# Modelling the Growth of Solar Electricity Capacity in Singapore – A System Dynamics Approach

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## Abstract

As part of its pledge towards combating climate change, the Singapore government is aiming to have a 2 Gigawatt-peak (GWp) of solar power capacity in the country by 2030. However, it is unclear whether this goal is realistic and if incentives must be introduced to accelerate growth in the land-limited country. Thus, it is important to model and quantify the growth in Singapore's solar capacity for the years ahead. This project uses the system dynamics approach to model the solar energy system in Singapore and simulates the growth of solar capacity as well as the potential carbon emissions saved. Results from model simulations show that Singapore's solar capacity will reach this 2GWp goal by 2028, 2 years ahead of schedule. However, should the government revise its goals for solar capacity higher for the years past 2030 i.e.8% share of total electricity generation by 2040, policies such as an increased area utilization, subsidies and higher panel efficiency have to be introduced such that Singapore reaches these goals.

## 1. Introduction

In recent times, renewable energy has been in the global spotlight as public concern over the impacts of global warming has increasingly pressured governments to reduce their national carbon footprints [1]. In response, countries have been steadily adopting greener energy, such as wind, solar and nuclear energy [2]. The Singapore government is aiming to have 2GWp of solar power capacity in the country by 2030 as part of its pledge towards combating climate change [3]. This is a more than six-fold increase from the current 300.3 megawatt-peak (MWp) installed capacity as of end Q3 2019 [4]. As a country reliant on natural gas for 95% of its energy needs today [5], Singapore stands to gain from increased energy security and savings on carbon emissions by diversifying its energy mix into renewables like solar energy. While the Housing Development Board (HDB) and Public Utilities Board (PUB) have spurred initiatives to increase solar capacity by utilising rooftops of flats as well as local catchment areas for solar panels [3], it remains uncertain if Singapore can reach this 2GWp capacity target by 2030, how much carbon emission savings Singapore can reap from diversifying into solar energy, as well as what percentage of electricity demand would be met by solar panels.

Among the various forms of alternative energy sources such as solar, wind, nuclear, etc, solar power has among the lowest energy returns on investment (EROI) [6]. However, other low-carbon alternatives to natural gas in Singapore are not as feasible compared to solar power. For example, wind turbines have a typical cut-in speed of 3-4 m/s [7], while the mean wind speed is only 2.19 m/s in Singapore [8], with a payback period on investment of 59 years [9]. Furthermore, nuclear energy in Singapore has to overcome legal constraints – a 30 km hazard zone for nuclear power plants is the international standard and virtually impossible for the land-scarce nation, which spans 50km from West to East and 25km from North to South [10].

In addition, energy security is an issue in Singapore, as the country lacks natural resources due to its small geographical footprint. The island-state relies on imported natural gas for 95% of its energy needs, and an increase in solar energy production offers an opportunity to improve Singapore's self-sufficiency in its energy needs. Ang, Ng, and Choong developed a framework for evaluating Singapore's energy security, based on inputs categorised by economic, supply chain, and environmental indicators [11]. While their results concluded that Singapore's energy security has remained "*fairly stable*" throughout the period of the study (1990-2010), the report also acknowledged that heavy investments into nuclear energy as well as renewables such as solar energy could yield an improved "*Singapore Energy Security Index*" (SESI) rating from 2.0 in the base scenario to 2.5 in this optimistic scenario. Thus, diversifying into alternative energy sources such as solar energy is a great opportunity for Singapore to improve its energy security in the long run.

This project aims to quantify the process whereby installations of solar panels in Singapore increases over time, which would provide insightful analyses to the uncertainties mentioned in the previous section. For example, model simulations could possibly show that solar adoption would not accelerate as quickly as the government had predicted, and further incentives would be needed to ensure Singapore hits its goal of 2GWp solar capacity by 2030. Ideally, this project aims to provide an accurate and valid system dynamics model that can be used to estimate Singapore's solar capacity, carbon emission savings and share of electricity demand met by solar energy. These results may be useful to organisations involved in the solar electricity system in Singapore which may consider the data from this model in future policy decisions, such as the HDB and the PUB.

## 2. Literature Review

Prior to this project, there have been studies relevant to the development of solar energy in Singapore. For example, Nobre et. al constructed a short-term forecasting model for PV cells based on environmental criteria such as temperature and irradiance [12]. This project uses their mathematical model (Appendix Figure A1) and extrapolates the timeframe to a yearly basis. Thus, using yearly averages of humidity, temperature and other variables, a performance ratio can be computed which is applied to the computation of the annual solar energy output.

Much of the data used to quantify the variables in this model come from the Solar Energy Research Institute of Singapore (SERIS) and their article *"Solar Photovoltaic (PV) Roadmap for Singapore (A Summary)"*, which provided crucial information on PV System cost, irradiance, and land area available for solar panels [13]. SERIS regularly provides updates to its projections for a multitude of variables for the Singapore Solar Energy System in its "*Solar Economics Handbook of Singapore*", including projections for future solar PV potential, costs of production, electricity tariffs, etc [14]. However, the modelling methodology behind these projections by SERIS is opaque and not clearly available to external users of this information. A system dynamics model that can accurately model these projections by SERIS would be useful to other external users, as any user who knows the basics of system dynamics can formulate policies and interventions to improve upon the current state of Singapore's solar energy system, and subsequently implement them using simulation software like Vensim [15].

Meanwhile, system dynamics research pertaining to energy systems in Singapore is still in its infancy. While there have been attempts to model the Singapore nuclear energy system [10], similar system dynamics modelling of the country's solar energy system is lacking. Therefore, the model presented in this report could serve as a basis for future modelling, and possibly be integrated with other system models such as the nuclear energy system from Chia et. al. to present a model which encapsulates the entire Singapore energy system.

Lastly, the Energy Market Authority (EMA) has been a useful source in quantifying the current solar capacity [4], and electrical consumption in Singapore [16]. This organization is a statutory board under the Ministry of Trade and Industry of Singapore, and it tracks a multitude of statistics pertaining to energy consumption, demand, and generation.

## 3. Methodology

### 3.1 System Dynamics Simulation

System dynamics is an approach used to understand the overall behaviour of a complex system based on the interconnections and interdependence of its components. It was pioneered by Jay W. Forrester in the mid-1950s, who sought a method of modelling complex industrial processes in his book "*Industrial Dynamics*" [17][18]. This modelling methodology was further developed and popularized by John D. Sterman in his book "*Business Dynamics: Systems thinking and modelling for a complex world*" [19]. By understanding the cause and effect relationships among the parts of the system, one can conceptualise reinforcing and balancing feedback loops in the system which result in the non-linear behaviour of the system. This conceptualisation is visualised through a qualitative model such as a causal loop diagram (CLD). The causal relationships conceived in the CLD are then used as a basis for the quantitative model - a stock and flow diagram (SFD), where the variables and stocks of the system are quantified with initial values and equations. Data is sourced from publicly available sources to provide quantities for the variables in Singapore's energy system, such as the area available for solar panels, irradiance, cost of producing solar energy, etc. With the necessary data, causal relationships, feedback loops, stocks and flows identified, simulations are then conducted in the software Vensim to provide insight into the problems mentioned in the introduction.

System dynamics modelling is an iterative process. It is rare for models to generate correct or expected behaviour in their first version. When models do not behave according to expectations laid out by the dynamic hypothesis, models are refined by re-evaluating causal relationships in the system as well as the data used to quantify the system's variables. Ideally, this process of repeatedly refining the model creates a well-validated model that produces useful and accurate results.

### 3.2 Model Assumptions

Modelling complex systems in the real world is a difficult task due to the numerous variables that could potentially affect the overall system's effect. Intangible variables, such as technical expertise, cannot be quantified without making some assumptions on its effect on other auxiliary variables. Furthermore, quantifying the causal relationships between system variables is impossible without making some assumptions about their mathematical relationship. Indeed, all models are wrong to some extent [20], and one can only create a sufficiently accurate system dynamics model through iterative validation. Thus, to set the boundary and quantify the relationships between the variables of this model, the following assumptions were made:

- Model Timeframe: 2013 to 2040.
- Total electricity demand in Singapore is equal to the total electricity supplied.
- Levelized Cost of Electricity: 100 S$/MWh in 2019. Average of 73.3 S$/MWh for 1MWp industrial rooftops and 125 S$/MWh for 10kWp residential rooftops [14] (p. 66, 69).
- Total effect on installation rate: From 2013 to 2019, the effect on installation rate is referenced from EMA statistics. From 2019 onwards, this effect is dependent on the levelized cost of electricity (LCOE).
- Initial Land available for PV [13] (p. 33, Table 4.1):
  - 4km$^2$ (Floating PV)
  - 34km$^2$ (Rooftop PV)
- Initial Installation Rate for PV:
  - Floating PV: Assume that the floating PV installations begin in 2020. Referencing the PV system installed in Tengah Reservoir, with a size of "*45 football pitches*", which equates to 45 * 7140 = 321300 m$^2$/year, is installed in the first year [21].
  - Rooftop PV: Assume that rooftop PV installations begin from 2013. Based off EMA statistics, from Q12012 to Q12013, capacity increased from 6.8 to 12.0MWp, which is 5200kWp [4]. Assuming 18% PV module efficiency and using SolarGy's online solar energy calculator [22], this amounts to an initial installation rate of 28888.89 sqm/year.
- Module Degradation Rate: 1% of installed area per annum [12] (p. 498).
- Average Temperature: Take an average temperature of 30°C, 2 degrees below the mean high of 32°C [23].
- Panel Efficiency: 18% in 2013, 23% in 2020, 25% in 2030 [13] (p. 21).
- Average Air Pollution: Assume a constant PSI of 50 in Singapore.
- Annual Irradiance: Average annual irradiance is 1580 kWh/m^2/year [24].

- Base Gross Domestic Product (GDP) Growth Rate: Assume long term growth rate of Singapore's GDP of 3 percent per year [25].
- Energy Conservation and Appliance Efficiency Factor: Assume that efforts in conserving energy and more efficient electric appliances lead to 1% savings in electricity demand every year. Value of 0.99.
- Total Electricity Demand in Singapore: Initial Value of $4.8*10^7$ MWh/year based on full year consumption in 2013 [16].
- Initial Solar Capacity 2013:
  - Floating PV: Assume no capacity from floating PV in 2013.
  - Rooftop PV: Based on the capacity of 12.0MWp in Q1 2013 [4], it is assumed that the initial area installed is 66666.7sqm, based off calculations at 18% efficiency [22].
- Government Expected Peak Solar Capacity: From 2013 to 2019, expected capacity follows EMA statistics [4]. To achieve the government's goal of 2GWp in 2030 from 232.1MWp in Q1 2019, there is needs to be an annual growth in capacity of roughly 21.63% (232.1 * 1.2163^11 = 2000MWp).
- Carbon emissions per MWh electricity by natural gas: Based on 2013 emissions intensity of the grid - 0.4388 tonnes CO2 per MWh electricity [26].
- Energy used to manufacture solar panels: 0.55774 MWh/$m^2$, based on data from data in Malaysia's production plants [27].

### 3.3 Model Structure and Conceptualisation

To understand the relationships between system variables, it could be helpful to have a top-level view of the subsystems in Singapore's solar energy system, as shown in the subsequent page (Figure 1). For example, producers of solar energy are motivated by profit and depend on the electricity market for revenue based on market prices, while contributing to the national grid. With this top-level perspective in mind, the conceptualisation of the CLD in Vensim is clearer, as seen in the subsequent page (Figure 2).

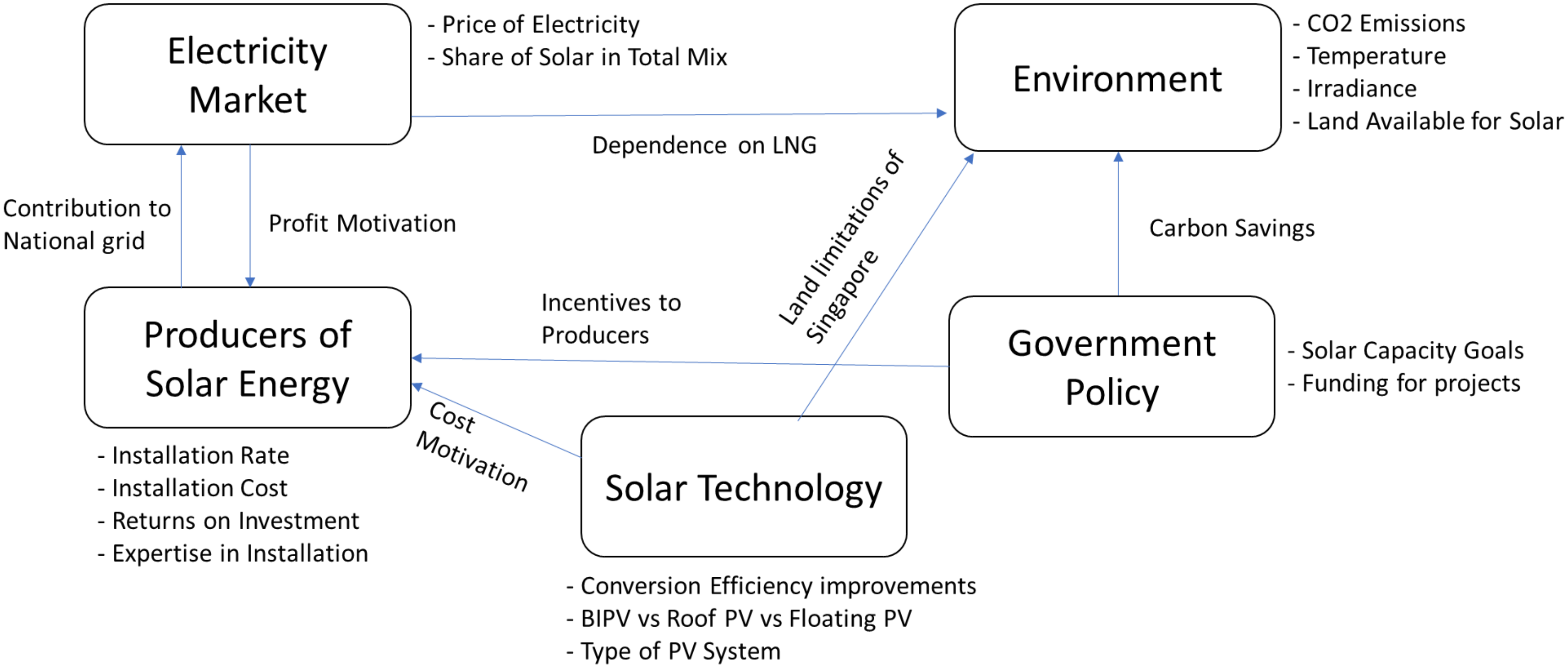



Figure 1. A General Overview of Singapore's solar energy subsystems

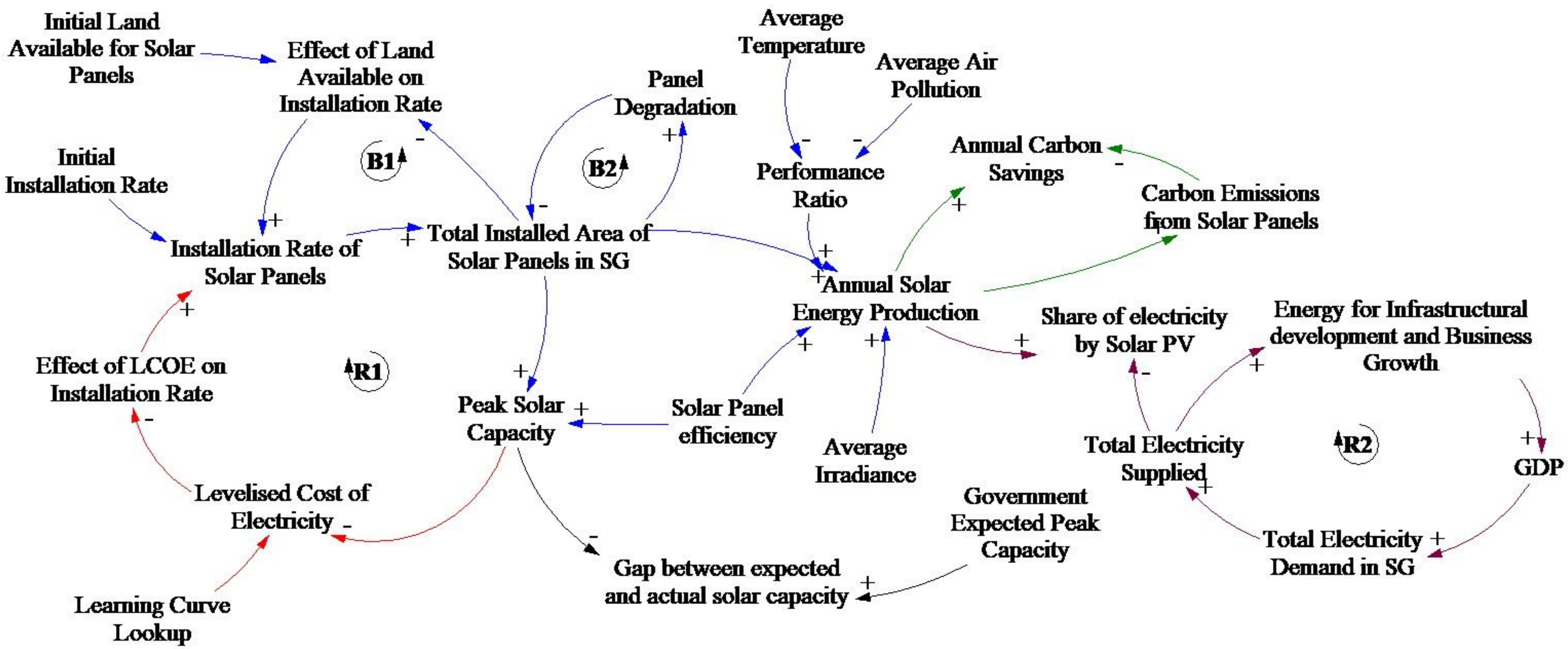



Figure 2. Causal Loop Diagram:

To have a clearer understanding of the CLD and the parts of the system, the model is broken down to subsystems as detailed below.

### 3.3.1 Installation of PV Panels Subsystem

The causal relationships denoted in blue (Figure 2) represent the installation of PV panels subsystem. Assuming electricity prices are constant, the installation rates of solar panels in Singapore is dependent on the profit margins of producing solar energy, which is in turn dependent on the LCOE. This effect of LCOE on installation rate is represented by the "*effect of LCOE on installation rate*" variable. Furthermore, the installation rate of PV systems depends on the amount of land available for it. For example, the higher the installed area of solar panels, the less land available for more installations. The less land available for PV panels, the lower the installation rate as the scarcity of suitable land leads to increasing costs of installing new systems. This results in the balancing feedback loop B1, and the installation rate decreases in a goal-seeking behaviour towards zero as the amount of land available for new solar panels decreases to zero.

Furthermore, solar panels undergo natural degradation over its lifespan. We assume that a percentage of installed panels become faulty due to rusting, accidental damage, etc. As the installed area of solar panels increases, a larger area would degrade on a yearly basis. The higher the area of module degradation, the lower the remaining installed area of solar panels, resulting in the balancing feedback loop B2.

By multiplying installed area of solar panels and their average conversion efficiency, the peak solar capacity can be obtained through simple calculations [22]. The average temperature, irradiance and air pollution contribute to the overall performance ratio of solar panels [12], which is multiplied by panel efficiency and the installed area of solar panels to obtain the annual solar energy production from the current solar capacity [28].

### 3.3.2 Cost of Solar Energy Subsystem

The causal relationships denoted in red (Figure 2) represent the cost subsystem. The LCOE is a composite of many factors that contribute to the overall cost of producing solar energy, such as interest rates, material cost, installation cost, etc. Swanson's law, which is an observation that costs of solar energy decrease by 20% for every doubling of cumulative solar capacity, is incorporated into this model [29]. LCOE thus depends on the current Peak solar capacity, and a learning curve lookup – where the LCOE is computed based on Swanson's law. A lower LCOE would incentivise producers to install more solar panels to increase their profits, and this increase in installations in denoted by the variable "*effect of LCOE on installation rates*". As installation rates increase, total area of installed solar capacity increases, and assuming panel efficiency is the same or higher, peak solar capacity increases as well. The increase in peak solar capacity due to lower LCOE reinforces the effect of Swanson's law, causing LCOE to decrease further in a reinforcing loop, as shown by R1.

### 3.3.3 Carbon Emission Savings Subsystem

Moreover, the causal relationships denoted in green (Figure 2) represent the carbon emission savings subsystem. The carbon emissions saved is calculated by multiplying solar energy produced and the amount of carbon emissions produced if that amount of solar energy came from burning natural gas instead. The carbon emissions from the manufacturing of solar panels is also accounted for, and thus the net carbon emission savings can be derived by subtracting the former from the gross carbon emissions saved.

### 3.3.4 Energy Demand Subsystem

Lastly, the causal relationships denoted in purple (Figure 2) denote the energy demand subsystem. Gross domestic product (GDP) is used as a proxy for economic activity. As economic activity (GDP) increases, the higher the electricity demand for continued business expansion. Assuming that electricity demand is equal to the energy supplied, the increase in energy supplied would support more infrastructural improvements as well as business growth For example, data centres which consume high amounts of electricity are restricted from much expansion as they consume a significant amount of energy from the grid. Increasing the total energy supply in Singapore would lift these restrictions and allow such businesses to expand further. This would lead to further growth in GDP, and thus results in a reinforcing loop as shown by R2. The share of solar energy in the national grid is the annual solar energy production divided by total annual energy supplied.

## 3.4 Dynamic Hypothesis

In any system dynamics model, it is helpful to have a dynamic hypothesis – preliminary expectations of how the system would behave. These expectations help in the modelling process as cause and effect relationships among system variables can be conceived based off these preconceptions. In other developed countries such as the United States of America, cumulative solar capacity has been on an exponentially increasing trend [30]. Extrapolating on past data [4], the installed solar capacity in Singapore is hypothesized to follow a similar reinforcing trend as LCOE decreases due to Swanson's law. Over time, as land scarcity grows, the balancing effects of the feedback loop involving land availability become more significant, resulting in slower capacity growth (Figure 3).

The share of electricity demand met by solar panels would follow a similar trend to the total installed solar capacity. Then, as growth in solar capacity slows and electricity demand continues to grow, the increase in the share of solar energy in the grid would slow significantly (Figure 3).

Lastly, net carbon savings is hypothesized to be negative at the beginning, before growing exponentially (Figure 3). Carbon emissions are produced during the manufacturing process of solar panels while savings in carbon emissions are accumulated over time. Thus, net carbon savings would be negative in the initial years from 2013, before accumulating rapidly in an exponential trend as installations in solar panels grow.

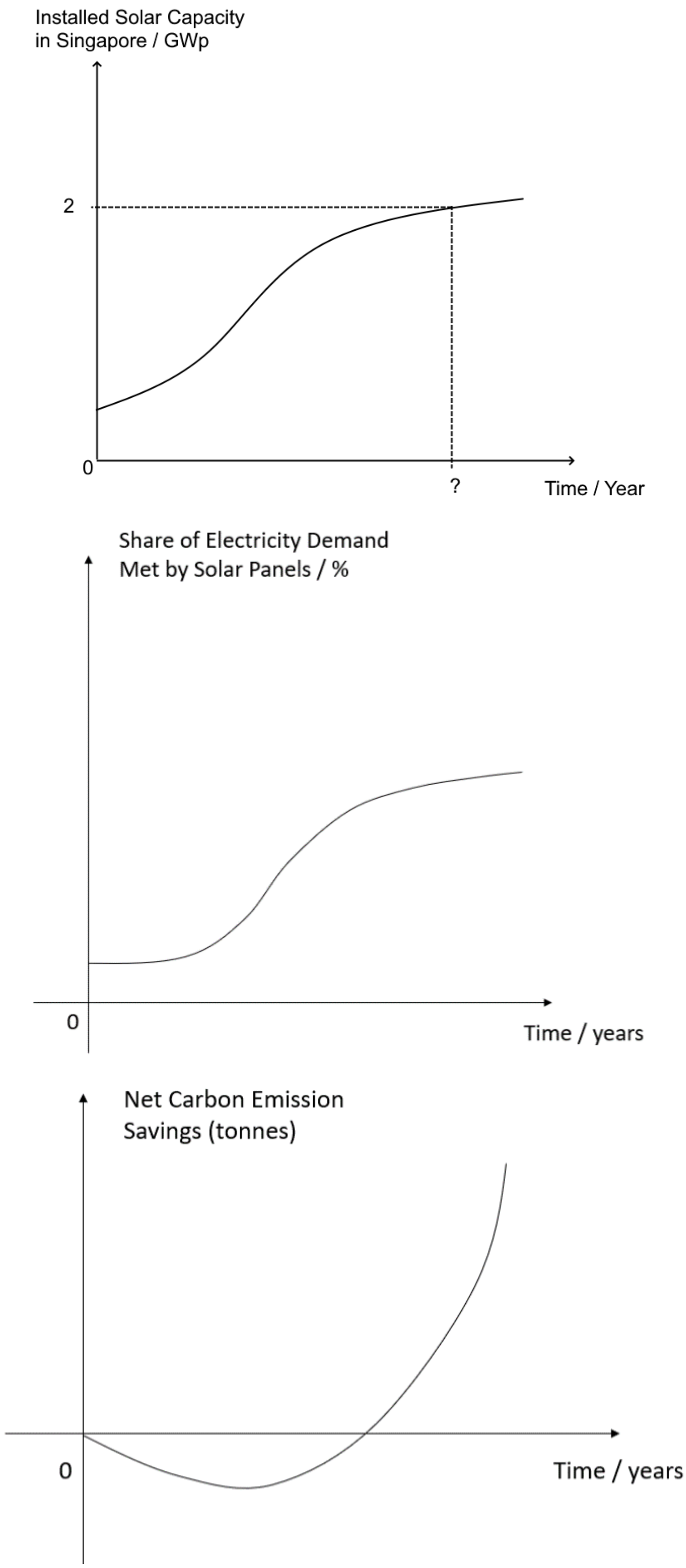



Figure 3: Dynamic Hypothesis Graphs.

### 3.5 Stock and Flow Diagram

Upon conceptualising the interdependent and interconnected causal relationships among the system variables, these variables can then be quantified using a stock and flow diagram (SFD) (Figure 4). There are four main subsystems in the model: 1) Installation of PV Panels 2) Cost of Solar Energy 3) Carbon Emissions 4) Energy Demand. These subsystems are elaborated upon below.

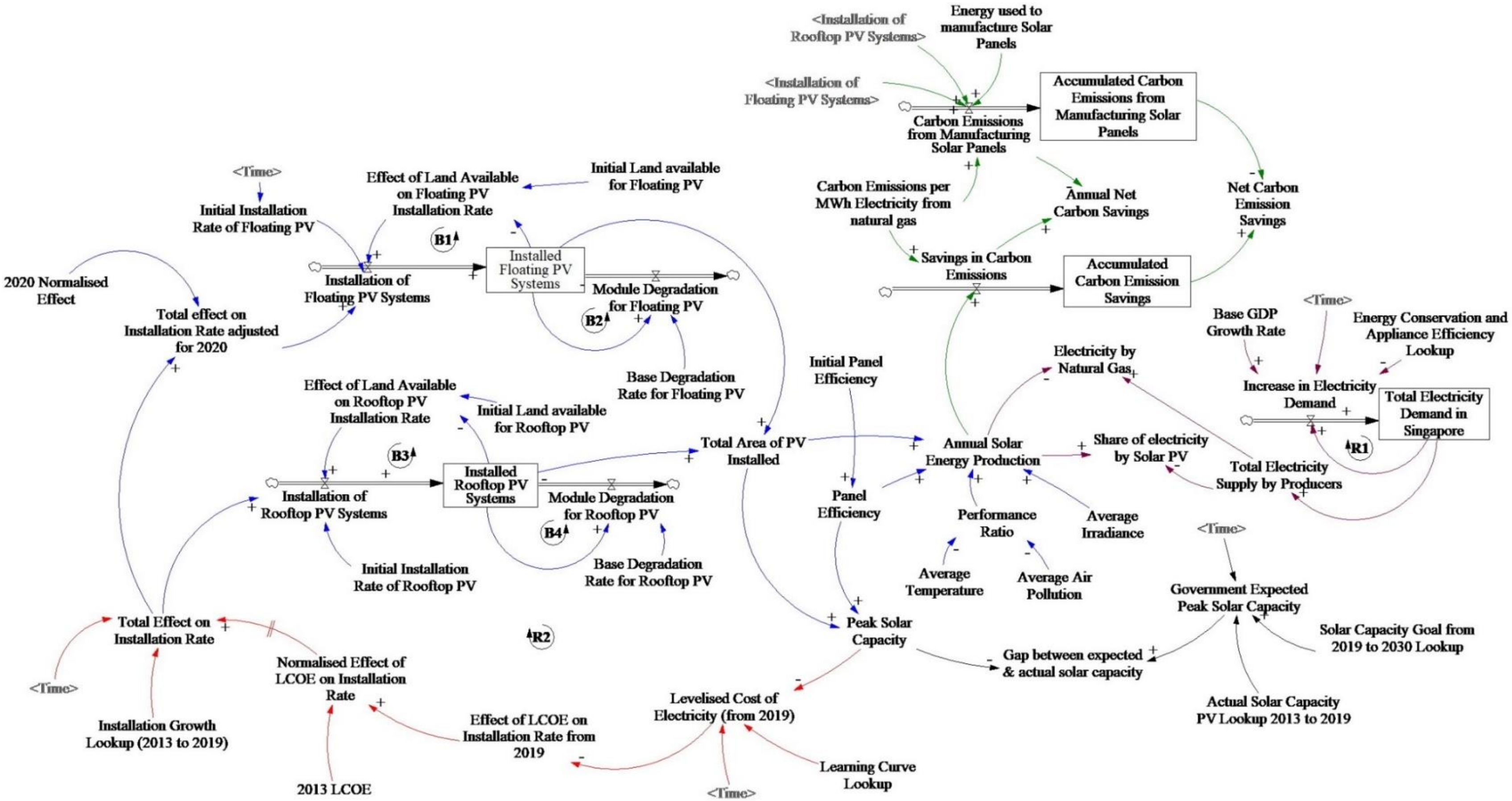



Figure 4: Stock and Flow Diagram

### 3.5.1 Installation of PV Panels Subsystem

Expanding upon the CLD, this subsystem focuses on the variables involved with the installation of PV panels. The stocks involved in this subsystem are the installed areas for rooftop PV panels and floating PV panels, which accumulate based on their respective installation rates and have an outflow based on module degradation. The installation rate inflows are dependent on the effect from LCOE as well as the effect from the remaining available land for solar panels. As mentioned in section 3.3.1, there are balancing feedback loops involving the stock of installed area of PV panels, their respective land available for PV panels, and the module degradation rate – denoted by B1, B2, B3 and B4. (Figure 5).

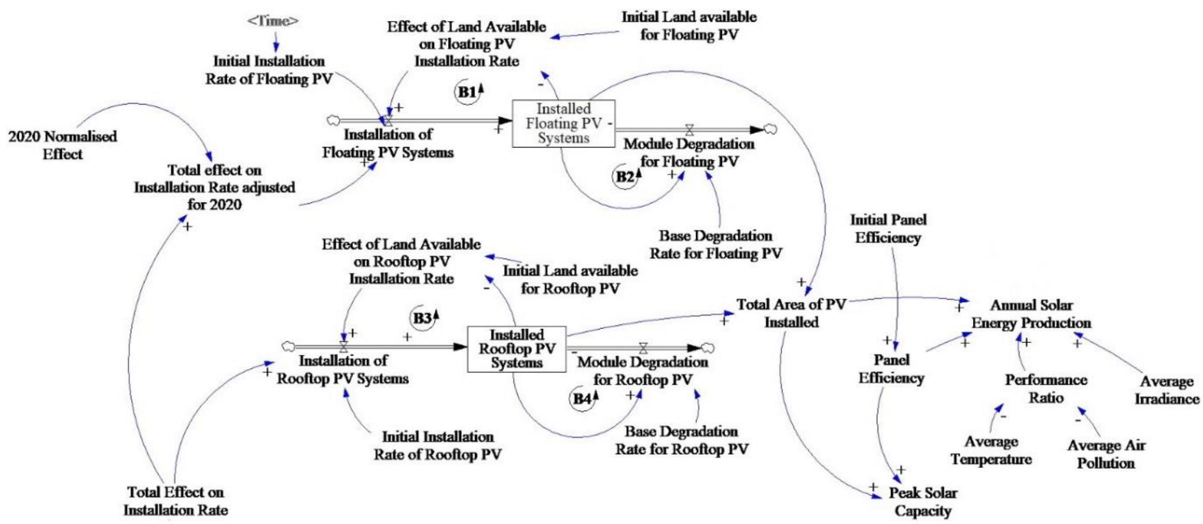



Figure 5: Installation of PV Panels Subsystem

### 3.5.2 Cost of Solar Energy Subsystem

The causal relationships among peak solar capacity, LCOE and its effect on the installation rate have been expanded upon, as shown in the cost of solar energy subsystem (Figure 6). To quantify the inverse relationship between higher cumulative solar capacity and decreasing LCOE due to Swanson's Law, the effect of LCOE on installation rate is equal to 1 / LCOE, which is then normalized to 1. Furthermore, to account for the assumption that installations of floating PV panels begins in 2020, the total effect on installation rate is normalized to 1 once again (Figure 5). For the years 2013 to 2019 this model references EMA statistics for the effect on installation rate. After 2019, the total effect is dependent on LCOE and Swanson's law.

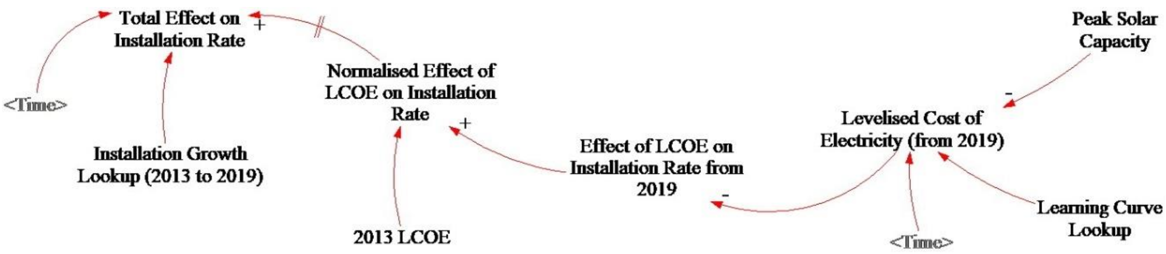



Figure 6: Cost of Solar Energy Subsystem

### 3.5.3 Carbon Emission Savings Subsystem

For the carbon emission savings subsystem, there are two key stocks – the accumulated carbon emission savings and the accumulated carbon emissions from manufacturing solar panels (Figure 7). The manufacturing process of solar panels requires energy of which most of it is derived from fossil fuels [27]. The annual gain in carbon emissions due to manufacturing solar panels is computed by multiplying the annual installation rate of PV panels by the energy used to manufacture a unit area of solar panel and the carbon emissions per unit of energy from natural gas. Meanwhile, the annual savings in carbon emissions is computed by multiplying the annual solar energy production by the carbon emissions produced by an energy-equivalent amount of natural gas. Thus, the net cumulative carbon savings as well as the annual net carbon savings can be calculated from these stocks and flows.

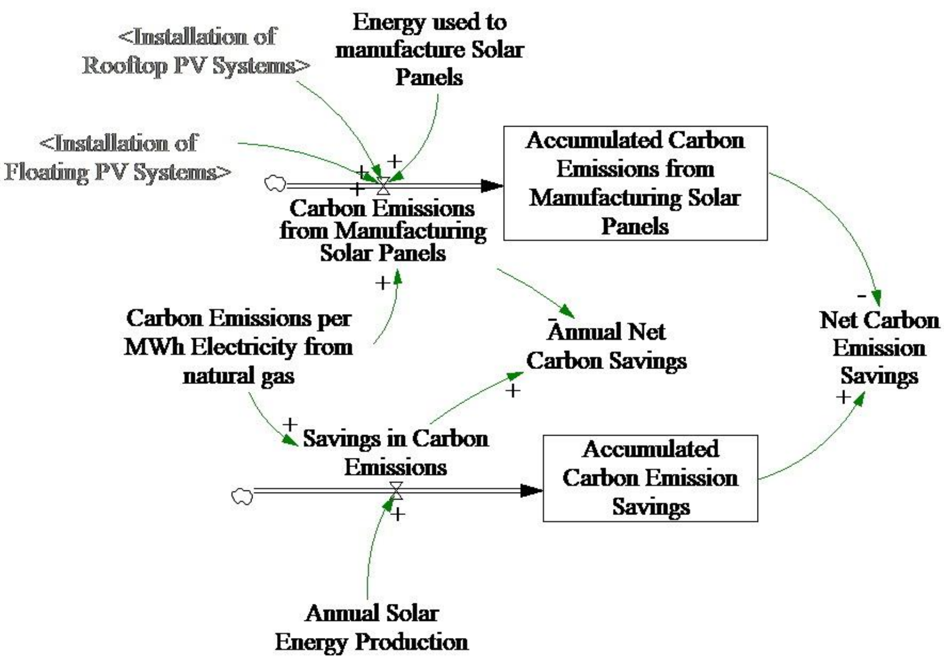



Figure 7: Carbon Emission Savings Subsystem

### 3.5.4 Energy Demand Subsystem

Lastly, the energy demand subsystem has the total electricity demand as its key stock (Figure 8). As described in section 3.3.4, total energy demand is dependent on GDP growth rate. An additional lookup is included to simulate improving energy conservation efforts as well as higher efficiency of industrial applications. The inflow - increase in energy demand - is equal to the percentage GDP growth multiplied by the current total electricity demand. This interdependent relationship leads to a reinforcing feedback loop denoted by R1, where an increase in electricity causes total electricity demand to increase and vice versa. Assuming that the electricity supplied is equal to the quantity demanded, then the share of electricity by solar PV in Singapore can be calculated by dividing the annual solar energy production by the total electricity supplied.

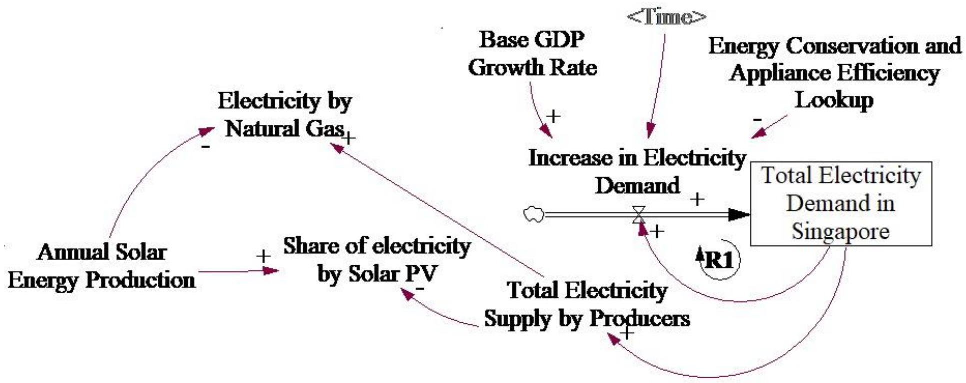



Figure 8: Energy Demand Subsystem

## 4. Results and Discussion

### 4.1 Base Run Simulation

After quantification of the system variables has been completed, simulations were conducted in the software Vensim. The following results are shown:

#### 4.1.1 Peak Solar Capacity vs Government Expected Peak Capacity

Results show that Singapore's peak solar capacity grows exponentially in the early years from 2013 to around 2025 (Figure 9). However, the rate of growth slows past 2025, due to the balancing effect from the decreasing land area available for solar panels. This affirms the dynamic hypothesis in Figure 3.

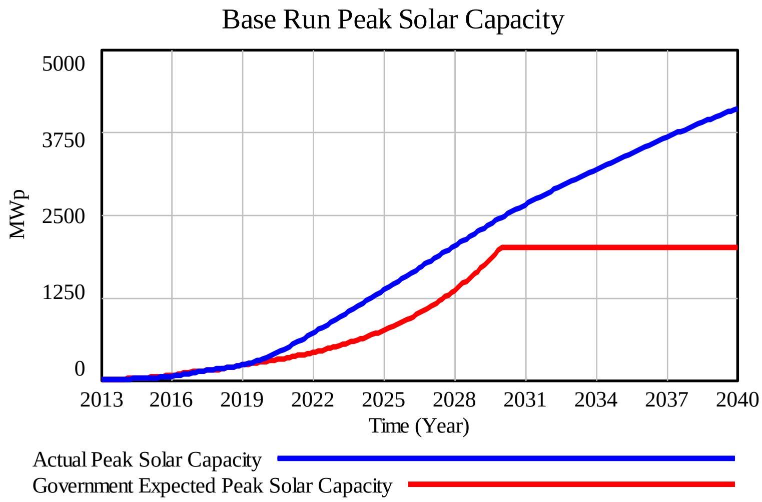



Figure 9: Growth of Peak Solar Capacity

This base model shows that Singapore meets its solar capacity goal, reaching 2GWp by 2028. This is realistic, as it is unlikely for the government to set unrealistic goals without devoting significant resources towards them. Thus, the Singapore government does not require to inject subsidies or introduce new policies to meet their 2030 solar capacity target.

### 4.1.2 Share of Solar Energy in the National Grid

From 2013 to 2040, the share of solar energy in Singapore's electricity generation has a similar trend to the peak solar capacity (Figure 10). As solar capacity increases exponentially, the area available for more solar panels decreases and there is a goal-seeking behaviour limiting the installation rate of solar panels. The balancing effects of module degradation and less area available for solar panels, combined with the increasing total electricity demand, cause the share of electricity to grow slower, reaching 3.9% in 2030 and 5.1% in 2040. This trend is in line with the dynamic hypothesis in Figure 3.

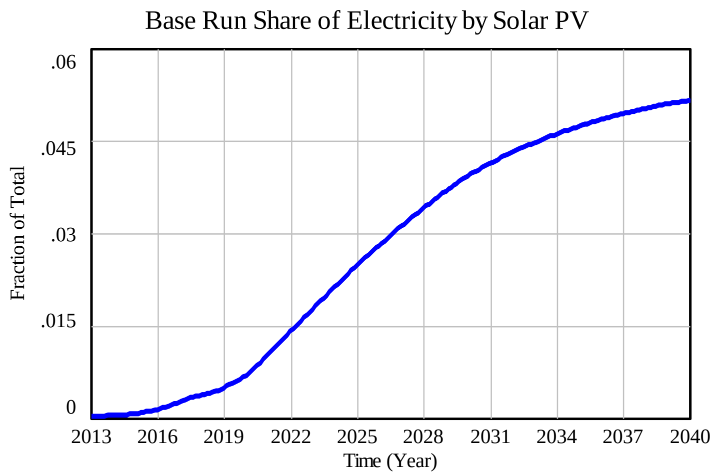



Figure 10: Share of Solar Energy in Singapore's Generation Mix

### 4.1.3 Net Carbon Emission Savings

The cumulative carbon emissions savings is computed by multiplying the annual solar energy production by the emissions produced if the equivalent energy is produced by burning natural gas. The net carbon emission savings is computed by subtracting the cumulative carbon emissions from producing, distributing, and running PV systems from the previous total (Figure 11). The results show that the net savings is approximately ~21 million tonnes. Note that net carbon savings is initially negative as manufacturing solar panels causes carbon emissions and it takes around 5 years (2018) for the net savings to be positive (Figure 11). This affirms the dynamic hypothesis in Figure 3.

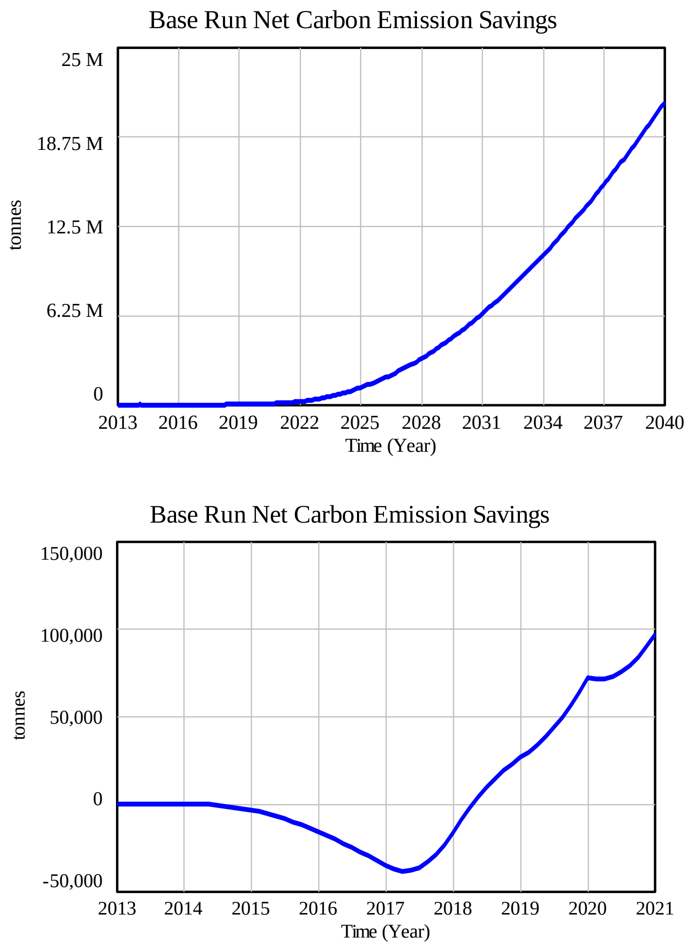



Figure 11: Net Carbon Emission Savings (Top: 2013 to 2040, Bottom: 2013 to 2022)

## 4.2 Model Validation

The results above cannot be reliably analysed without prior validation of the model. System dynamics models ought to be structurally validated such that the causal relationships in the model are appropriate. Furthermore, models ought to be behaviourally validated, whereby the simulation results are reasonable and realistic [31]. Prior to these simulations, structural flaws in the system variables have been identified and removed accordingly. Thus, the structural integrity of the model has been validated. The peak solar capacity simulated from the model matches the historical solar capacity in Singapore from 2013 to 2019 [4], as seen from Figure 9. Furthermore, according to projections made by SERIS, the share of solar energy in the national grid is projected to be between ~2-6% in 2030 and ~3.5-8% in 2040, while carbon emission savings are projected to reach ~0.5-1.4 and ~0.8-2.1 million tonnes per annum in 2030 and 2040 respectively [14] (p. 19-20). The results from this model supports these projections, as the share of solar energy reaches 3.9% in 2030 and 5.1% in 2040 (Figure 10), whereas annual net carbon emission savings reaches 1.1 million tonnes per annum in 2030 and 2 million tonnes per annum in 2040 (Figure 12). Thus, apart from being structurally validated, the model presented in this project is sufficiently validated in behavioural terms as well.

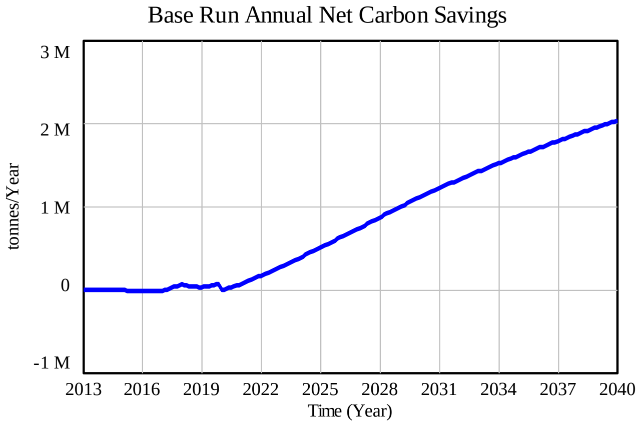



Figure 12: Annual Carbon Emission Savings

### 4.3 Policy Analysis

The base model of this project has produced simulation results which show that Singapore will meet its 2030 solar capacity goal of 2GWp. However, it is likely that the government will introduce a new goal for the years after, i.e. 2040, in order to further increase the country's environmental sustainability as well as improve the country's energy security. In this sensitivity analysis, it is assumed that the government sets a new solar capacity goal in 2030 – to reach 8% share of the total electricity generation by 2040. From Figure 10, the share of solar electricity grows up to 5.1% in the base model, which is below expectations. Thus, policies must be introduced to boost solar capacity growth, such that the target of 8% share is achieved.

While formulating potential policies to improve the share of solar energy's contribution to the grid, it is important to consider the leverage point in which the policy is affecting the system [32]. Leverage points are places in a system where a solution or policy can be applied to affect the system's outcomes. Proposed by Donella Meadows, there are 12 main leverage points to intervene in a system ranging from lower level interventions where constant values of system variables are changed to higher level, abstract leverage points such as adjusting the goals of the system or paradigm of thought. Policies which have a higher degree of leverage on the system have a bigger impact on the system's behaviour and are thus more effective at addressing systematic problems.

### 4.3.1 Policy A: Area and Utilisation Factor for PV Installations

The initial land area available for solar panels is a net area estimated provided by SERIS, computed by multiplying the gross area available by a utilisation factor [13] (p. 32). This is a conservative estimate, and this policy assumes that gross area increases by an additional 20km$^2$ from the years 2020-2040, due to new buildings built over the years and increased available building area from building-integrated PV (BIPV). Furthermore, the utilisation factor of rooftop area and reservoir area is ramped up as the Housing Development Board and private developers make use of these spaces for solar panels more efficiently (Figure 13). This policy causes a minor increase in solar energy's share in the grid, increasing from 5.1% in the base model to 5.84% in 2040, while net carbon emission savings by 2040 increased from 21 to 22 million tonnes (Figure 14). The marginal results of policy A could be attributed to the lower level of leverage on the system, as only constant values of the system's variables have been changed.

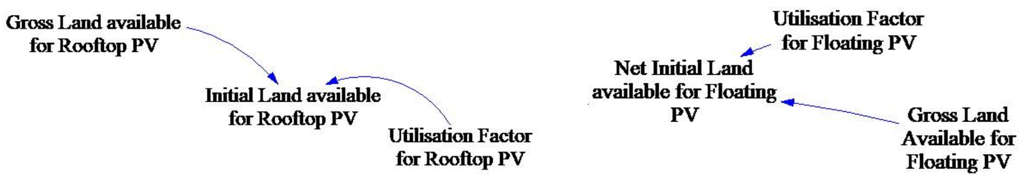



Figure 13: Gross Land Available and Utilisation Factor

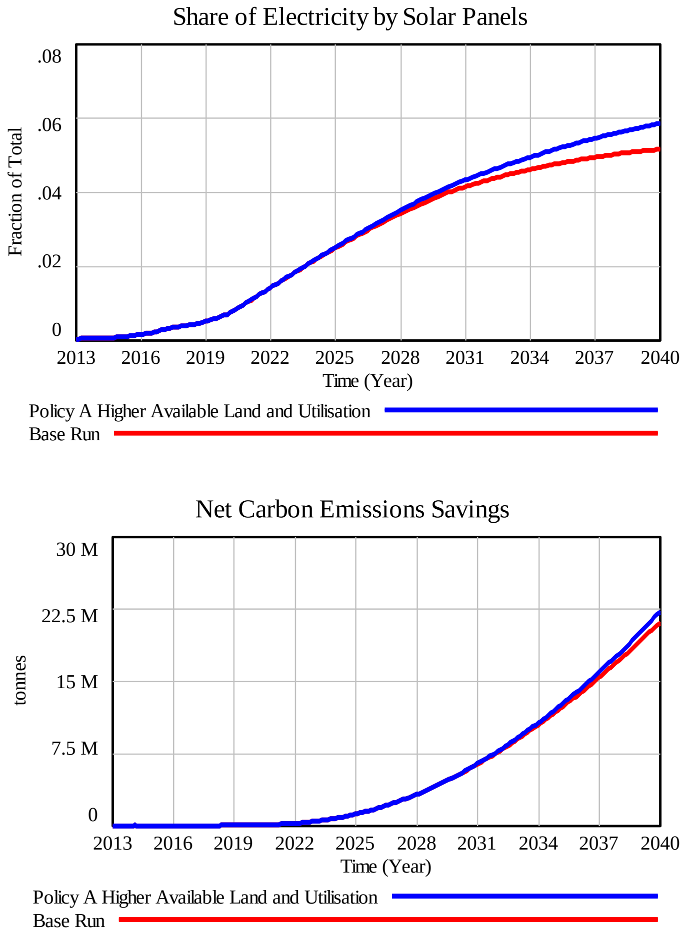



Figure 14: Policy A Effects (Top: Share of Electricity; bottom: Carbon Emission Savings)

### 4.3.2 Policy B: Panel Efficiency and Subsidies

In addition, subsidies could be introduced to reduce the LCOE. The percentage of subsidy is determined by the gap between the actual and expected solar capacity, divided by the expected solar capacity (Figure 15). For example, if the gap is 40% of the total expected solar capacity, then the LCOE for solar energy producers would be reduced by 40%. This causes a balancing feedback loop – when the gap increases, the subsidies are increased, causing LCOE to decrease and installation rate to increase. As installation rates increase, solar capacity increases and the gap is reduced. This introduction of a balancing loop which stabilizes peak solar capacity towards the expected value acts on the system from a higher leverage point, where the "rules of the system" have been changed as incentives are introduced and the "goals of the system" are adjusted to align the actual solar capacity with the government's goals [32].

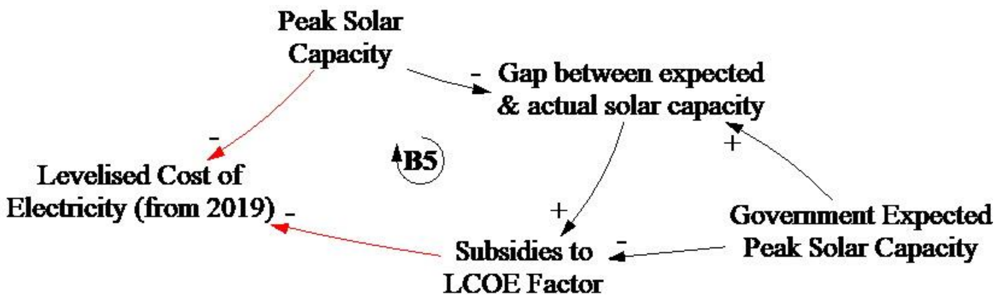
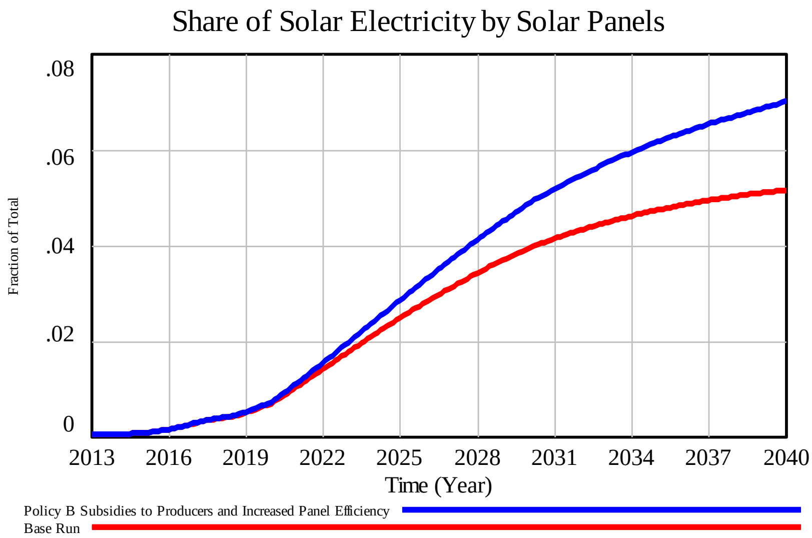



Figure 15: Introduction of a Subsidy Factor into the Model

In addition, the conversion efficiency of solar panels is increased. In the base model, solar efficiency was ramped from 18% in 2013, up to 23% in 2020, and 25% in 2030. Assuming that global developments in solar panel technology accelerate, commercial conversion efficiencies are expected to grow to 24% in 2020, 30% in 2030, and 32.5% by 2040 (an average between 30% in 2030 and 35% in 2050) [13] (p. 20).

Policy B results in a significant increase in the share of solar energy in Singapore's grid, from 5.1% to 7% (Figure 16). Furthermore, the savings in carbon emissions also increase significantly, from 21 to 27.5 million tonnes (Figure 16). However, policy B alone is insufficient to raise the share of solar energy to 8%.



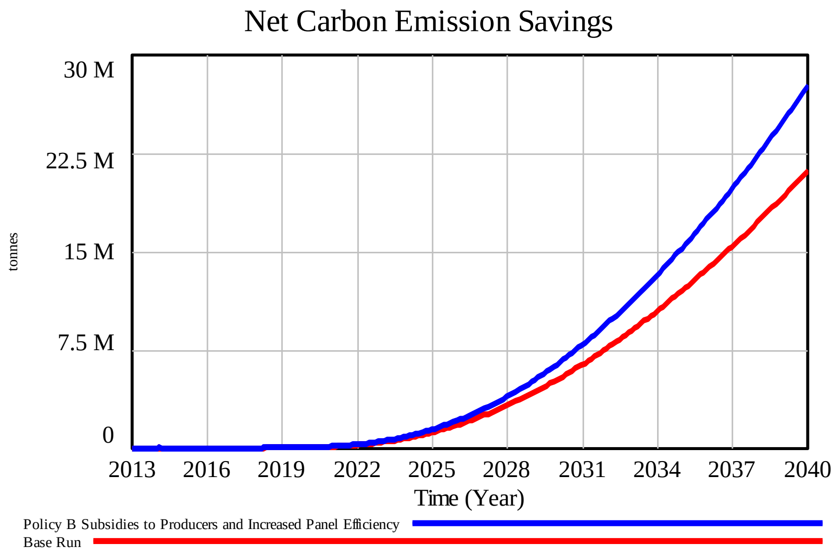
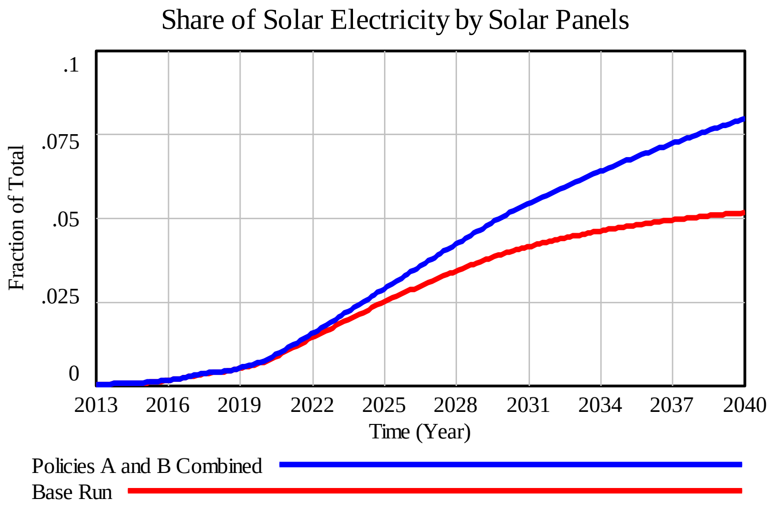




Figure 16: Policy B Effects (Top: Share of Electricity; bottom: Carbon Emission Savings)

### 4.3.3 Combination of Policy A and B

If both policies A and B are introduced, the combined effect of these policies would raise solar energy's share of Singapore's electricity generation mix to 7.95%, in line with the new target of 8% (Figure 17). Moreover, the net carbon emission savings would rise to 29.1 million tonnes from 21 million tonnes in the base model (Figure 17). Therefore, a combination of policies is required to raise solar capacity in Singapore and carbon emission savings meaningfully.



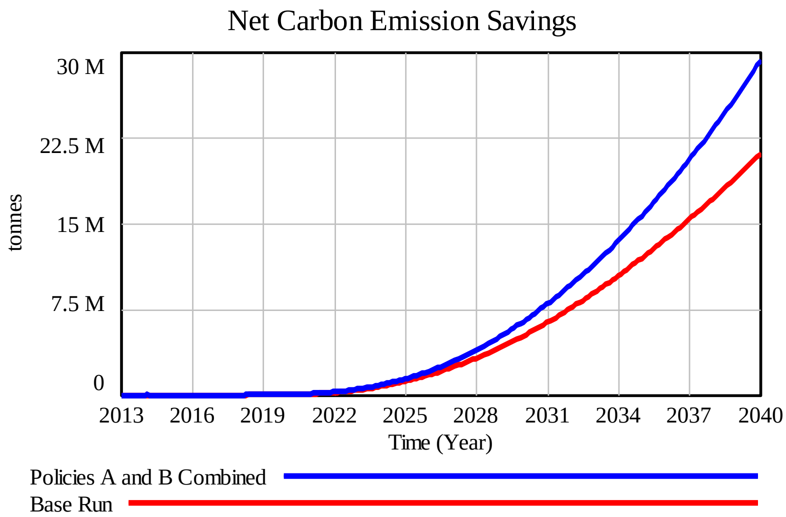




Figure 17: Combined Policy Effects

(Top: Share of electricity; bottom: Carbon Emission Savings)

## 5. Conclusion

In conclusion, this model shows that Singapore is sufficiently prepared to meet its solar capacity target of 2GWp by 2030. Although diversifying into solar energy would reduce Singapore's dependence on imported natural gas, this reduction is small as the share of solar energy in the country's generation mix reaches just 3.9% in 2030 and 5.1% in 2040. Pushing solar energy's relevance in Singapore further is a difficult task due to the scarcity of land available, and the SESI would improve marginally at best from this push towards solar energy. Thus, to further increase Singapore's energy security and environmental sustainability, a multitude of policies such as the ones mentioned in this report have to be considered. Nevertheless, Singapore stands to gain from 21 million tonnes of avoided carbon emissions, which may further increase should policies promoting installations of solar panels be introduced.

## 6. Acknowledgements

This project and report would not have been made possible without the supervision of Dr Bellam Sreenivasulu; whose guidance has proven invaluable throughout this semester. Our discussions spurred the development of this system dynamics model and I have learnt much from them. I would also like to thank Residential College 4 (part of the National University of Singapore), for giving me this opportunity to embark on this project in system dynamics. During this academic year, my experience with systems thinking and system dynamics in this college has taught me how to approach as well as model complex systems in society, a skill which I will continue to apply in the future.

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# 8. Appendix

## 8.1 Short-term Solar Production Forecasting Model

**Table 7**
Power conversion guidelines and execution steps for a PV system in a tropical environment, taking low wind influence into account.

| Step | Formula | Recipe | Remark |
|---|---|---|---|
| 1 | Perez model | Generate $G_{mod}$ values based on global horizontal irradiance readings | As demonstrated in (Yang, Dong et al., 2013, Khoo, Nobre et al., 2014) Skip step 1 if $G_{mod}$ is known |
| 2 | $T_{mod} = T_{amb} + \gamma\, G_{mod}$ | Choose $\gamma = 0.032$ $Cm^2W^{-1}$ for metal and $\gamma = 0.025$ $Cm^2W^{-1}$ for concrete rooftops | Skip step 2 if $T_{mod}$ is known |
| 3 | $\eta_{mpp}(G_{mod},T_{mod}) = \eta_{mpp,25}(G_{mod})$ $[1 + \alpha\,(T_{mod}-25\,°C)]$ | Choose $\alpha = -0.0045$ $°C^{-1}$ for crystalline wafer-based systems | Adjust $\alpha$ based on known specification sheet of solar modules |
| 4 | $\eta_{mpp}(G_{mod},T_{mod}) = \eta_{mpp}(G_{mod},T_{mod})$ $*\,(sh)$ | Choose value of "shading coefficient" ($sh$) according to shading severity<br>Use $sh = 0.10$ for hard shade<br>Use $sh = 0.45$ for soft shade | Assessment in shading condition at specific times of the day/year to be considered |
| 5 | $\eta_{mpp}(G_{mod},T_{mod}) = \eta_{mpp}(G_{mod},T_{mod})$ $*\,(1 + deg)$ | Choose value of "degradation rate" ($deg$) according to system age<br>Use $deg = -1.2\%$ per annum for tilt angles < 10°<br>Use $deg = -0.8\%$ per annum for tilt angles > 10° | Special attention to be given in knowing the start performance baseline of a PV system |
| 6 | $\eta_{mpp}(G_{mod},T_{mod}) = \eta_{mpp}(G_{mod},T_{mod})$ $*\,(air)$ | Choose value of "air pollution" ($air$) according to condition at hand<br>$air = 0.80$ for PSI > 200<br>$air = 0.85$ for 150 < PSI < 200<br>$air = 0.90$ for 100 < PSI < 150<br>$air = 0.95$ for PSI > 70 | PSI = Pollutant Standards Index, air pollution metric for Singapore, see (Velasco and Roth 2012; Liu, Nobre et al., 2014) |

Figure A1. Forecasting model based on environmental variables [12]