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

Background and Problem Statement

- Singapore aims to increase its solar electricity capacity to 2 Gigawatt-peak by 2030, as part of its commitments to environmental sustainability.
- Main questions:
    1. Feasibility: Will Singapore be able to achieve this goal? If not, will incentives have to be introduced?
    2. Value: How much carbon emissions can be saved? To what extent can Singapore be self-sufficient on solar energy?

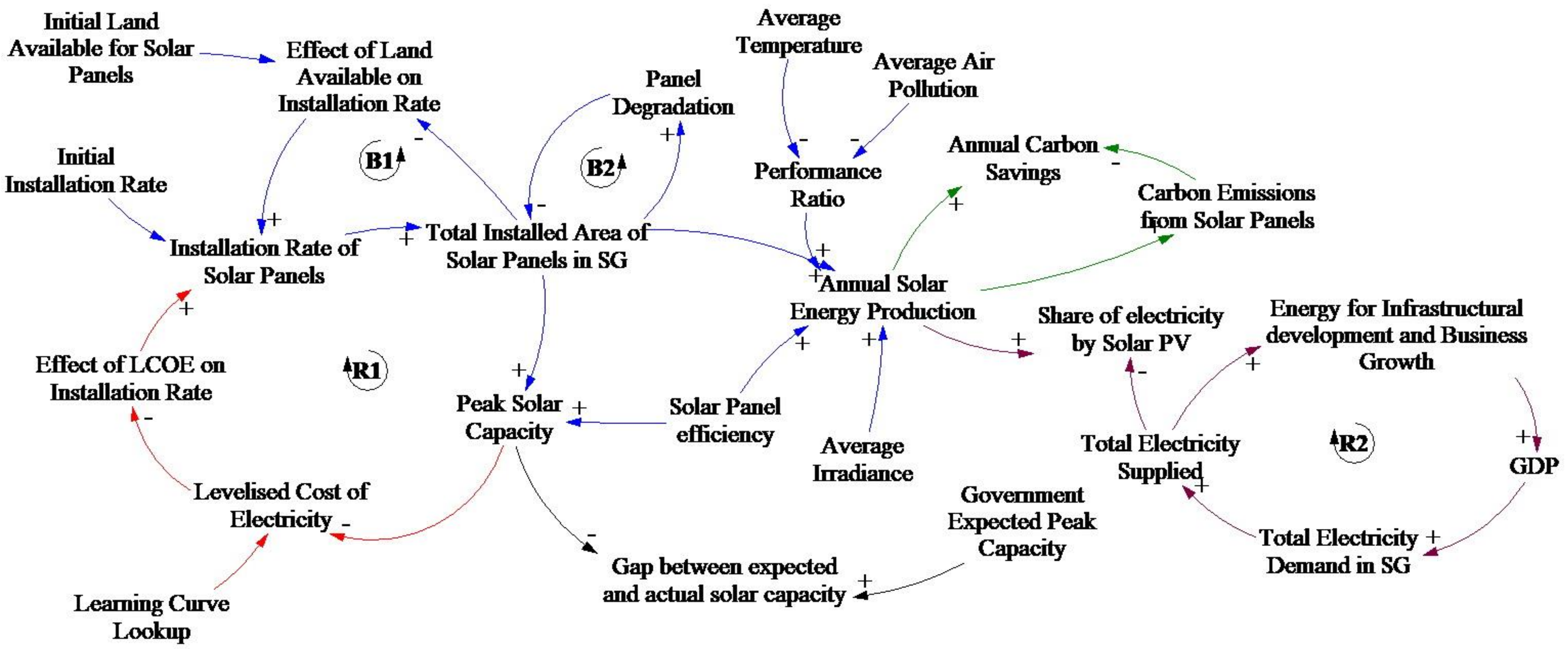
Methodology

Systems Thinking and System Dynamics are used to conceptualize the energy system in Singapore.

Reinforcing and balancing feedback loops contribute to the overall system effect.

Literature Review

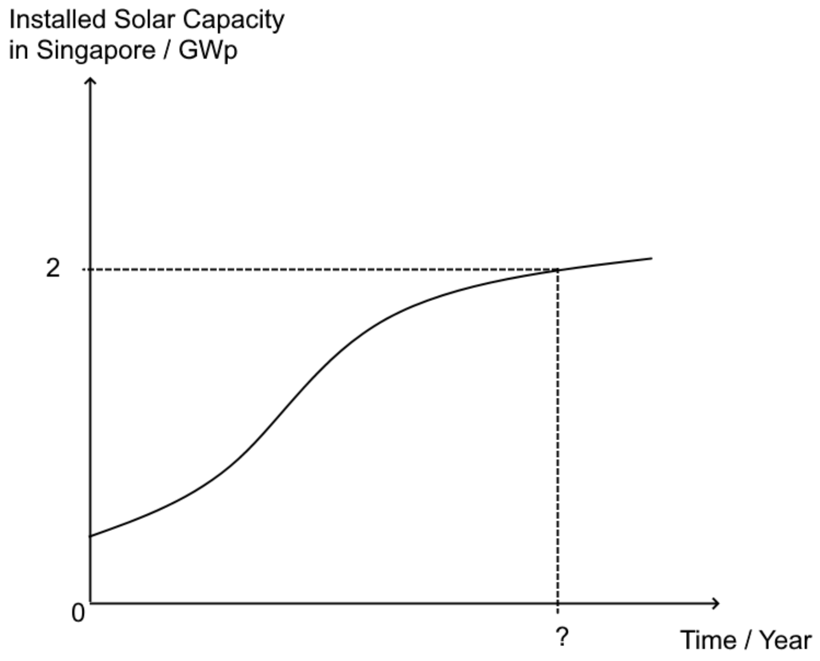
- Energy Market Authority – Statistics on historical solar capacity, energy demand, and grid emissions factor
- SERIS - Solar Photovoltaic (PV) Roadmap for Singapore – Available area for solar panels, projected panel efficiencies, and cost
- PV power conversion and short-term forecasting in a tropical, densely-built environment in Singapore (Nobre et. al, 2016) – Mathematical modelling of solar energy generation.

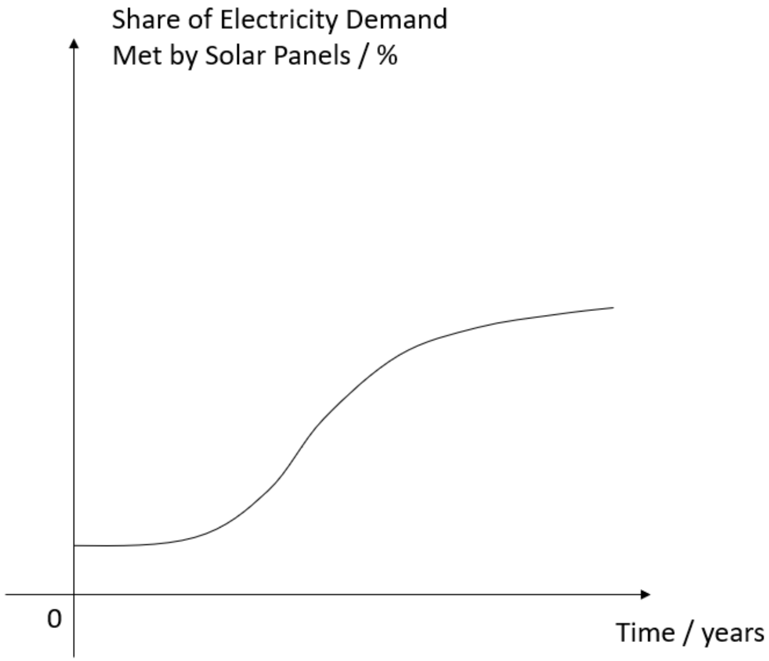


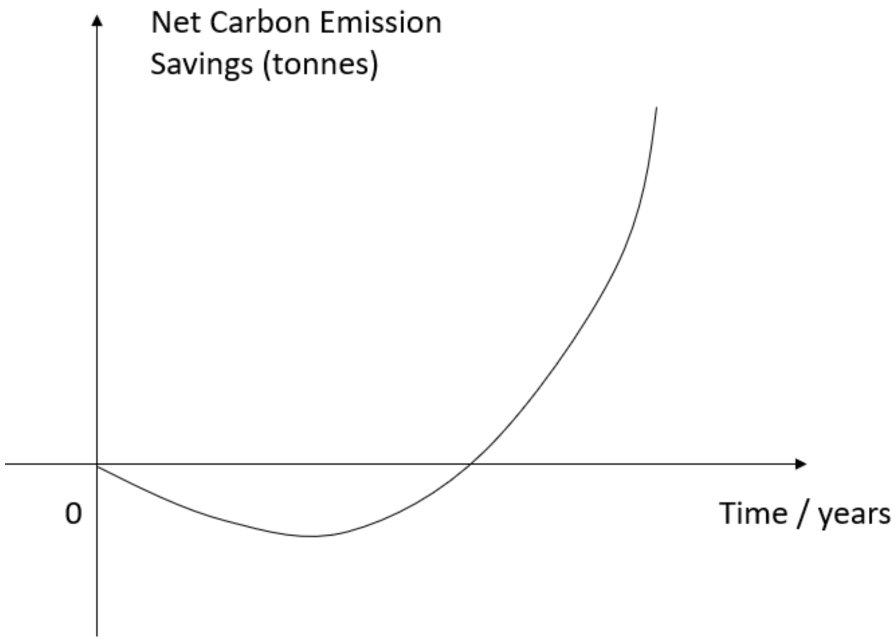
Causal Loop Diagram

Key Modelling Assumptions

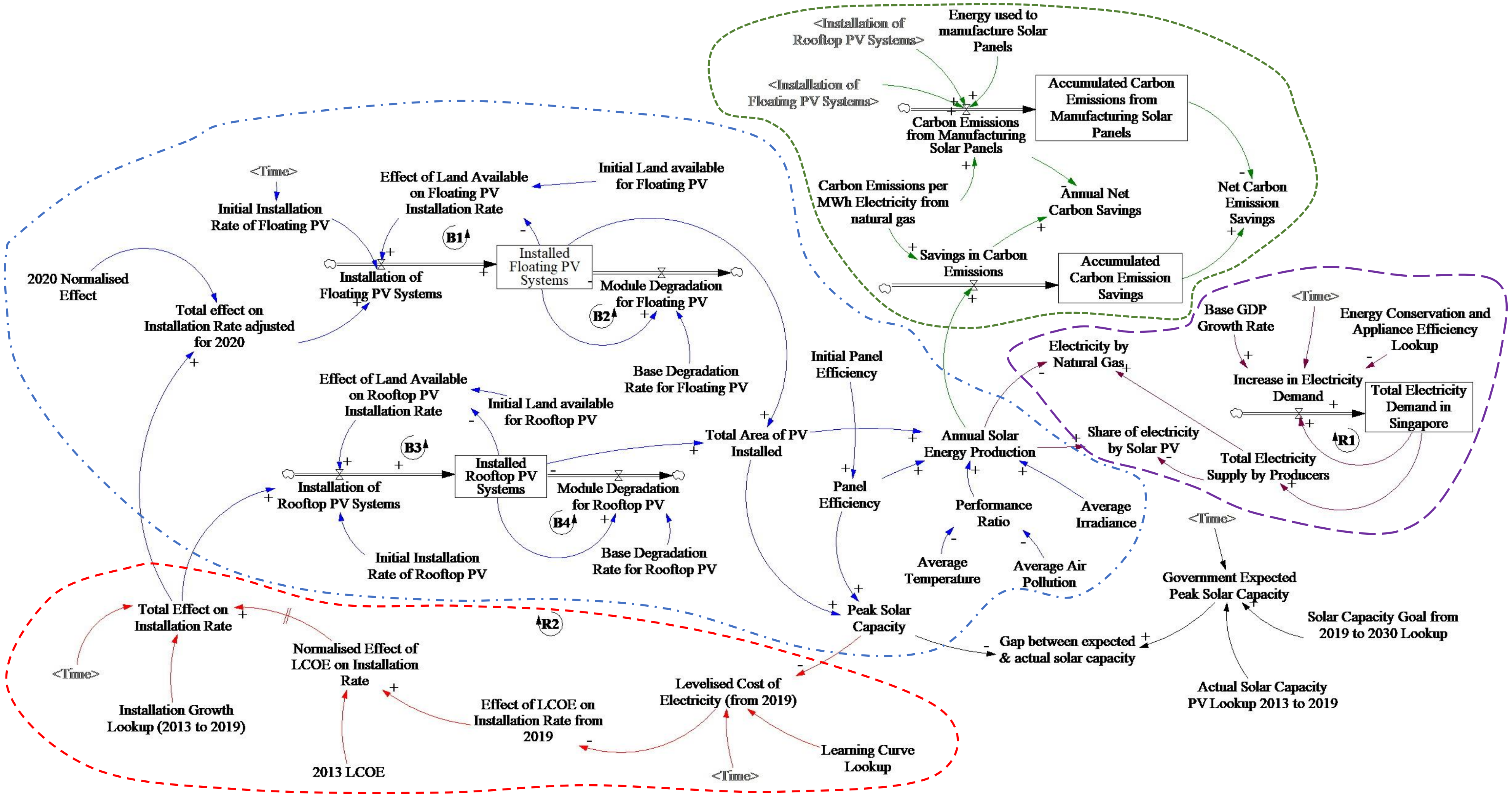
- Timeframe – 2013 to 2040
- Two types of Solar PV in Singapore: Rooftop, Floating
- Initial Land available for PV: $34km^2$ (Rooftop), $4km^2$ (Floating)
- Initial Installation Rates: $28889m^2$/year (Rooftop, 2013), 321300 m^2/year (Floating, 2020)
- Levelized Cost of Electricity: S$100/MWh in 2019.
- Grid Emissions intensity: 0.4388 tonnes CO2 per MWh
- Energy used to manufacture solar panels: 0.55774 MWh/m2



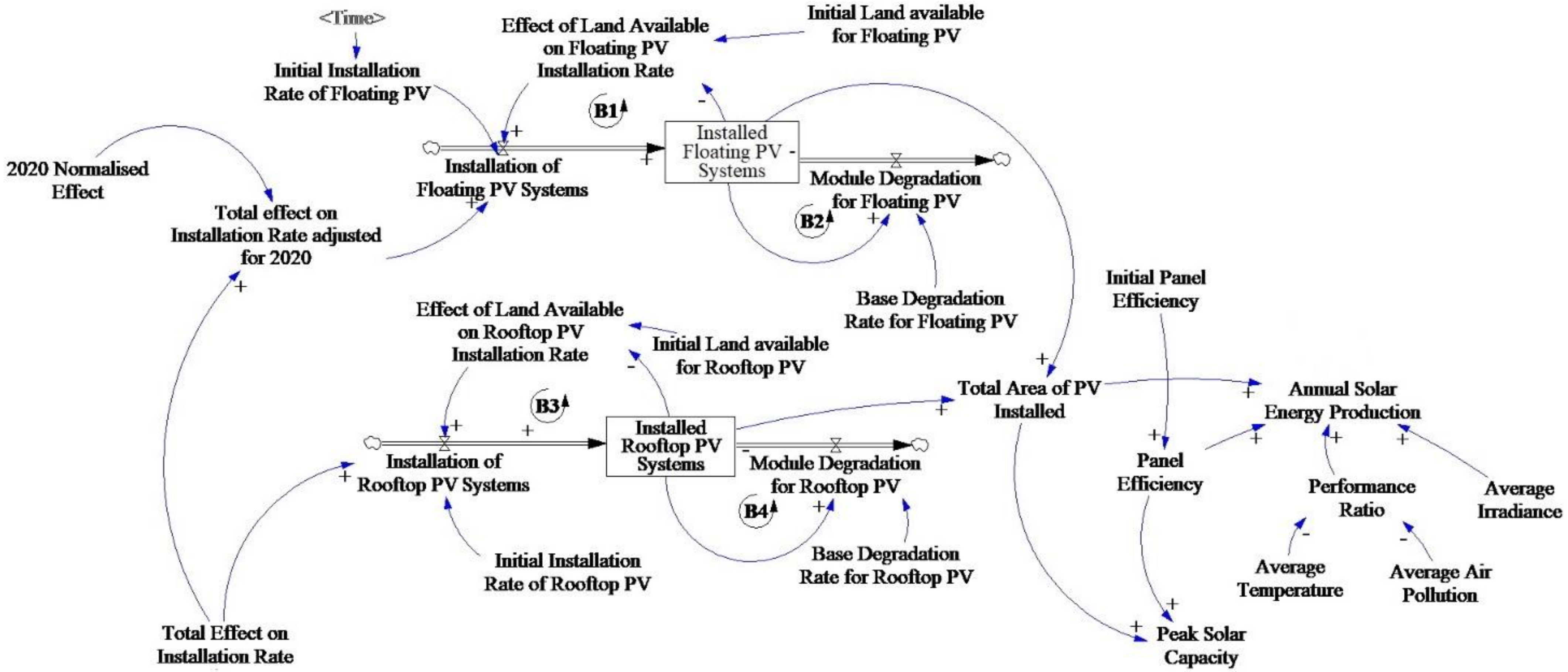




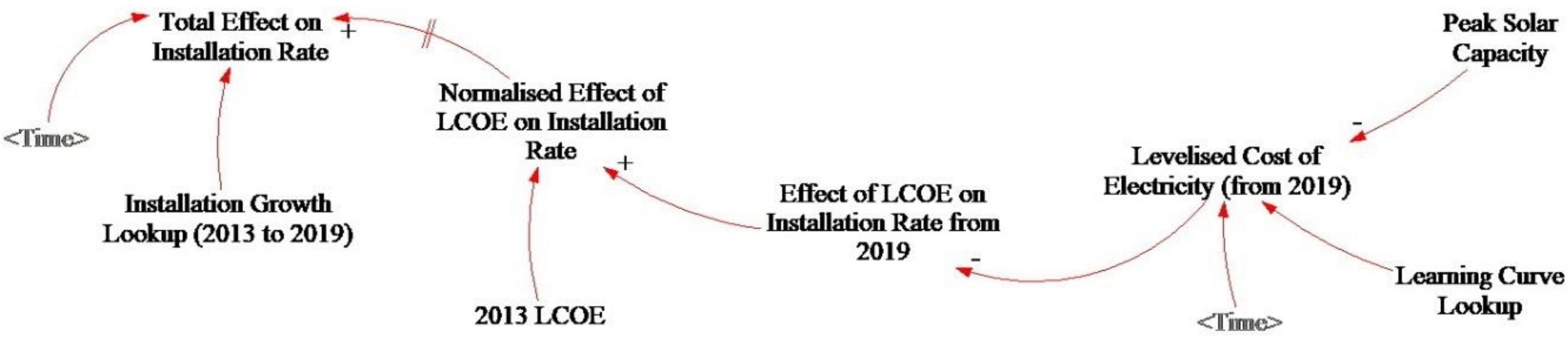
Dynamic Hypotheses



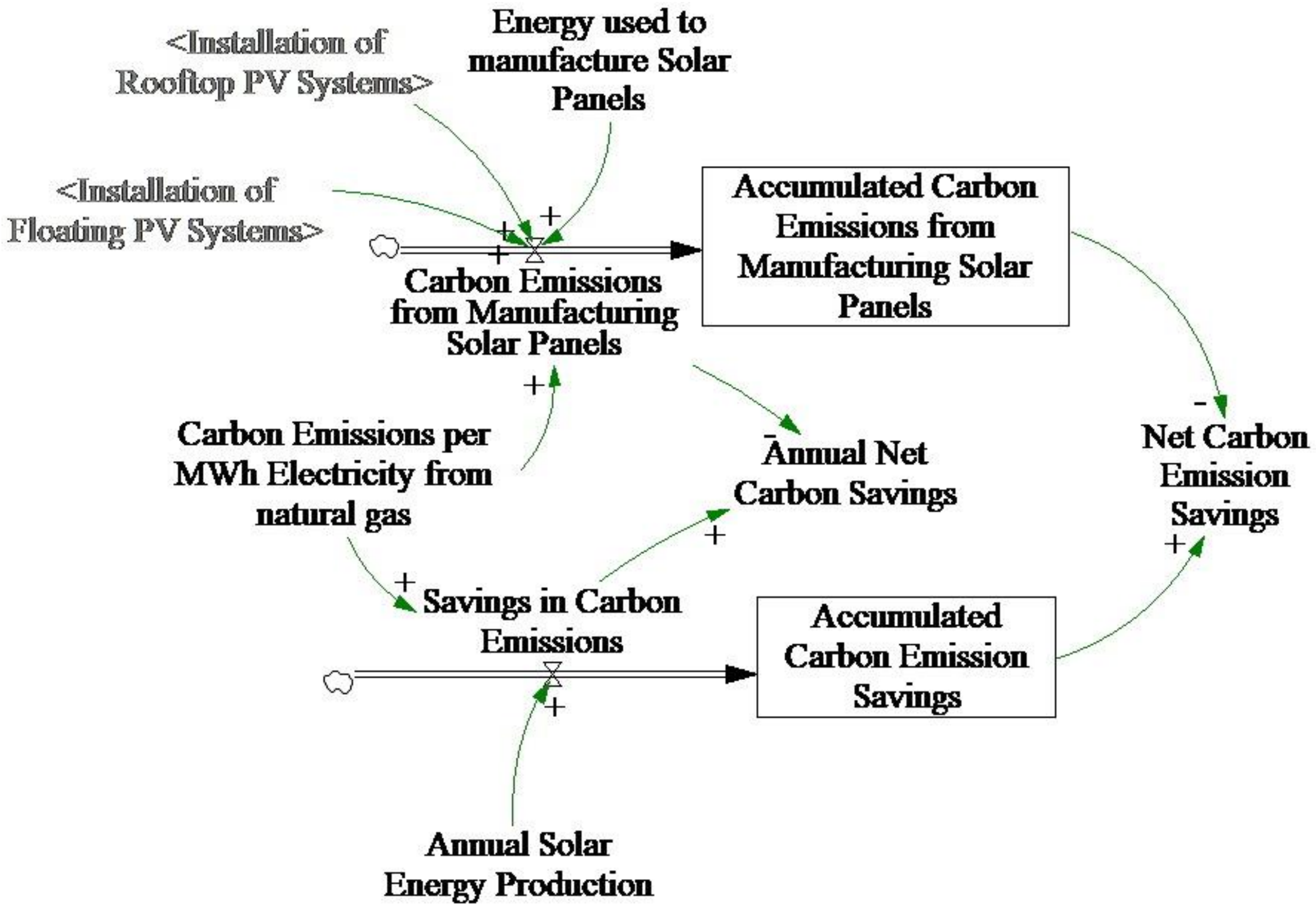
Stock and Flow Diagram



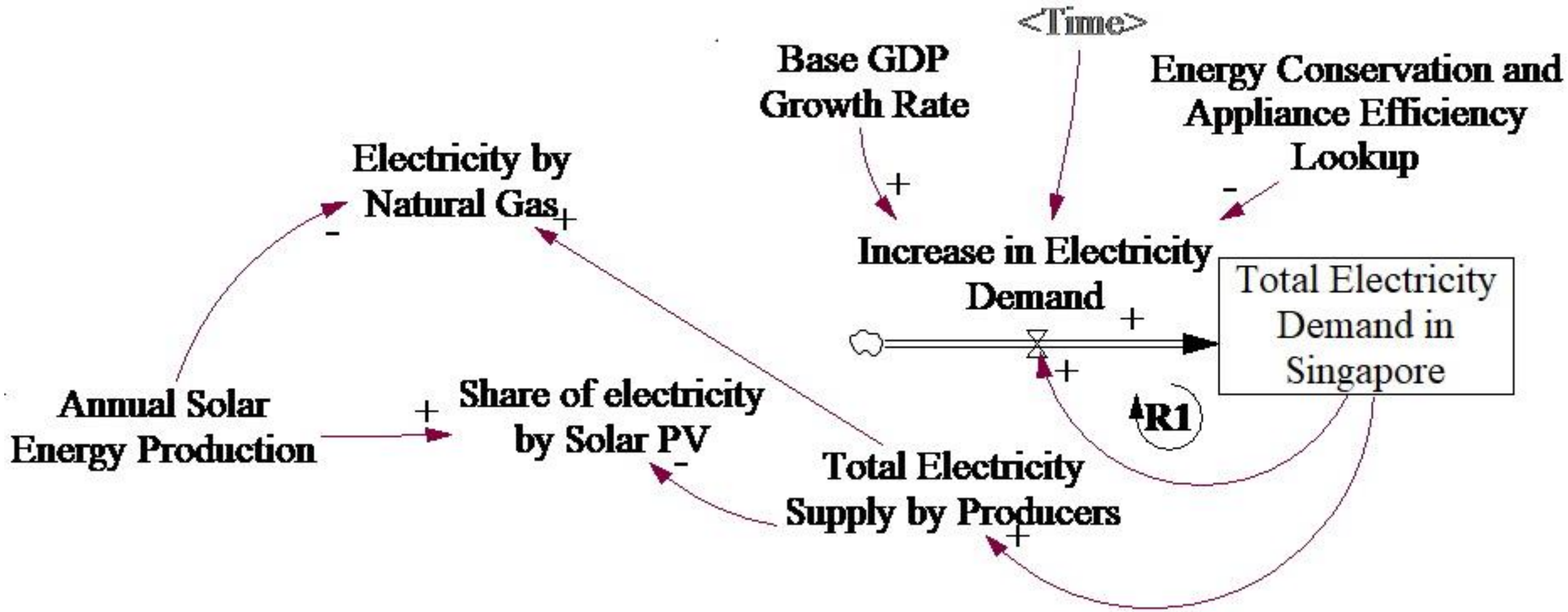
Installation of PV Panels Subsystem



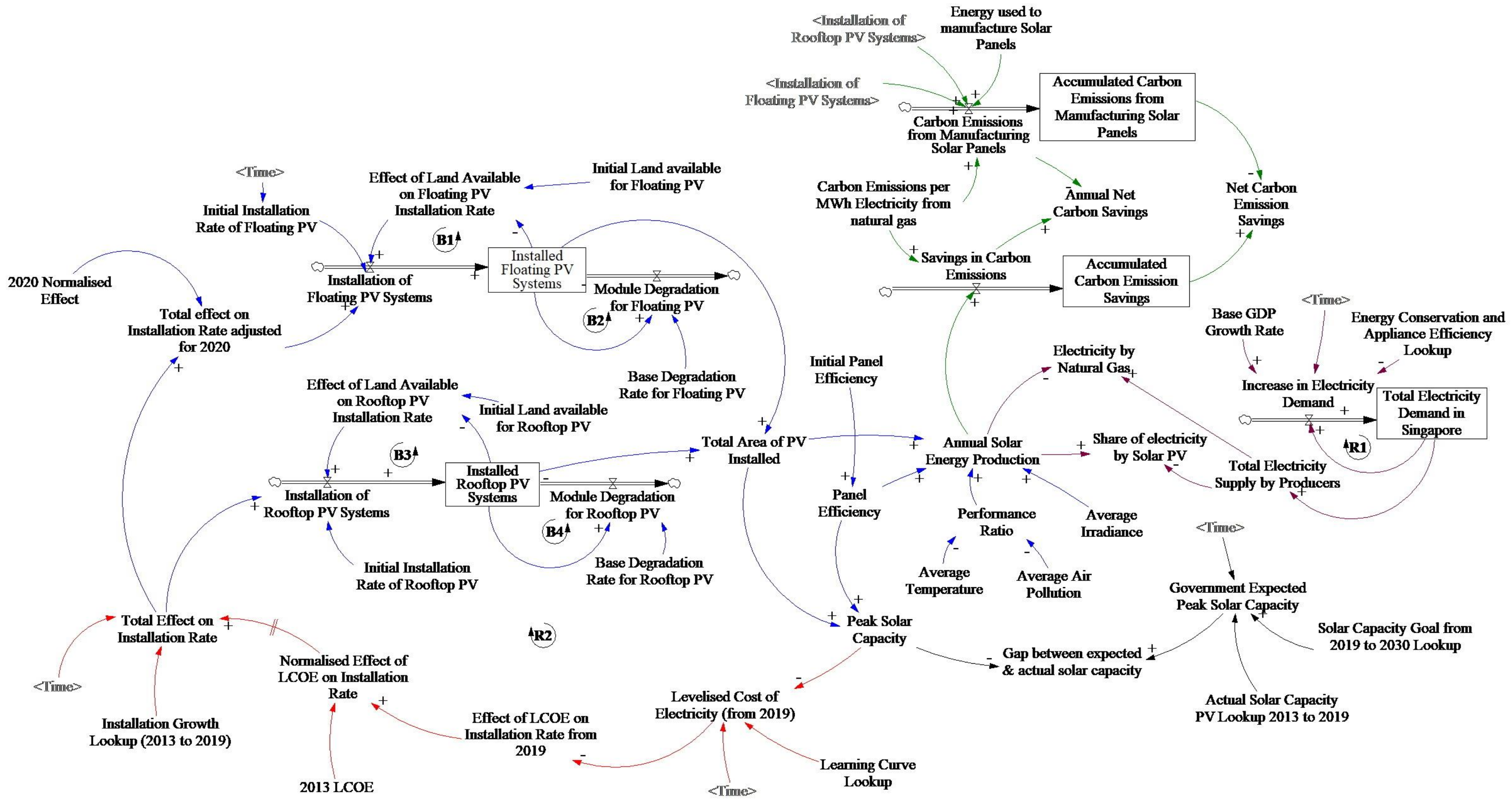
Cost of Solar Energy Subsystem



Carbon Emission Savings Subsystem



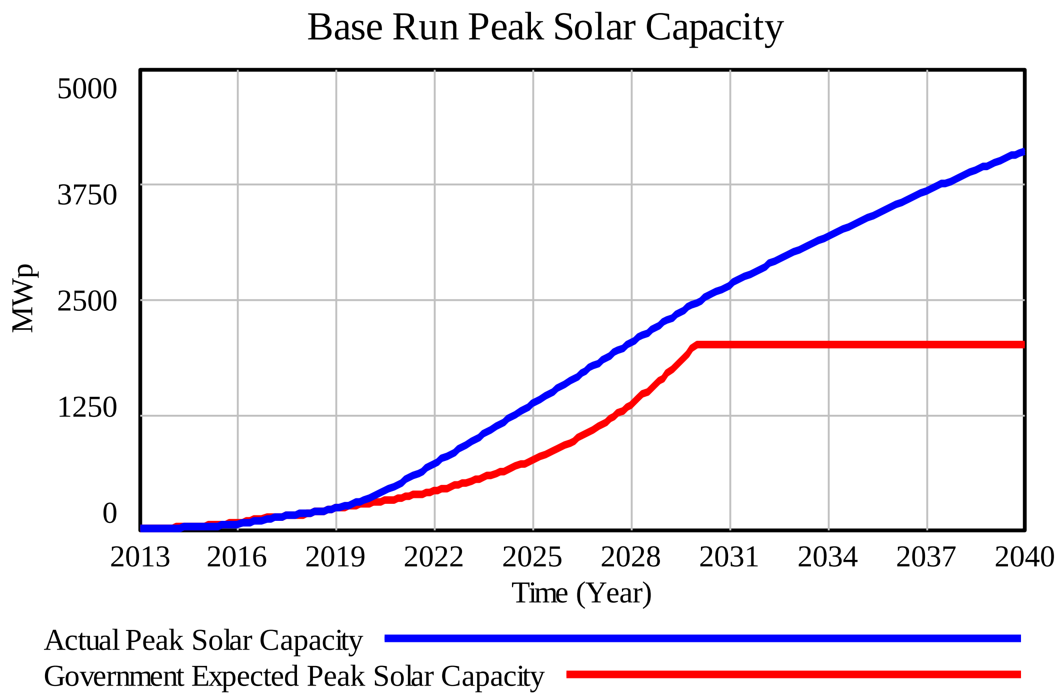
Energy Demand Subsystem



Stock and Flow Diagram

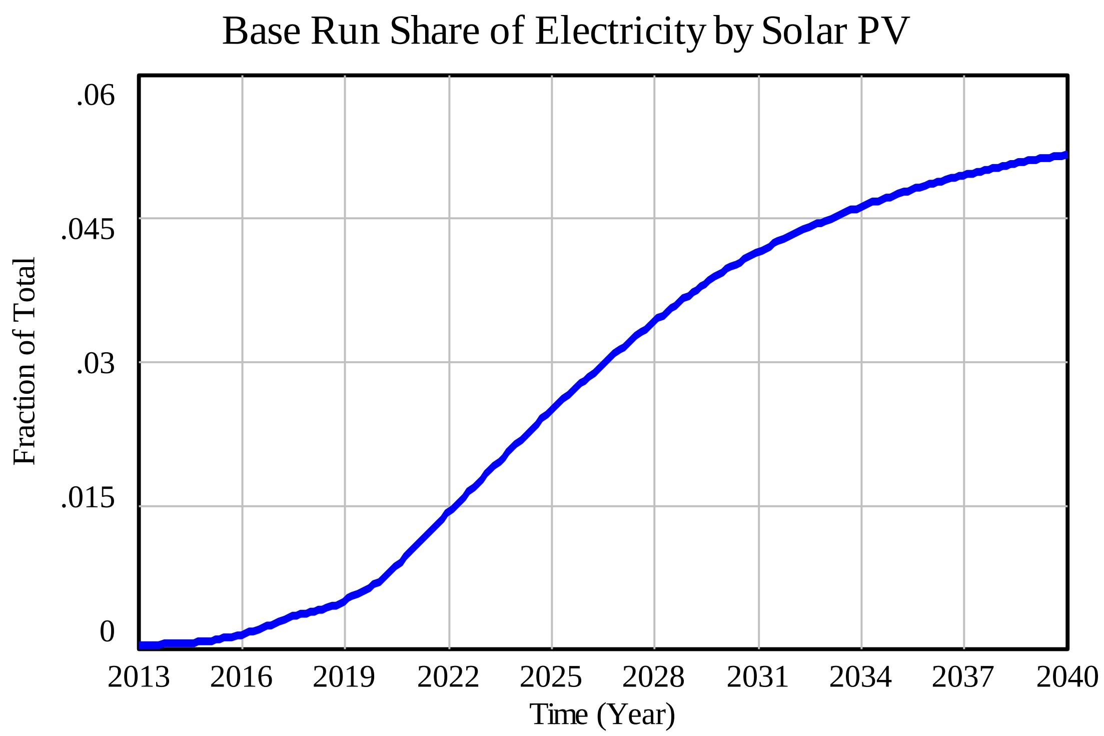
Simulation Results - Solar Capacity

- Exponential growth of solar capacity in the early years from 2013 to around 2025.
- The rate of growth slows past 2025, due to the balancing effect from the decreasing land area available for solar panels.
- Base model shows that Singapore meets its solar capacity goal, reaching 2GWp by 2028.



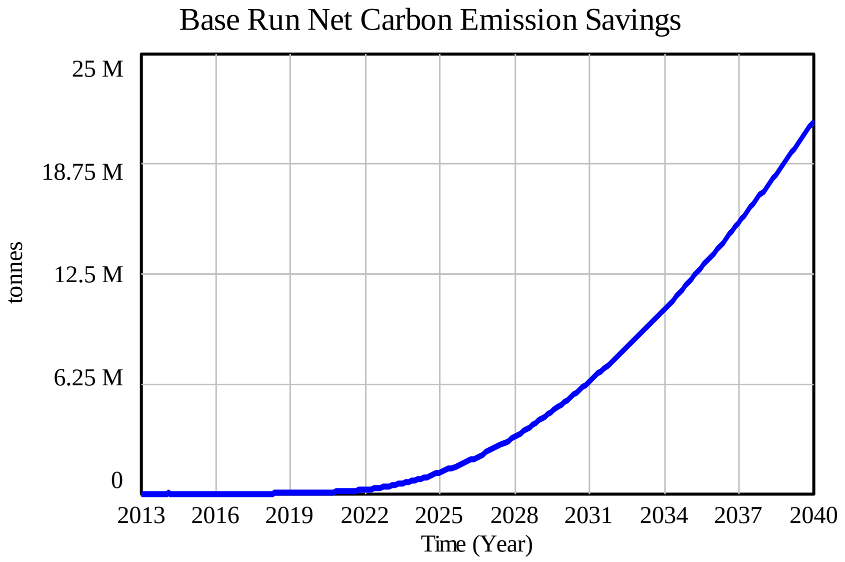
Simulation Results - Share of Solar Energy in the National Grid

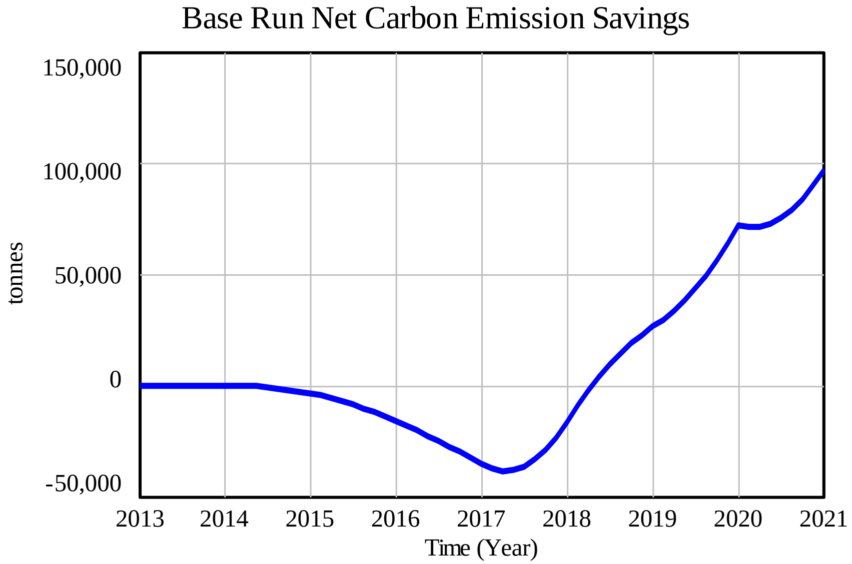
- Similar trend to peak solar capacity. The share of electricity reaches 3.9% in 2030 and 5.1% in 2040.
- Affirms dynamic hypothesis, but it is uncertain whether this share will drop in subsequent years.



Simulation Results – Net Carbon Emission Savings

- Initially, net carbon emission savings is negative due to carbon emissions from the manufacturing of solar panels.
- Over time, net carbon emission savings grows exponentially due to the growth in peak solar capacity – every year, more carbon emissions are saved.
- ~21 million tonnes of cumulative carbon savings by 2040.





Policy Analysis

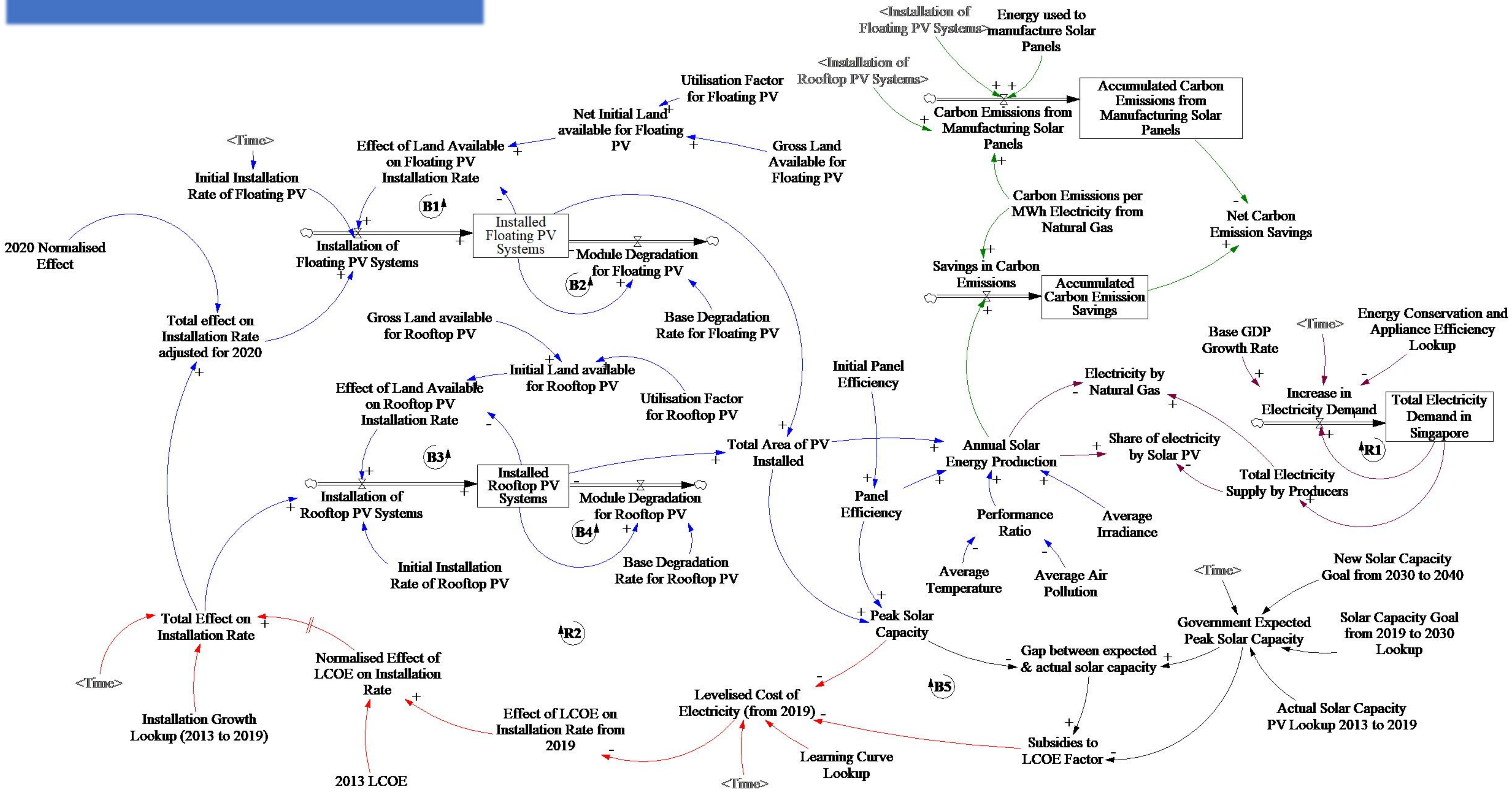
What if SG's government updates its goal to 8% share of total electricity in 2040?

Base Case only reaches 5.1% - policies required

Policy A: Increased Area and Utilisation Factor – scenario where the government makes better use of the gross land area in SG.

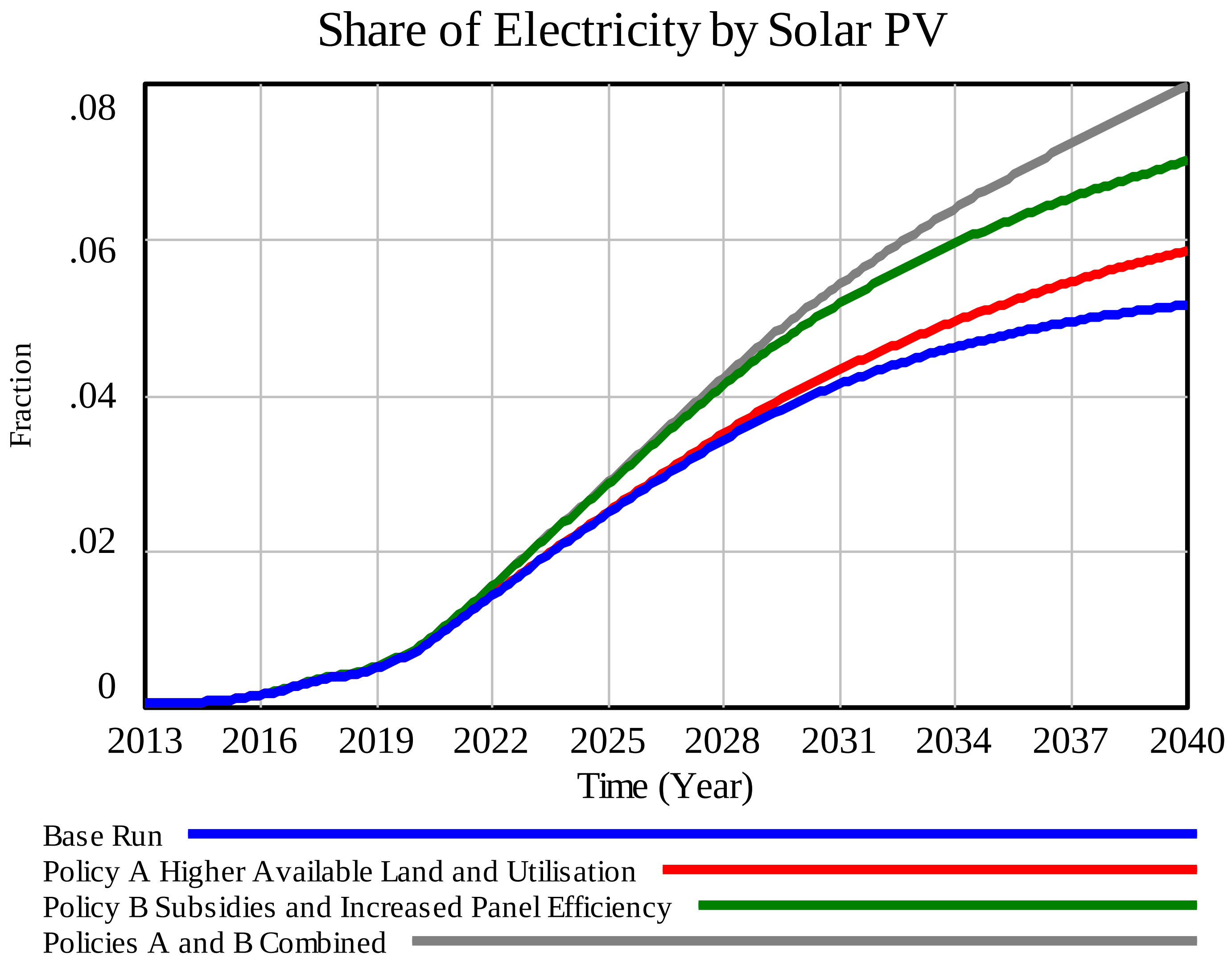
Policy B: Increased Panel Efficiency and Subsidies – accelerated global development in solar panel efficiency, and subsidies to make up for a shortfall between actual and expected capacity.

Model with Policies

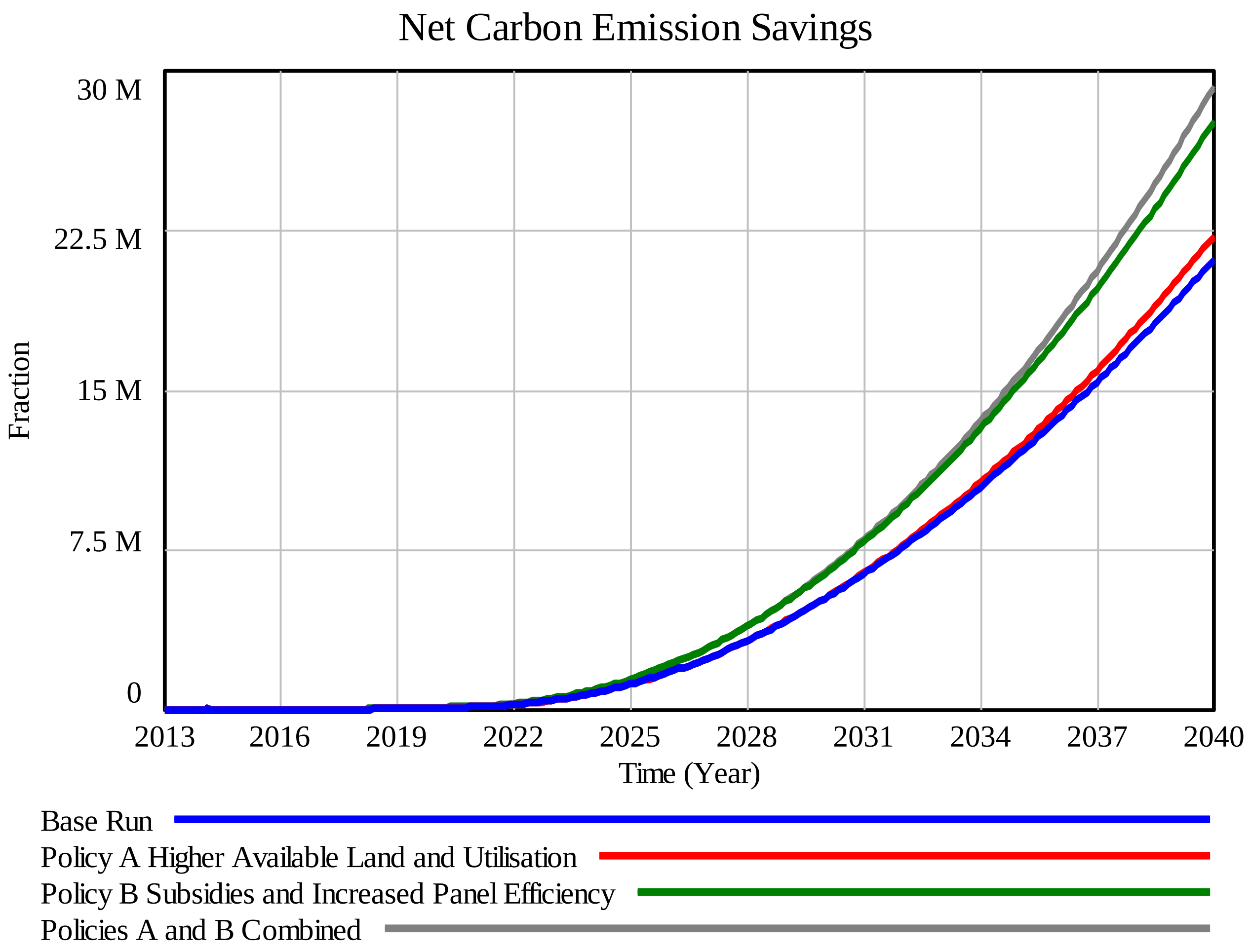


Policy Analysis Results

- Policy A alone has weak effects: policy has a low level of leverage
- Policy B has a stronger effects: Higher impact of technological improvements compared to increasing available land area.
- Combination of both policies lead to 7.95% share of total electricity supply in 2040.



Policy Analysis Results



- Increase in Net Carbon Emission Savings are marginal for policy A – increase from 21 to 22 million tonnes.
- More significant savings from policy B – increase to 27.5 million tonnes.
- Combined policy gain from 21 to 29.1 million tonnes of CO_2.

Conclusion

- Singapore is sufficiently prepared to meet its solar capacity goal of 2GWp by 2030, simulation shows this goal is met by 2028.
- However, pushing solar energy's relevance further is difficult due to the scarcity of land available.
- In order to further increase Singapore's energy security and environmental sustainability, policies must be introduced to support the growth of solar panel installations.

Selected References

1. King, S., & Wettergren, P. (2011). Feasibility Study of Renewable Energy in Singapore. Stockholm.
2. Chia, E. S., Lim, C. K., Ng, A., & Nguyen, N. H. (2015). The System Dynamics of Nuclear Energy in Singapore.
3. Luther, J., & Reindl, T. (2014). Solar Photovoltaic (PV) Roadmap for Singapore (A Summary).
4. Paton, C., Tan, C., & Reindl, D. T. (2019). Solar Economics Handbook of Singapore.
5. Energy Market Authority. (2019). Electricity generated.
6. Sterman, J. D. (2000). Business Dynamics: Systems Thinking and Modelling for a Complex World.
7. Energy Market Authority. (30 October, 2018). Solar Photovoltaic Systems.
8. Barlas, Y. (1996). Formal aspects of model validity and validation in system dynamics.
9. Meadows, D. (1999). Leverage Points.