Short-Term Demand-Supply Balance on Price -	The Demand-Supply Balance is converted to a ratio with a reference Demand-Supply Balance to normalize the value. It is then raised to the sensitivity factor. This formula is based on the Equation 20-47 in Sterman 2000, where the effect of Demand-Supply Ratio is likened to inventory coverage and what was used in Moallemi et. al. 2017.
-101	EIA Fuel Forecast Growth Rate -	EIA reported three scenarios in their Annual Energy Outlook 2019. High Oil and Gas Techn: 3.2% Reference case: 3.5%. Low Oil and Gas Tech: 3.8%.
-104	Electricity Price -	The energy price is expected to change according to the its past values and also dependent on the effects of the demand supply ratio and variable costs. Modelled based on Sterman 2000, Chapter 20.2.6 The Price-Setting Process, with a market clearing mechanism.
-111	Expected Carbon Tax -	Singapore would be implementing carbon tax starting from 2019 September. As such, a switch is added with the carbon

		tax payable calculations in order to determine to reflect this segment at the correct time.
-112	Expected Fuel Price -	This uses a simple trend extrapolation forecast of the future value of Fuel Price based on past 12 months time and in next 6 months time horizon.
-113	Expected Marginal Costs -	The expected variable cost that will thus form the minimum market price. Built on the unerstanding from Eqn. 20-32 and 20-33 in Sterman 2000
-115	Expected Price -	The energy price is expected to adjust according to the indicated price similar to the price setting process (Sterman, 2000, p. 537 and p. 813). Initial value obtained from database in https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/ses/2018/energy-prices/index.html, specifically the Average Monthly Uniform Singapore Energy Price for Jan 2010.
-117	Extra Value for Waste to Energy -	Estimated benefit from ash and heavy metal sale.
-125	Fuel at Last Database Time -	Last reported price for natural gas used in model.
-126	Fuel Cost in USD per MWh -	Fuel cost for natural gas incorporates data from fuel price forecast while fuel cost for other is basically the full carbon tax for the corresponding technology. Fuel Cost for waste to energy subtracted with expected benefit cost as listed in: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf
-127	Fuel Price (with Noise) -	Only natural gas and nuclear have fuel price. Other systems do not have fuel price. Fuel price is adjusted with yearly inflationary increase and pink noise with 20% value as standard deviation. Natural gas and nuclear yearly increased adjusted according to scenario projected by EIA, while waste to energy is projected based on inflation adjustment.
-128	Fuel Price Database -	Natural Gas Fuel Price is obtained from EIA: https://www.theice.com/marketdata/reports/77 Other fuel price estimate obtained from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Waste to Energy assumed at 0 as it does not "buy fuel" but rather provide a service and the fuel cost would be more dependent on operations.
-129	Fuel Price Forward Period -	Period in which the fuel price will be forecasted for.

-130	Fuel Price Lookback Period -	Period in which the fuel price will be used to lookback for forecasting forward.
-133	GDP -	GDP for Singapore. Initial Value was for 2010. Obtained from the World Bank database.
-144	Heat Rate -	Data obtained from https://www.eia.gov/outlooks/aeo/assumptions/pdf/electricity.pdf
-145	Hours per Year -	Number of hours per year.
-153	Indicated Price -	The indicated price for each technology is different. However, the market price should be based on the technology that is best able to provide energy at the lowest price.
-158	Inflation Rate -	Estimated at 1.6%. Median value of reported Core Inflation rate from 2000 to 2018. Data obtained from the Monetary Authority of Singapore and Department of Statistics, Singapore. https://www.tablebuilder.singstat.gov.sg/publicfacing/createDataTable.action?refId=12008.
-164	Input Demand -	This is the input demand to the trend estimation function that considers the total demand and is then discounted according to the expected savings from energy efficient measures implemented.
-165	Input Demand in MWh -	Input demand is converted to a subscripted version and converted to a MWh/Year format.
-178	kg to g -	Converts kg to g.
-179	kW to MW -	Converts kW to MW.
-180	LCOE -	Levelized Cost of Electricity, includes cost of carbon tax. Equation obtained from https://www.nrel.gov/analysis/tech-lcoe-documentation.html.
-182	Lifecycle Emission Intensity by Generator -	Mapping of Lifecycle Emissions Intensity between Source Type and Generator
-187	Market Clearing Mechanism -	Marketing clearing mechanism in which the lowest effected LCOE technology get used first and the final technology to clear demand sets the market clearing price.
-189	MBtu to Btu -	Converts Mbtu to Btu
-201	Overnight Investment Cost -	2010 Overnight Investment Cost for different type of generating plants. Obtained from the IPCC https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Used Table A.III.1 Cost and Performance Parameters of selected electricity supply technologies. Waste to Energy cost assumed as Biomass-CHP in this case. Overseas systems have all added a 200,000USD/MW cost for undersea cable cost. Estimated at an average of 150km of undersea

		cable. Cost estimated from SAPEI project, which is the world's deepest undersea cable, as reported in: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC97720/ld-na-27527-en-n.pdf
-206	Pink Noise Maker -	Pink noise maker with 10% standard deviation.
-220	Proportion of Non-Baseload Installed Capacities -	Proportion of installed capacities that is of non-baseload technologies (solar and wind in this thesis).
-228	Ref Year for EIA AEO Forecast -	Data in EIA AEO 2019 reported in 2018 values. This is used to reference the fuel price growth rate.
-229	Ref Year for Inflation Normalization -	Year that the overnight investment cost is used.
-233	Reference Fixed O&M Cost -	Represents Yearly expected operations and maintainence costs. 2010 Data obtained from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Used Table A.III.1.
-237	Reference Variable O&M Cost -	Data obtained from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Used Table A.III.1.
-244	Reserve Capacity Requirements -	The Singapore Government has mandated for supply of at least 30% higher than peak annual demand. https://www.ema.gov.sg/cmsmedia/Singapore_Electricity_Market_Outlook_2018_Final_rev11Jan2019.pdf
-247	Sensitivity of Price to Demand-Supply Balance -	Electricity generation is centrally planned with years in advance and with extra reserve power planned as well. It is expected that the effect of demand and supply would play a stronger effect when renewables play a larger role and the energy landscape is less dependent on the generally more stable fossil fuels generating plants.
-248	Sensitivity of Price to Marginal Cost -	Price sensitivity value are estimated based on proportion of renewables introduced into the market. Production cost reliability data is expected to be less reliable than demand and supply balance information in the market.
-251	Supply Curve Function -	Supply curve definition for each technology.
-252	Supply Curve pExtra -	supply curve extra subscript, set at 0 as it is not ignored in a rectangular ptype.
-253	Supply Curve Price -	pPriority depended on the effected price for each technology, where eventually it will form the order to be used, with the lowest LCOE item be used first.
-254	Supply Curve pType -	supply curve type of the different generating technologies. 1: Rectangular

-255	Supply Curve pWidth -	supply curve width of the different generating technologies. Set to a small amount to lower overlaps as we are expecting no variations of cost between each technology.
-267	Time Adjusted Fixed O&M Cost -	Time adjusted fixed O&M cost to reflect a realistic view relative to projection forward where we expect costs to rise according as time progresses.
-268	Time Adjusted Overnight Investment Cost -	This is the investment cost of technology for each source throughout the years in the value of money at that specific year. It follows the general formula of present value and future value, where overnight investment cost was reported 2010 USD dollars is adjusted according to the time periods forwards to the corresponding year Future Value: https://www.investopedia.com/terms/f/futurevalue.asp
-269	Time Adjusted Variable O&M Cost -	Time adjusted data to reflect a time-realistic variable cost for projection purposes.
-271	Time to Adjust Expected Price -	Estimated time to perceive current conditions. This is dependent on the expectations of conditions in the near-term market like demand-supply balance, fuel price fluctuations. Estimated from information that tariffs gets adjusted every 3 months.
-272	Total Electricity Price Paid: GDP -	Proportion of energy price compared to GDP. Used as a proxy to show how costly energy prices are getting relative to the GDP. Expressed as a number signifying the percentage from 0 to 100 and not as a fraction from 0 to 1.
-287	Unit Price -	Unit of price to normalize unit values to Dmnl, if required.
-290	Weight Average Cost of Capital -	Assumed at 5% as used in https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.
-295	Yearly Fuel Increase Adjustment Rate -	Final adjustment rate to be applied for fuel price estimate.
-296	Yearly Inflation Adjustment Rate -	Yearly inflation adjustment rate for future projections to adjust for inflation for better comparison against GDP growth.

Table II-3: Descriptions for Variables in [3] Infrastructure Investment

Eq. #	Variable Name	Description
-14	Annual Investment in Electricity Infrastructure -	Actual amount used per year for energy infrastructure investments.
-24	Capacities Waiting for Build Completion (Local) -	This is the stock of generation capacities which is under constuction and has not been operationalised yet. Initial Value modelled based on writeup explained in footnote 5, pg. 424 (Chapter 11.2.6) of Sterman 2000.
-25	Capacities Waiting for Build Completion (Overseas) -	This the stock of generation capacities from overseas locations which is under constuction and has not been operationalised yet. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities yet.
-46	Change in GDP -	Estimated annual growth in Singapore GDP in 2010's USD.
-56	Cumulative Expenditure -	Total investment for electricity infrastructure in 2010 dollars.
-72	Desired Capacity (Local) -	This is the desired local capacity each year which is based on the targets set forth for each generator type in each year.
-73	Desired Capacity (Overseas) -	This is the desired overseas capacity each year which is based on the targets set forth for each generator type in each year.
-76	Desired Capacity's Technology Cost -	Annual investment needs of the various technologies.
-90	Effect of Generation Profit -	Modelled similarly to Moallemi et. al. 2017 and p 89 of Steel 2008. Generator's profit ratio is considered here based on the smoothed inputs of long term revenue from energy price against the levelized cost of electricity.
-104	Electricity Price -	The energy price is expected to change according to the its past values and also dependent on the effects of the demand supply ratio and variable costs. Modelled based on Sterman 2000, Chapter 20.2.6 The Price-Setting Process, with a market clearing mechanism.
-105	Electricity Price Forward Period -	Long term forward looking period for energy price.
-106	Electricity Price Lookback Period -	Period in which past energy price will be used for long term forward forecasting.
-131	Future Market Electricity Price -	Modelled similarly to Vogstad 2004, eq. 7.6. Forecasted energy price with using 2 years of past data and 3 years of time horizon forward.
-132	Future Proportion of GDP for Infrastructure -	Proportion of GDP that Singapore should invests in energy infrastructure. The Global Infrastructure Outlook (https://outlook.gihub.org/countries/Singapore) reported an

		estimated of 0.3% to 0.7% from 2010 to 2017. Assumed at 0.5%.
-133	GDP -	GDP for Singapore. Initial Value was for 2010. Obtained from the World Bank database.
-135	GDP Growth Rate -	Estimated GDP growth rate based on data used from 2000 to 2018. Data calcualted from World Bank data in USD 2010 dollars. Data calcualted at 4.18%. Includes subtraction from inflation rate of 1.6%.
-166	Installed Capacity (Local) -	Modelled similar to Figure 17-7 of Sterman 2000. Equations are extracted from Chapter 11 and Chapter 17 of Sterman 2000. Initial Values for Installed Capacity obtained through the Singapore Energy Statistics 2018 published by the Energy Market Authority of Singapore. Data used was specifically the 2010 data.
-167	Installed Capacity (Overseas) -	This the stock of generation capacities from overseas locations which is generating power. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities for Singapore yet.
-169	Investment Attractiveness of Sources -	Combined multiplicative effect of resource availability with the effect of generator profit. In the event that there is no resource availble, then there is no investmen attractiveness for that resource.
-173	Investment in Each Generator -	Annual investment growth for each source. It is a function of two main components: The annual investment in whole electricity sector is allocated to different sources based on the investment attractiveness of each.
-174	Investment Priority -	Relative priority of different investment choice.
-175	Investment Resource Allocation -	Allocation of the GDP for infrastructure investment into the various technologies, based on the investment priority.
-180	LCOE -	Levelized Cost of Electricity, includes cost of carbon tax. Equation obtained from https://www.nrel.gov/analysis/tech-lcoe-documentation.html.
-186	Long Term Generator Price Forecast -	Long term profits is considered based on weighted average of future market energy price and the most competitive technology available for consideration. Built based on Moallemi et. al. 2017 and Vogstad 2004 eq. 9.1.
-208	Policy: Boost Infrastructure Investment (BII) -	Policy Target for boosting government investment priority in energy projects according to the social pressure.
-214	Profit Consideration Horizon -	Estimated time generator companies would use for consideration in determining past information before deciding if a large value investment is worth it.

-218	Proportion of GDP for Electricity Infrastructure -	Estimated spending between 2010 to 2017 was 0.5%, as reported in the Global Infrastructure Outlook (https://outlook.gihub.org/countries/Singapore) reported an estimated 0.5% of GDP from 2010 to 2017.
-230	Reference Clearing Price -	Smoothed value of past 1 year of energy price data.
-243	Remaining Resource Ratio -	Estimated remaining resources expressed as a ratio and smoothed as a first order delay.
-245	Resource Limits -	Renewable energy resource limit estimates obtained from Ahmed et. al. 2017. Local resources estimates for natural gas plants and waste-to-energy set at approximately double of current capacity levels, where the base data is obtained the Energy Market Authority of Singapore. Local resource for solar assumed to be at 5GW, according to estimates provided by the Sustainable Energy Association of Singapore White Paper on Renewable Energy (https://www.seas.org.sg/white-papers). Overseas limits (Solar, Geothermal, Wind, Hydro) assessed at 10% of Malaysia's and Sumatra's capability. Nuclear potential estimated at 5000GW, which is a possibility if built on barges, underground, or on overseas land as a shared resource.
-268	Time Adjusted Overnight Investment Cost -	This is the investment cost of technology for each source throughout the years in the value of money at that specific year. It follows the general formula of present value and future value, where overnight investment cost was reported 2010 USD dollars is adjusted according to
-279	Total Spent Per Year -	Total amount of spent each year for generating capabilities.
-280	Total Spent: GDP Ratio -	Actual ratio of amount spent per year to GDP.
-291	Weight of LCOE on Profit Forecast -	Used to determine the weight that LCOE is used in determine future profits as compared to the forecast of energy price. Reference from Vogstad 2004 eq. 9.1.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.
-296	Yearly Inflation Adjustment Rate -	Yearly inflation adjustment rate for future projections to adjust for inflation for better comparison against GDP growth.

Table II-4: Descriptions for Variables in [4] Electricity Capacity

Eq. #	Variable Name	Description
-1	Actual Proportion Overseas -	Proportion of electricity generated by overseas generation capacities.
-6	Adjustment for Installed Capacity (Local) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-15). Represents the annual net adjustment that will be applied to the indicated local order capacity.
-7	Adjustment for Installed Capacity (Overseas) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-15). Represents the net adjustment that will be applied to the indicated overseas order capacity.
-8	Adjustment for Waiting Capacities (Local) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-15). Represents the net annual adjustment that will be applied to the indicated local order capacity.
-9	Adjustment for Waiting Capacities (Overseas) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-15). Represents the net adjustment that will be applied to the indicated overseas order capacity.
-24	Capacities Waiting for Build Completion (Local) -	This is the stock of generation capacities which is under constuction and has not been operationalised yet. Initial Value modelled based on writeup explained in footnote 5, pg. 424 (Chapter 11.2.6) of Sterman 2000.
-25	Capacities Waiting for Build Completion (Overseas) -	This is the stock of generation capacities from overseas locations which is under constuction and has not been operationalised yet. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities yet.
-26	Capacity Average Lifetime -	The average lifetime of technology for each source. Based on information from: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf, https://www.ema.gov.sg/cmsmedia/Annex%202_Review%20of%20the%20Vesting%20Contract%20Technical%20Parameters_Final__.pdf
-27	Capacity Construction Time (Local) -	This is the expected construction lag that the Singapore government has estimated for all energy projects. This does not include the time taken for approval, which is expected seperately. Data is estimated from the public consultation paper that the Energy Market Authority of Singapore has published. https://www.ema.gov.sg/cmsmedia/Determination_Paper_%20Preparing_for_Future_Power_Generation_Investments_Final_29_Jul.pdf.

-28	Capacity Construction Time (Overseas) -	These figures are estimated at based on the construction time estimated in https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Solar PV was estimate to have no construction time in the IPCC data which is assumed to be not reflective of actual. As such, it is assumed that there it would be the same as the local case at 3 years.
-30	Capacity Depreciation Rate (Local) -	This is the outflow from the local installed capacity which is the average capacity that gets shutdown permanantly per year, based on the overall installed capacity and the average lifespan of the specific generator systems.
-31	Capacity Depreciation Rate (Overseas) -	This is the outflow from the overseas installed capacity which is the average capacity that gets shutdown permanantly per year, based on the overall installed capacity and the average lifespan of the specific generator systems.
-47	Change in Investment (Local) -	Subrange of change in investment, representing only the local capacities.
-48	Change in Investment (Overseas) -	Subrange of change in investment, representing only the overseas capacities.
-53	Construction Completion (Local) -	This is the rate that local generation capacities under construction become operationalised. It is equal to the stock of Local Capacities Waiting for Build Approval divided by the delay time that the construction of a project is completed.
-54	Construction Completion (Overseas) -	This is the rate that overseas generation capacities under construction become operationalised. It is equal to the stock of Overseas Capacities Waiting for Build Approval divided by the delay time that the construction of a project is completed.
-72	Desired Capacity (Local) -	This is the desired local capacity each year which is based on the targets set forth for each generator type in each year.
-73	Desired Capacity (Overseas) -	This is the desired overseas capacity each year which is based on the targets set forth for each generator type in each year.
-74	Desired Capacity Acquisition Rate (Local) -	Modelled according to equation p. 679, 17-4a in Sterman 2000. The logic is such that there is a non-negative capacity acquisition rate as there would always be power plants retiring every year while demand is slated to increase year-on-year, even in conditions where there are excess supply in the market.
-75	Desired Capacity Acquisition Rate (Overseas) -	Modelled according to equation p. 679, 17-4a in Sterman 2000. The logic is such that there is a non-negative capacity acquisition rate as there would always be power plants retiring every year while demand is slated to increase year-on-year,

		even in conditions where there are excess supply in the market.
-78	Desired Local Generating Proportions -	Total must sum to 1. Desired proportion of local generating capabilities. Baseload technology for local refers solely to Natural Gas fired.
-79	Desired Minimum Total Capacity Required -	Desired Capacity developed based on the peak demand and reserve capacity requirements, adjusted for the weighted average of the capacity factors, considering that more capacity is required from low capacity systems.
-80	Desired Non-Baseload Proportion -	Estimated target proportion of non-baseload class (solar and wind) that states like (Sri Lanka and Taiwan) set as benchmark for the energy diversity. Taiwan: https://www.power-technology.com/features/taiwan-pursuing-new-green-energy-revolution-east/ Sri Lanka: https://www.export.gov/article?id=Sri-Lanka-Energy
-81	Desired Overseas Generating Proportions -	Total must sum to 1. Desired proportion of overseas generating capabilities. Under the assumption that 80% of energy needs should be fulfilled by baseload capabilities. Order: Overseas Geothermal,Overseas Hydro,Overseas Onshore Wind,Overseas Solar PV,Overseas Nuclear
-85	Desired Waiting Capacities (Local) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-16). Represents the local waiting capacity that will be built.
-86	Desired Waiting Capacity (Overseas) -	Formulated analogously to adjustment for stock (Sterman 2000, equation 17-16). Represents the overseas waiting capacity that will be built.
-88	Duration to Achieve Overseas Capacity -	Expected duration it would take for the final proportion to be achieved. Currently set at 20 years as we expect the government to take careful planning and implementation considerations when it comes to allowing overseas generators to provide electricity in Singapore. The duration will thus determine the slope that it takes for the final proportion to be fully allowed.
-114	Expected Order Capacity (Overseas) -	The order rate for new overseas capacities. It is equal to Indicated Overseas Order Capacity and limited to have a non-negative value.
-116	Extra Baseload For Non-Baseload Rate -	As wind and solar are considered non baseload technology due to their intermittent performance and would be unable to fulfil peak capacity requirements when required, there is a need to build additional baseload capabilities to fulfil the demand. The factor would be applied to current amount of wind and solar contribution to determine additional baseload requirements.

-118	Final Proportion of Capacity Allowed Overseas -	Final target that the Singapore government will allow for overseas proportion.
-133	GDP -	GDP for Singapore. Initial Value was for 2010. Obtained from the World Bank database.
-151	Indicated Order Capacity (Local) -	As per Sterman 2000, equation 17-14. The Indicated Local Order Capacity is formulate as an anchiring and adjustment process. DLCAR is the anchor while the ALWC is the adjustment.
-152	Indicated Order Capacity (Overseas) -	As per Sterman 2000, equation 17-14. The Indicated Overseas Order Capacity is formulate as an anchiring and adjustment process. DOCAR is the anchor while the AOWC is the adjustment.
-162	Initial Solar Proportion Target -	Initial target proportion of solar to be part of Singapore's national grid.
-166	Installed Capacity (Local) -	Modelled similar to Figure 17-7 of Sterman 2000. Equations are extracted from. Initial Values for Installed Capacity obtained through the Singapore Energy Statistics 2018 published by the Energy Market Authority of Singapore. Data used was specifically the 2010 data.
-167	Installed Capacity (Overseas) -	This is the stock of generation capacities from overseas locations which is generating power. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities for Singapore yet.
-170	Investment Based Expected Order Rate (Local) -	Expected investment rate for each overseas capacity after allocation.
-171	Investment Cost (Local) -	Subrange of time-value cost of investment for local generators
-172	Investment Cost (Overseas) -	Subrange of time-value cost of investment for overseas generators.
-173	Investment in Each Generator -	Annual investment growth for each source. It is a function of two main components: The annual investment in whole electricity sector is allocated to different sources based on the investment attractiveness of each.
-176	Investment Tied Order Rate (Overseas) -	Expected investment rate for each overseas capacity after allocation.
-191	Net Project Approval Time (Local) -	Net waiting time that incorporates effect of policy pressure for approval rate. The concept is that with the right governmental pressure, policies should be able to get approval at a higher rate as compared to policies with no pressure. Expected that

		there is a minimum wait time of 6 months for basic project assessment.
-192	Net Project Approval Time (Overseas) -	Net waiting time that incorporates effect of policy pressure for approval rate. The concept is that with the right governmental pressure, policies should be able to get approval at a higher rate as compared to policies with no pressure. Expected that there is a at least minimum of 1 year for project assessment.
-198	Order Rate (Local) -	Limited to a physical constraint where orders can only occur when physical estimated capacity is available. Order rate to put through is based on the sum between what is expected from the stock management structure and the investment based input.
-199	Order Rate (Overseas) -	Limited to a physical constraint where orders can only occur when physical estimated capacity is available. Order rate to put through is based on the sum between what is expected from the stock management structure and the investment based input.
-205	Perception Delay for Capacity Adjustment -	Delay in perception of adjustment required for the capacity on the desired capacity.
-207	Policy: Allow Nuclear Only -	Switch factor for policy analysis to study a pure nuclear import option rather than diversified overseas electricity import. 0: Allow Nuclear with Other Overseas Sources. 1: Allow Nuclear Only.
-209	Policy: Renewables Approvals Rate Impact (RARI) -	Policy Target for boosting speed of renewable energy projects approval rate. It should be noted that this only affects the approval speed and not the construction speed as that is assumed to be relatively constant.
-212	Population Growth Rate -	Population growth rate (births and deaths inclusive) estimated using CAGR formula and referencing the 2050 population growth values (p. 46, IPS). Three scenarios in the projection. Low CAGR: 0.4843%; Mid CAGR: 0.6462%; High CAGR: 0.9307% https://lkyspp.nus.edu.sg/docs/default-source/ips/pos2050_web_final_3009141.pdf?sfvrsn=1cb99e0b_2.
-215	Project Approval Time (Local) -	This is the expected approval lag that the Singapore government has estimated. This does not include the time taken for construction, which is expected seperately. Data is estimated from the public consultation paper that the Energy Market Authority of Singapore has published. https://www.ema.gov.sg/cmsmedia/Determination_Paper_%20Preparing_for_Future_Power_Generation_Investments_Final_29_Jul.pdf. Data stated 36 weeks from the start of investor's

		request to invest to the actual local site approval. Potential investors from the public consultation then replied that they expect the timeline to be closer to a year.
-216	Project Approval Time (Overseas) -	This is the an estimated approval lag. This does not include the time taken for construction, which is expected seperately. Information was estimated from a Singapore's company investment timeline in Vietnam, where they began operations in Vietnam in 2015 but only gt governmental approval for grid scale electricity in 2018. https://www.sunseap.com/SG/about/sunseap_group/milestones.html
-217	Proportion of Capacity Allowed Overseas -	As electricity is a strategic asset required for the economic livelihood of Singapore, it may be expected that the Singapore Government would limit the amount of overseas generating capacity that it would support.
-220	Proportion of Non-Baseload Installed Capacities -	Proportion of installed capacities that is of non-baseload technologies (solar and wind in this thesis).
-243	Remaining Resource Ratio -	Estimated remaining resources expressed as a ratio and smoothed as a first order delay.
-268	Time Adjusted Overnight Investment Cost -	This is the investment cost of technology for each source throughout the years in the value of money at that specific year. It follows the general formula of present value and future value, where overnight investment cost was reported 2010 USD dollars is adjusted according to the time periods forwards to the corresponding year Future Value: https://www.investopedia.com/terms/f/futurevalue.asp
-274	Total Installed Capacities -	Total installed capacities available.
-275	Total Installed Capacities (Local) -	Total local installed capacities available.
-276	Total Installed Capacities (Overseas) -	Total overseas installed capacities available.
-277	Total Spent Each Year (Local) -	Amount of money spent each year on local generating capabilities.
-278	Total Spent Each Year (Overseas) -	Amount of money spent each year on overseas capabilities.
-279	Total Spent Per Year -	Total amount of spent each year for generating capabilities.
-283	Total Waiting and Installed Capacities -	Total installed and waiting capacities.

-284	Total Waiting and Installed Capacities (Local) -	Total waiting and installed capacities from overseas sources.
-285	Total Waiting and Installed Capacities (Overseas) -	Total waiting and installed capacities from overseas sources.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.
-294	Year When Overseas Generators are Allowed -	Currently, Singapore generates all its electricity within Singapore. Overseas generating capabilities have been discussed but no current plan has come into fruition. This variable allows for model testing in which the year that such generator capabilities can be allowed.

Table II-5: Descriptions for Variables in [5] Electricity Generation

Eq. #	Variable Name	Description
-11	Amount Supplied by Each Generator -	Amount of electricity supplied by each technology at the market clearing priority.
-15	Available Electricity -	Combined variable to represent the various technologies available.
-32	Capacity Factor -	Refers to the ratio of maximal plant operating hours in a year. Generally high for baseload capabilities where it is expected to be operational for all times except for planned maintainance period. Low values for non-baseload technologies such as wind and solar. Average values from relevant reports regarding data from Singapore/ ASEAN are used when applicable. Gas Fired Plants: https://www.ema.gov.sg/cmsmedia/Annex%202_Review%20of%20the%20Vesting%20Contract%20Technical%20Parameters_Final__.pdf
-33	Capacity Utilisation -	The output represents how much the power plant would be producing in a year based on the profitability possibility as indicated in the Table for Capacity Utilisation. This approached is modelled analogously from Kubli 2014. A smoothing function was added in order to smooth out noise from the fuel price input and reflect that the incentive to generate is a decision that considers past information as well.
-34	Capacity Utilisation Delay Time -	Period in which past information is considered for the LCOE on Capacity Utilisation.
-103	Electricity Generated by Type -	Electricity generated based on broad classification of renewable or not.
-104	Electricity Price -	The energy price is expected to change according to the its past values and also dependent on the effects of the demand supply ratio and variable costs. Modelled based on Sterman 2000, Chapter 20.2.6 The Price-Setting Process.
-113	Expected Marginal Costs -	The expected variable cost that will thus form the minimum market price. Built on the unerstanding from Eqn. 20-32 and 20-33 in Sterman 2000
-142	Grid Losses -	Assumed that grid losses take up 10% of total supply.
-145	Hours per Year -	Number of hours per year.
-165	Input Demand in MWh -	Input demand is converted to a subscripted version and converted to a MWh/Year format.
-166	Installed Capacity (Local) -	Modelled similar to Figure 17-7 of Sterman 2000. Equations are extracted from. Initial Values for Installed Capacity obtained through the Singapore Energy Statistics 2018 published by the Energy Market Authority of Singapore. Data used was specifically the 2010 data.

-167	Installed Capacity (Overseas) -	This the stock of generation capacities from overseas locations which is generating power. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities for Singapore yet.
-187	Market Clearing Mechanism -	Marketing clearing mechanism in which the lowest effected LCOE technology get used first and the final technology to clear demand sets the market clearing price.
-238	Relative Incentive to Generate -	This is the ratio between the current energy price and the LCOE. This represents potential profitability ratio for the generator companies. Values less than 1 signify that the generators are losing money if operate while values greater than 1 signify that there is profitability incentive for generators to produce electricity. This approach is based on the approach suggested in Kubli 2014.
-251	Supply Curve Function -	Supply curve definition for each technology.
-256	Supply Sufficiency -	To determine if basic demand has been met by the total supply of electricity. Should always be at 1. If below 1, indicates that market did not clear at input demand and there are demand not fulfilled.
-257	Table for Capacity Utilisation -	Table function data for how capacity utilisation would shift according to the profitability of production. Flexible energy sources. Reference data obtained from documentation used in Kubli 2014. Overseas Geothermal is equivalent to capacity utilisation[thermal] and Overseas Hydro is equivalent to capacity_utilisation[dam] in Kubli 2014. Local Waste to Energy's capacity utilisation curve is similar to other baseload technology as it's primary purpose is as a incineration plant to minimize amount of waste for landfills so direct profitability is not a critical concern here.
-265	Technical Availability (Local) -	Technical availability of each generator capability within Singapore.
-266	Technical Availability (Overseas) -	Technical availability of each generator capability outside Singapore.
-273	Total Generating Capacities -	Available capacity to produce electricity in MW, after factoring in capacity utilisation, seasonal factors and grid losses.
-281	Total Supply -	Total electricity generated.

Table II-6: Descriptions for Variables in [6] CO2 Emissions

Eq. #	Variable Name	Description
-2	Adjusted Desired GHG Emissions -	Adjusted desired state for the GHG emissions dependent on current desired target value and the effect of reference state. Modelled similiarly to hill-climbing optimization used in p. 537 of Sterman 2000 and also in Moallemi et. al. 2017.
-12	Annual Growth Rate of Vehicles -	Estimated growth rate of vehicles in Singapore as used in Nian 2015.
-13	Annual Increase in Vehicles -	Actual number of growth in vehicles in Singapore.
-17	Average Vehicle Pollution Rate -	Average (2010, 2012, 2014's data) amount of pollution based on total number of vehicles and total reported CO2 pollution by the transport sector in Singapore. CO2 data: https://www.nccs.gov.sg/docs/default-source/default-document-library/singapore's-fourth-national-communication-and-third-biennial-update-repo.pdf Vehicle numbers: https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/MVP01-1_MVP_by_type.pdf
-41	Change in Desired Target -	This is the rate in which the internal target for GHG emissions will change.
-60	Current GHG Emissions -	Total GHG emissions from all production.
-84	Desired Target for GHG Emissions -	This is the floating of the GHG emissions. This is modelled similarly to Moallemi et. al. 2017. Broadly modelled as a floating goal mechanism (Sterman 2000) approach but the feedback from the desired state does not affect the state that directly.
-98	Effect of Targets for GHG Emissions -	This nonlinear function outputs the relative effects of a normalized GHG data that will then be used on determining the desired GHG
-99	Effected GHG Curtailment Rate for Other Sources -	GHG emissions curtailment from non-electricity related initiatives (i.e. no flaring at petrochemical plants, CCS installations) etc.
-103	Electricity Generated by Type -	Electricity generated based on broad classification of renewable or not.
-108	EV Annual Growth Rate BAU -	Electric vehicle growth rates in the BAU scenario as estimated in Nian 2015.
-109	EV Annual Growth Rate Conservative -	Electric vehicle growth rates in the conservative scenario as estimated in Nian 2015.

-110	EV Annual Growth Rate Optimistic -	Electric vehicle growth rates in the optimistic scenario as estimated in Nian 2015.
-120	Fixed Total Emission Target -	Mechanism to capture the value of 2030's emissions and fix it as a target for future use, if used.
-133	GDP -	GDP for Singapore. Initial Value was for 2010. Obtained from the World Bank database.
-134	GDP @ 2030 -	Variable to hold GDP value when time = 2030.
-135	GDP Growth Rate -	Estimated GDP growth rate based on data used from 2000 to 2018. Data calcualted from World Bank data in USD 2010 dollars. Data calcualted at 4.18%. Includes subtraction from inflation rate of 1.6%.
-137	GHG Curtailment Rate for Other Sources -	GHG emissions curtailment from non-electricity related initiatives (i.e. no flaring at petrochemical plants, CCS installations) etc.
-138	GHG Emissions from Other Sources -	Stock of GHG present. Initialized value according to 2010 value reported by the NCCS of Singapore.
-139	GHG Emissions from Transport -	Total GHG emissions from transport sector, referrring mainly to the non-EV land and sea motor vehicles. Does not include EV and public rail network systems.
-140	GHG in GgCO2 -	Reexpressed in GgCO2/Year
-141	GHG Target Mechanism -	GHG Emissions Target mechanism switch. 0: Emissions target based on yearly GDP (Holding Emission Intensity Constant) 1: Emissions target based on fixed total output (Holding Total emissions after 2030 as fixed target)
-150	Increase in GHG from Other Sources -	Expected yearly change in GHG estimated. Industry, Commercial, and Residential growth rate estimated at GDP growth rate while transport growth rate assumed at 0.6% per year (Nian 2015) as vehicle growth in the highly urbanized Singapore does not growth that fast due to the high cost of ownership.

-159	Initial (2010) GHG from Other Sources -	This is the baseline CO2 produced from sectors other than electricity. The target to the Paris Agreement includes emission from all source. The dynamics of the other sectors is not modelled here and is treated as an exogenous baseline, estimated to grow similarly at a rate similar to GDP. 2010 Data is obtained from Singapore's Third National Communication and First Biennial Update Report (2014), pg. 64, obtained from the National Climate Change Secretariat group of Singapore. https://www.nccs.gov.sg/docs/default-source/publications/singapores-third-national-communication-and-first-biennial-update-report.pdf. Fugitive emissions, industrial processes, and waste is classified under Industry sector.
-160	Initial (2010) Number of Vehicles -	Number of vehicles in Singapore as reported by the Land Transport Authority of Singapore. https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/MVP01-1_MVP_by_type.pdf
-179	kW to MW -	Converts kW to MW.
-181	Level of Energy Efficiency Intiatives -	Signifies the relative level of energy effiency initiatives where: 0 = BAU condition; 0.5 = Conservative; 1 = Optimistic
-182	Lifecycle Emission Intensity by Generator -	Mapping of Lifecycle Emissions Intensity between Source Type and Generator
-183	Lifecycle Emission Intensity of Resources -	Data used is median lifecycle emissions. Table A.III.2. Data obtained from the IPCC's Annex III to Climate Change 2014. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf. Waste to Energy estimate obtained from Kuo et. al. 2011. https://www.sciencedirect.com/science/article/pii/S1750583611000314
-184	Light-Duty Electric Vehicles -	Total number of light-duty electric vehicle. Formulation setup according to description listed in Nian 2015.
-193	New EV Each Year -	EV is expected to have a penetration rate of 0 to 3% of total light-duty vehicles by 2030 and 0 to 5% of total light-duty vehicles by 2050.
-194	Non-Electric Vehicles -	Number of non-electric vehicles that will be used to determine transport sector pollution levels.
-196	Normalized GHG levels -	Fraction of the internal target for EDI to the reference EDI that is based on Singapore's 2030 first NDC reported to UN.

-219	Proportion of Light-Duty Vehicles -	Average proportion of vehicles that are light-duty vehicles, according to data provided by the Land Transport Authority of Singapore.
-234	Reference GHG in GgCO2 -	Reference GHG target expressed again in GgCO2
-236	Reference Target GHG Emissions -	Estimated GHG emissions target based on Singapore to UN NDC. 0.113 kgCO2e/S$(2010 dollars) by 2030. Target here is set according to GDP levels so it is not a straight line but you get a shifting target as the year progresses.
-242	Relative Social Need for GHG Emissions -	The ratio between current and desired GHG emissions to give a relative scale if we are above or below what is desired. If the current GHG is higher than the Desired (Ratio > 1), a social need is thus generated.
-249	Singapore UN NDC GHG Target -	Based on the target of 0.113kgCO2/S$ (2010 SGD) by 2030 released by the Singapore government. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Singapore%20First/Singapore%20INDC.pdf. Assumed exchange rate of 1.364SGD to USD in 2010. https://data.worldbank.org/indicator/PA.NUS.FCRF?end=2018&locations=SG&start=2008.
-259	Table for Normalized GHG on Desired -	Table function for the effect of the floating goal of GHG Emissions benchmarked against Singapore to UN NDC Target. In cases where the internal target is less than or equal to the benchmark, this signifies an emission that has reach a lower than targeted level. The output effect is thus kept at 1 as it is assumed that there is no need to accelerate emissions lowering once Singapore has outperformed the benchmark. In cases where emissions is more than the benchmark, this signifies that there should be pressure to lower the desired from the current. The output effect when that occurs is thus to have a factor < 1, till a mimimum of 0.1 as seting it to 0 then creates a target of zero emissions for the country, which seems to be unrealistic in the short term measure for goal setting.
-264	Target GHG Adjustment Time -	This the adjustment time for the internal target for GHG emissions. Policy makers might assume that refreshing the target too often might not be useful so the target is estimated to adjust every 5 years.
-282	Total Vehicles -	Total number of motor vehicles in Singapore.

-288	USD Adjusted Singapore UN NDC Target -	The CO2 emission target is adjusted to reflect it based on USD basis for consistency with rest of model.
-289	USD to SGD -	Assumed exchange rate of 1.364SGD to USD in 2010. https://data.worldbank.org/indicator/PA.NUS.FCRF?end=2018&locations=SG&start=2008.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.
-293	Year when GHG Target is met -	Difference between actual emitted and target levels. Useful for tracking time in which target is met.If met and is emitting below target, will reflect as 0 for easy reference on actual time met.

Table II-7: Descriptions for Variables in [7] Energy Related Jobs

Eq. #	Variable Name	Description
-5	Adjusted Target for GJC -	Desired state for the gross jobs created in the energy sector on current internal target value and the effect of reference state. Modelled similiarly to hill-climbing optimization used in p. 537 of Sterman 2000 and also in Moallemi et. al. 2017.
-10	Adjustment Time for Floating Target for Jobs -	This the adjustment time for the internal target for job creation. Policy makers might assume that refreshing the target too often might not be useful so the target is estimated to adjust every 5 years.
-45	Change in Floating Target for Jobs -	This is the rate in which the internal target for job creation.
-80	Desired Non-Baseload Proportion -	Estimated target proportion of non-baseload class (solar and wind) that states like (Sri Lanka and Taiwan) set as benchmark for the energy diversity. Taiwan: https://www.power-technology.com/features/taiwan-pursuing-new-green-energy-revolution-east/ Sri Lanka: https://www.export.gov/article?id=Sri-Lanka-Energy
-93	Effect of Policy Targets on Job Creation -	This nonlinear function outputs the relative effects of a normalized job created that will then be used on determining the adjusted target for job created. If normalized > 1, then there is no additional adjustment required. If the normalized < 1, then there is a need for the desired job to increase further to increase the difference between desired and current to increase social pressure.
-103	Electricity Generated by Type -	Electricity generated based on broad classification of renewable or not.
-123	Floating Target for GJC -	This is the internal target of the Net Job creation. This is modelled similarly to Moallemi et. al. 2017. Broadly modelled as a hill climbing optimization (p. 539 Sterman 2000) approach but the feedback from the desired state does not affect the state that directly.
-143	Gross Jobs Created (GJC) -	Total energy jobs created on a job per year basis.
-168	Installed Capacity by Type -	Installed capacities reorganized in energy source type.
-177	Job Creation Reference Data -	Job data estimate obtained from review provided by the UK Energy Research Centre. Waste to Energy estimate assumed under category of renewable energy category for this case as the closest job data was from biomass data reported in the study. Nuclear was excluded in the study and data was obtained via: https://rael.berkeley.edu/wp-content/uploads/2015/04/WeiPatadiaKammen_CleanEnergyJo

		bs_EPolicy2010.pdf and https://www.sciencedirect.com/science/article/pii/S0301421509007915
-190	MW to GW -	Converts MW to GW.
-197	Normalized GJC -	Fraction of the internal target for gross job created to the reference gross job created that is based on a 100% renewable market.
-235	Reference GJC -	Reference gross job created based on the an assumption of 100% of the highest job creation technology.
-241	Relative Social Need for Energy Job Creation -	This ratio represents how far the current job creation are from the desired job creation levels. To thus reflect this as social needs (> 1), the ratio of desired to current is used. Ratios larger than 1 represent that the current job available for the energy sector is higher than the desired.
-260	Table for Normalized GJC -	Non-linear function to determine adjustment factor to be applied to desired target.
-281	Total Supply -	Total electricity generated.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.

Table II-8: Descriptions for Variables in [8] Energy Security

Eq. #	Variable Name	Description
-3	Adjusted Floating Target for EDI -	Adjusted desired state for the energy diversity dependent on current floating target and the net effect against the reference state. Modelled similiarly to hill-climbing optimization used in p. 537 of Sterman 2000 and also in Moallemi et. al. 2017.
-44	Change in Floating Target -	This is the rate in which the internal target for energy diversity index will change.
-59	Current Energy Diversity Index (EDI) -	Energy Diversity index calculated using the Herfindahl-Hirschman Index. This is similar to how energy diversity is calculated in the Energy Transition Index. HHI here is normalized to between 1 to 10000.
-89	EDI Adjustment Time -	This the adjustment time for the internal target for energy diversity index. Policy makers might assume that refreshing the target too often might not be useful so the target is estimated to adjust every 5 years.
-92	Effect of Normalized EDI on Desired State for EDI -	This nonlinear function outputs the relative effects of a normalized EDI that will then be used on determining the desired EDI.
-122	Floating Target for EDI -	This is the floating target of the energy diversity index. This is modelled similarly to Moallemi et. al. 2017. Broadly modelled as a hill climbing optimization (p. 539 Sterman 2000) approach but the feedback from the desired state has further impacts before returning into the change in the internal target.
-166	Installed Capacity (Local) -	Modelled similar to Figure 17-7 of Sterman 2000. Equations are extracted from. Initial Values for Installed Capacity obtained through the Singapore Energy Statistics 2018 published by the Energy Market Authority of Singapore. Data used was specifically the 2010 data.
-167	Installed Capacity (Overseas) -	This the stock of generation capacities from overseas locations which is generating power. The initial value of this variable has been assumed 0 as Singapore does not have the policy to have overseas generating capacities for Singapore yet.
-168	Installed Capacity by Type -	Installed capacities reorganized in energy source type.
-195	Normalized EDI -	Fraction of the internal target for EDI to the reference EDI that is based on literature values.
-221	Proportion Per Generating Type -	Proportion of energy produced by type, expressed as percentage points instead of decimals.
-232	Reference Energy Diversity Index -	Benchmarked against other states reported in Ioannidis et al. 2019. https://www.sciencedirect.com/science/article/pii/S0960148119306391?via%3Dihub

-240	Relative Social Need for Energy Diversity -	This ratio represents how far the current energy diversity index is from the desired levels of energy diversity. Due to the nature of what HHI represents, a larger HHI value signifies that energy is less diverse and less secure. To thus reflect this as social needs (> 1), the ratio of current to desired is used. Ratios larger than 1 represent that the current is actually less diverse than the desired while values smaller than 1 represent current state as more diverse than the desired.
-258	Table for Normalized EDI on Desired -	Table function for the effect of the internal value of EDI benchmarked against a target EDI of 5000. In cases where the internal target is less than or equal to the benchmark, this signifies a more diverse current market. The output effect is thus kept at 1 as it is assumed that there is no need to accelerate diversity once Singapore has outperformed the benchmark. In cases where diversity is more than the benchmark, this signifies a less diverse current market. The output effect is thus lower than 1 so that the desired goal be a value lower than the current.
-274	Total Installed Capacities -	Total installed capacities available.

Table II-9: Descriptions for Variables in [9] Social Needs

Eq. #	Variable Name	Description
-39	Change in CSN -	This is the change in social need over time. Modelled using Eq 21 in Fiddaman 1997 and Moallemi et. al. 2017.
-57	Cumulative Social Needs (CSN) -	The central idea is that social needs in the energy sector arises when concerns are not met. The concerns modelled here are namely demand-supply problem, GHG emissions, energy security, and energy job market. As social needs increases relative to its recent values, it will put pressure on drivers of change. This overall structure is built based on Moallemi et. al. 2017.
-61	Current Total Social Needs -	The structure of the utility for the social needs is shown through the multiplicative effects of the various important factors of the model (Demand-Supply Balance, GHG Emissions, Energy Security, Job Creation), and this represents the performance of the system.
-87	Discount Factor -	Discount factor is a factor which changes the future values of societal needs, dependent on the rate of time preference used. This formula is used as per Eq. 20 of Fidderman 1997, and Moallemi et. al. 2017.
-100	Effective Social Pressure -	The effective social pressure that is based on recent pressure and the adjustment from it that causes pressure. Similar to where recent observations have a higher effect.
-163	INITIAL TIME -	The initial time for the simulation.
-226	Rate of Inequality Aversion (RIA) -	Factor set at 2.5 so that the needs of current generation are of greater urgency (Fiddaman 1997).
-227	Rate of Time Preference (RTP) -	This is the weight given to the satisfaction of societal needs across generations. The value for this constant is based on Fiddaman 1997 and Moallemi et. al. 2017. A RTP of 0 signifies equal welfare treatment of all generations while a RTP of 0.03 causes a resultant discount factor that factors the current generation's needs more.
-231	Reference CSN -	Reference cumulative social need that is pased on past information, smoothed over 5 years.
-239	Relative Social Need for DSB -	The current demand supply ratio is divided by the desired demand supply ratio to express the relative social need between. A number > 1 signifies that desired demand/supply has a higher value than current, implying insufficient capacity while a number < 1 signifies the desired demand/supply has a lower value than the current state, implying excess current capacity.
-240	Relative Social Need for Energy Diversity -	This ratio represents how far the current energy diversity index is from the desired levels of energy diversity. Due to the nature

		of what HHI represents, a larger HHI value signifies that energy is less diverse and less secure. To thus reflect this as social needs (> 1), the ratio of current to desired is used. Ratios larger than 1 represent that the current is actually less diverse than the desired while values smaller than 1 represent current state as more diverse than the desired.
-241	Relative Social Need for Energy Job Creation -	This ratio represents how far the current job creation are from the desired job creation levels. To thus reflect this as social needs (> 1), the ratio of desired to current is used. Ratios larger than 1 represent that the current job available for the energy sector is higher than the desired.
-242	Relative Social Need for GHG Emissions -	The ratio between current and desired GHG emissions to give a relative scale if we are above or below what is desired. If the current GHG is higher than the Desired (Ratio > 1), a social need is thus generated.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.

Table II-10: Descriptions for Variables in [10] Policy

Eq. #	Variable Name	Description
-19	BII Adjustment Time -	This is the estimated time it would take for investment rate policies to be refreshed, which does not happen often.
-37	Carbon Tax Rate (CTR) -	Carbon is slated to be introduced in Singapore from 2019 onwards at a rate of about 3.7USD per tonne of GHG emitted. https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/carbon-tax. As the cumulative social need represents the needs in light of considerations such related to the energy domain, policy mechanism such as the carbon tax can be employed and adjusted according to the output from the social need.
-38	Change in BII -	This is the adjustment rate for the infrastructure investment boost. It is divided by the adjustment time to normalize the rate in which the change is effected as we cannot expect changes for these policies to be constant.
-40	Change in CTR -	This is the adjustment rate for the carbon tax rate based on the gap between the current levels and the updated desired levels of carbon tax and by considering an adjustment time.
-50	Change in RARI -	This is the adjustment rate for the impact of the renewable energy project approval rate. It is divided by the adjustment time to normalize the rate in which the change is effected as we cannot expect changes for these policies to be constant.
-51	Change in RARI Adjusment Time -	This is the estimated time it would take for renewable project approval rates and its relevant policies to be refreshed, which does not happen often.
-55	CTR Adjustment Time -	Value referenced from Moallemi et. al. 2017. This is the estimated time it would take for carbon tax policies to be refreshed, which does not happen often.
-57	Cumulative Social Needs (CSN) -	The central idea is that social needs in the energy sector arises when concerns are not met. The concerns modelled here are namely demand-supply problem, GHG emissions, energy security, and energy job market. As social needs increases relative to its recent values, it will put pressure on drivers of change. This overall structure is built based on Moallemi et. al. 2017.
-71	Desired BII -	Desired Investment Rate for each generator technology, dependent on the output effect of social pressure and the current levels.
-77	Desired CTR -	Desired carbon tax rate based upon the adjusted value and the effect of the cumulative social needs value.
-82	Desired RARI -	Desired impact level of the renewable energy project approval rates.

-95	Effect of Social Pressure on BII -	Output effect of social pressure on priority level to boost.
-96	Effect of Social Pressure on CTR -	The output effect of the normalized value of the cumulative social needs on the carbon tax rate.
-97	Effect of Social Pressure on RARI -	The output effect of the normalized value of the cumulative social needs on the the renewable energy project approval rate.
-100	Effective Social Pressure -	The effective social pressure that is based on recent pressure and the adjustment from it that causes pressure. Similar to where recent observations have a higher effect.
-208	Policy: Boost Infrastructure Investment (BII) -	Policy Target for boosting government investment priority in energy projects according to the social pressure.
-209	Policy: Renewables Approvals Rate Impact (RARI) -	Policy Target for boosting speed of renewable energy projects approval rate. It should be noted that this only affects the approval speed and not the construction speed as that is assumed to be relatively constant.
-261	Table for Social Pressure on BII -	Table values of adjustment factors for different generator types, dependent on the effective social pressure need as input value.
-262	Table for Social Pressure on CTR -	Lookup table for effect of normalized cumulative social need on the adjustment to the carbon tax rate. In the event that the social pressure is not met (> 1), there then should be an effect to increase the carbon tax rate. On the other end, if social pressure is met, (< 1), then there is no need to further increase the carbon tax rate and thus stay the same.
-263	Table for Social Pressure on RARI -	This is similar to the lookup table of the effect of normalized cumulative social need on the adjustment to the carbon tax rate. In the event that the social pressure is not met (social pressure > 1), there then should be an effect to increase the rate of renewable project which renewable projects are approved.
-292	Year Unit -	Year unit used to normalize some of the time related functions when required.

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