The Electricity City – Modelling the Dynamics of Queensland's Electricity Trends

R. G. Richards[a], S. Staby[a] and C. Smith[a]

[a] ***School of Business, University of Queensland, St Lucia, Brisbane, s.staby@business.uq.edu.au***

Keywords: *Queensland; electricity; photovoltaic (PV); battery; modelling*

Abstract

The objective of this paper was to successfully and accurately apply systems thinking and systems dynamics to the problems associated with Queensland's electricity behaviour. Systems thinking and systems dynamics allows for a model structure to be inferred and constructed based upon the observable behaviour. This modelling process was a five step framework that incorporated a problem identification, a qualitative model. A quantitative model and scenario testing. Currently, we are at step the quantitative modelling step.

Introduction

The Queensland electricity supply is 'currently' dominated by a centralised distribution network, known as the 'grid' (Abdullah, Agalgaonkar & Muttaqi, 2014). This grid-based supply is characterised by (i) baseload power component, which is relatively low-cost and provides a steady supply of reliable power to meet minimum level of demand (Berk, 2015) and (ii) a dispatchable load power component, that provides a variable supply of power which is used to meet demand beyond the baseload amount (Berk, 2015). In Queensland, the baseload power is provided by coal-fired power stations (AER, 2018) and the distributed power is provided by predominantly gas fired.

Households connected to the electricity supply grid pay a *fixed* monthly service fee that entitles them to be connected to this grid. They also pay a *variable* cost that is linked to how much electricity they draw from the grid i.e. the more they use the more they pay.

The First Wave: The Uptake of solar PV

A disruptive dynamic to the traditional grid-based electricity system has been the recent emergence of rooftop solar as a supplementary electricity source. This has allowed these households to self-generate a portion of their total electricity requirement, thus reducing the amount of electricity drawn from the grid (i.e. the *Variable* cost).

Ten years ago, solar PV installation was limited to only a relatively small proportion of the city households (Agnew et al., 2018). In the beginning, the high cost of installing solar PV was a source of resistance in uptake rates. However, installation costs have been getting cheaper and it was clear that those who had installed solar were benefitting from it financially (Agnew et al., 2018). This made it a more attractive proposition, resulting in many other households 'jumping onboard' and 'installing solar'.

Over the last 10 years, many, but not all, Queensland households have installed photovoltaic solar cells (rooftop solar). Recent Australian Energy Regulator's statistics indicate that 29% of households in Queensland have rooftop solar (AER, 2018).

One ramification of the rise of rooftop solar has been an increased burden of 'cost recovery' of the grid operation and infrastructure on those households that do not have rooftop solar. Recovery of the debt burden by the suppliers in Queensland is done by increasing the fixed service fee (Fan & Hyndman, 2011), so that all households equally carry this burden, regardless of whether they have rooftop solar or not. However, the electricity suppliers also recover their debt burden through increasing the price of their product i.e. their electricity – thus if you use more, then you pay more – non-PV houses use more so they pay more for their Variable cost component (Green Energy Markets, 2018).

A Second ramification is that the generation capacity of the electricity grid does not decrease even with the rise of household solar. This is because whilst solar PV reduces the daily electricity demand for 'PV houses' from the grid, when the sun goes down, their electricity needs have to come entirely from the grid just like the 'non-PV houses'. This means that the power station needs to have sufficient capacity to meet the maximum or 'peak' demand from all households connected to the Grid, regardless of whether they have solar PV or not (AEMO, 2019b).

With a growing population requiring higher 'peak demands' and an aging power supply infrastructure that requires refurbishment and/or replacement, there will be a continued increasing debt burden to the suppliers of electricity.

The Second Wave: The Uptake of Batteries

Queensland is on the verge of undergoing a second wave of rapid transition - households are starting to go to the next step of electricity self-generation and install batteries alongside the solar PV (AEMO, 2019a). These households (PV & Battery) bring a new dynamic of disruption to the existing electricity supply profile because they can now self-generate their entire electricity demand. During the day when the sun is shining, they can store the excess electricity from their solar PVs into their batteries, and at night time, they can use this stored electricity to meet household demand.

However, the uptake rate of battery storage is in its early stages and currently slow, mainly because of the current high cost of installing a battery system (AEMO, 2019a). However, like the rapid uptake of rooftop solar that has been already observed, this cost is expected to decrease quickly over the next 10 – 20 years (AEMO, 2019a), making it an attractive option for households, leading to increased uptake rate.

This raises a pertinent question of why do these households need to be connected to the Grid if they can meet their own needs if they can self-generate their entire electricity demand? The migration of households with rooftop solar and battery off-grid is likely to cause further disruption to the traditional centralised electricity system. Existing power stations are long-lived and cannot be readily replaced with smaller (and cheaper) infrastructure. Consequently, the debt burden remains and needs to be recovered from the households still connected to the grid.

If adoption of PV-battery occurs rapidly over the next 10 years as was observed for rooftop solar, and this results in some households migrating away from the grid then what are the ramifications for those households still connected?

In this paper, we use a systems thinking approach (Sterman, 2000) to explore how Queensland's electricity system might respond over the next 10 years if there is a rapid uptake of PV-battery storage at the household level, and if there is migration away from the grid. The model explores both current and projected problems.

The problem of stranded houses that cannot adopt either PV or battery, and the price elasticity of grid electricity are current problems, with emerging problems relating to houses transferring off grid en mass. These problems are incorporated into the system dynamics methodological framework (Maani & Cavana, 2007), which informed the model building process.

The objective of creating the model is to evaluate different scenarios and interventions, to establish which is the most realistic and feasible leverage point.

The model is part of a collection of case studies, called UQ Cases. UQ Cases is funded by the Business School at the University of Queensland, and is an innovative project that parcels system dynamic models into user-friendly apps. The purpose of UQ Cases is to communicate instructive, modern, easy-to-understand, and informative teaching.

Methodology

A description of Queensland's electricity supply and demand is essential for the methodological framework of the model, given that it incorporates these behaviours within its structure. The electricity supply comprises generation, transmission, distribution, and retail.

Generation

Queensland's energy profile consists of 53% black coal, 24% gas, 14% rooftop solar, 5% hydro and the remaining from solar farms and other dispatched (AER, 2018; Renew Economy, 2019a). The predominant focus of this paper is upon coal and solar generation. Government corporations own 65% of Queensland's generation capacity (Queensland Government, 2019).

Stanwell Corporations and CS Energy (CS Energy, 2019) are government owned, with Stanwell Corporations providing 13,261 MW, while CS Energy provides 3,583MW. Two of the biggest coal power stations – Gladstone (1976) and Tarong (1986) have expected decommissioning dates (AIP, 2019), with power stations, on average, having a 40 year lifespan (Woody, 2013).

Transmission

There is 15,000km of transmission network across Queensland (Queensland Government, 2019). It is a high voltage network that extends 1,700km from NSW to Cairns (Powerlink, 2019). Powerlink Queensland is the main provider of transmissions, and is owned by a Government Corporation (Powerlink, 2019). In 2017/2018, its debt requirements remained unchanged at 5.3 billion.

Distribution

The electricity distribution system connects household premises with the transmission network (Shahnia, Arefi &, Lich, 2018). The main suppliers are Energex and Ergon Energy, with a total combined length line of 350,000 kilometres, which include power lines, power poles, and transformers (Queensland Government, 2019). The asset value of the distribution network is approximately 24 billion (Energex, 2018; Ergon Energy, 2016).

Retail

The retail structure of Queensland is primary through Residential Tariff 11, which is a general supply tariff that is a flat rate payable (Ergon Energy, 2019). Costing constitutes fixed and volumetric component. Queensland's electricity supply is 13,520 MW of installed electricity generation (Queensland Government, 2019).

Systems Thinking and System Dynamics Approach

Development of the System Dynamics Model (SDM) follows the standard four step process outlined in Maani and Cavana (2007) of (i) problem articulation, (ii) development of a causal loop diagram (CLD), (iii) development of a dynamic model, and (iv) scenario testing.

The articulation of the problem will be based on evaluating behaviour over time charts. The development of the CLD is based on a desktop study of available literature, in conjunction with building a CLD in Vensim (www.vensim.com) to represent the causal behaviour. The development of the dynamic model is based on the CLD (Sterman, 2000). We have used Stella Architect 1.8.2 (www.iseesystems.com) to develop the simulation model.

Currently, the electricity model is at step (iii) of the modelling process, and as such this paper does not include a fully developed scenario planning step. Continuous model parametrizations of the model variables are consistent with the iterative nature of systems thinking (Sterman, 2000), and as such, the model is still under review.

Results and Discussion

Problem articulation

The model simulates for a time horizon of 40 years (2000 – 2040). The start year of 2000 was selected given that the rapid uptake of solar PV in Queensland occurred at approximately 2010 (Green Energy Markets, 2018). This timeframe is also supported by Figure 3's predictions, which can be compared with result outputs from the model simulation to legitimise the model accuracy.

Problem 1: Electricity Price

Components of price increase are predominantly because of wholesale costs, network charges, and retail margins (Parliament of Australia, 2019) along with the gap between supply and demand (Agnew et al., 2018).

The price of electricity in Australia has increased by 117% since 2008 (ABC, 2018). The Queensland electricity price increase during 2003 – 2013 was 73% (Parliament of Australia, 2019). Figure 1 displays the Queensland spot price increase from 2010 to 2018. This behaviour displays an increasing trend until approximately 2017, when prices dipped due to government intervention.

The problem of why electricity prices increased at an increasing rate has been attributed to the uptake of solar PV.

Problem 2: PV Uptake

There has been a rapid increase in PV installation since 2010 in both Queensland and other states (Figure 2). 29% of residential households in Queensland have residential solar PV systems, which account for 550,000 solar PV systems installed (Green Energy Markets, 2018) (Figure 2). The cumulative capacity of these solar units is 2,000 MW, which is the highest amount of capacity worldwide (Figure 2). For comparison, Gladstone's capacity is 1,680MW (Green Energy Markets, 2018). Solar capacity is instantaneous, however with batteries this electricity can be stored.

Problem 3: PV Uptake and Battery Uptake

Saturation of Queensland PV systems is expected by 2031-2 (Figure 3), due to suitable rooftop space availability issues, however attached battery systems are expected to have high growth (AEMO, 2019a). Queensland's PV capacity is expected to grow from 5 GW today to 19.7 GW by 2036-7 (AEMO, 2019a). Whereas, battery capacity today is close to zero, but is expected to reach 5.6 GW by 2036-7 (AEMO, 2019a) (Figure 3).

Problem 4: Peak Demand

Solar capacity causes grid issues that relate to: volatility in system demands, low daytime demand, and morning and afternoon ramping up and down (AEMO, 2019b). Daily patterns of demand and supply are significantly changed by solar capacity. The Duck Curve (Renew Economy, 2019b) illustrates this, as solar capacity peaks at mid-day than levels off around sunset.

Conventional power stations and the grid must still be able to meet base demand and peak demand, despite the solar capacity available. This is for a number of reasons, but a significant factor is because solar capacity is dependent on weather. This dependency is both a seasonal (Figure 4) and weather event based.

Figure 4 shows that Queensland uses more electricity in summer than in winter. An example of a weather event is that, during a five day heat wave in 2016 of more than 40 degrees Celsius, the grid demand in Queensland reached 9,796MW (which did not include solar capacity). The demand was the highest ever recorded.

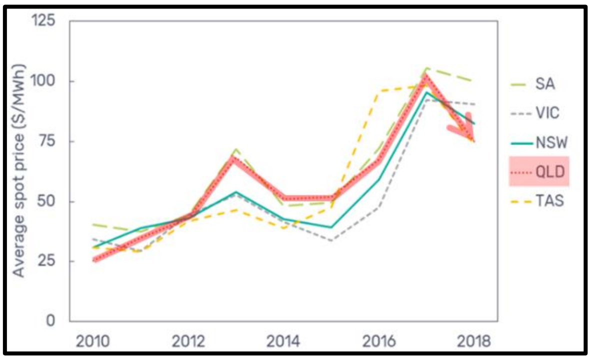

Figure 4. Average Spot Price ($/MWh) of Electricity from 2010 to 2018 (Energy Synapse, 2019).

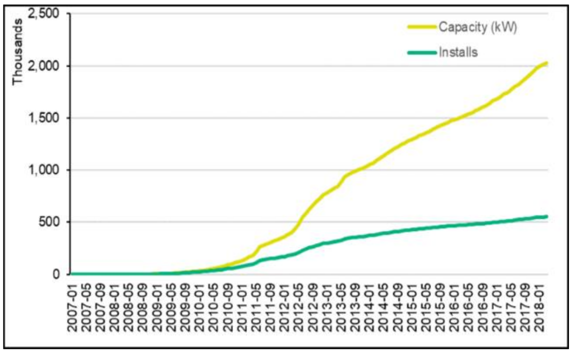

Figure 4. Cumulative Residential Solar Installations and Capacity from 2007 to 2018 (Green Energy Markets, 2018).

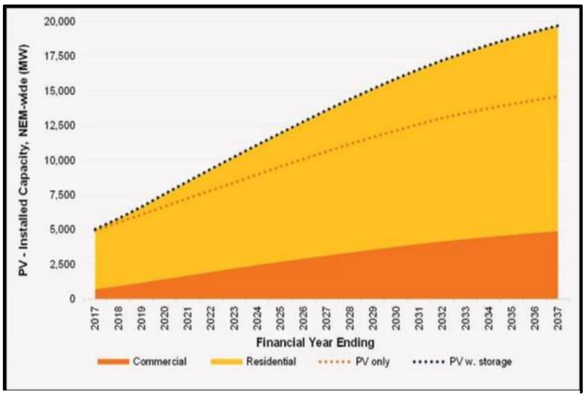

Figure 4. Expected Forecast of Australia's Residential and Commercial PV, with Battery Storage. Queensland is expected to follow National Trends (AEMO, 2019a).

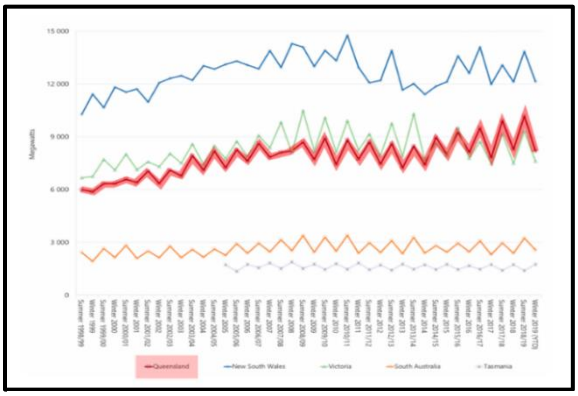

Figure 4. Queensland Seasonal Peak Demands for Summer and Winter for Years 1998 - 2019 (AER, 2019).

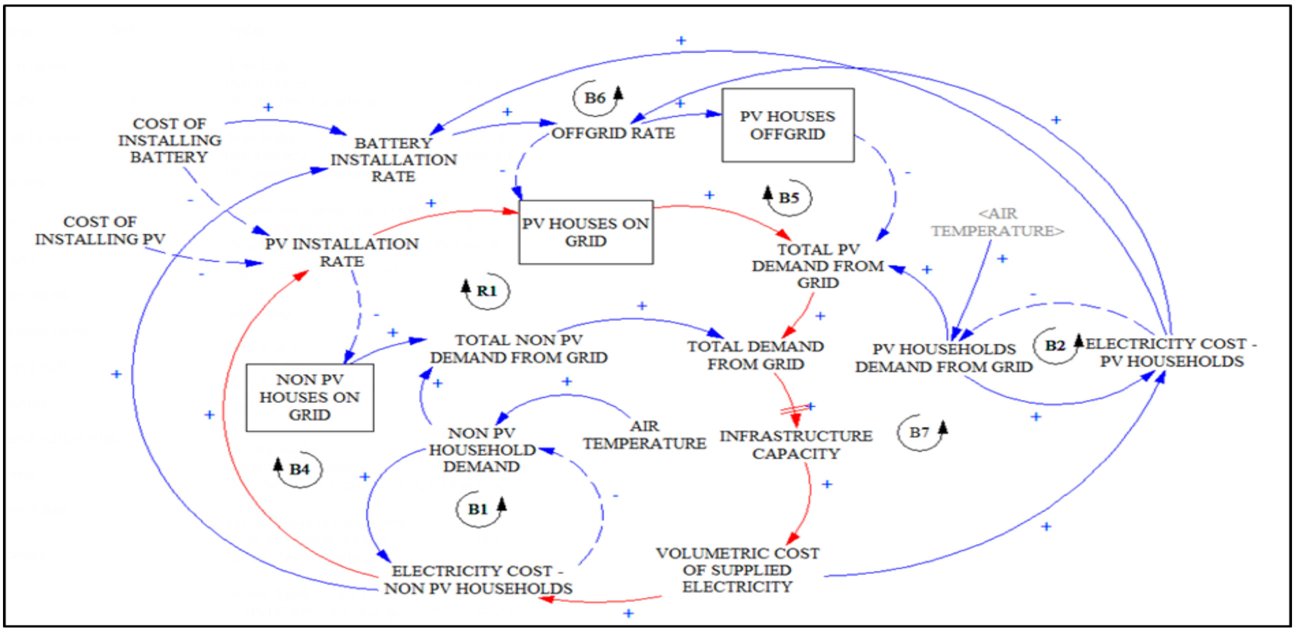

Figure 5. CLD of the Electricity Model

Causal Loop Diagram

The causal loop diagram (CLD) that helps explain the observed behaviour of Queensland’s electricity system is presented in Figure 5. This CLD is a qualitative model that helps isolate feedback loops and causal linkages between variables. Additionally, it helps to explain the observed behaviour of electricity dynamic trends. The blue lines help to highlight the balancing loops, of which there are 7 (Table 1), and the red lines help to highlight the reinforcing loops, of which there is currently 1 (Table 1).

This CLD is still under review, given that a second reinforcing feedback loop needs to still be included. The intervention strategies should also still be included. The reinforcing loop describes the uptake of solar PV, while the balancing loops describe key variables interactions with electricity cost.

Dynamic Modelling

The objective of dynamic modelling is to test the CLD (Sterman, 2000) and assess the model’s output behaviour to determine the feasibility of selected intervention points. The SDM was developed from the CLD. The Electricity Model is separated into 16 modules (Figure 6). The dotted lines on Figure 6 are in reference to the intervention points.

Table 1. Summary of feedback loops in the CLD

Loop	Loop variables
B1	Non PV Household Demand → Electricity Cost – Non PV Households
B2	PV Household Demand From Grid → Electricity Cost – PV Households
B3	Non PV Household Demand → Total Non PV Demand from Grid → Total Demand from Grid → Infrastructure Capacity → Volumetric Cost of Supplied Electricity → Electricity Cost – Non PV Households
B4	Electricity Cost – Non PV Households → PV Installation Rate → Non PV Houses on Grid → Total Non PV Demand from Grid → Total Demand from Grid → Infrastructure Capacity → Volumetric Cost of Supplied Electricity
B5	Offgrid Rate → PV Houses on Grid → Total PV Demand from Grid → Total Demand from Grid→ Infrastructure Capacity → Volumetric Cost of Supplied Electricity → Electricity Cost – Non PV Households → Battery Installation Rate
B6	Electricity Cost – Non PV Households → Battery Installation rate → Offgrid Rate → PV Houses on Grid → Total PV Demand from Grid → Total Demand from Grid → Infrastructure Capacity → Volumetric Cost of Supplied Electricity
B7	Electricity Cost – PV Households → Offgrid Rate → PV Houses on Grid → Total PV Demand from Grid → Total Demand from Grid → Infrastructure Capacity → Volumetric Cost of Supplied Electricity
R1	PV Houses on Grid → Total PV Demand from Grid → Total Demand from Grid → Infrastructure Capacity → Volumetric Cost of Supplied Electricity → Electricity Cost – Non PV Households → PV Installation Rate

Population Growth Module – This module accounts for the expected growth of Queensland's population, and the resulting effect it will have upon household construction rates.

Household Module – The household module (Figure7) represents the five different household types. STRANDED HOUSES represent households that do not have the potential to uptake either PV or battery. HOUSES represents households that can adopt either/both PV and battery, but have not done so yet. PV HOUSES NEW represents households that have installed solar PV systems that are still new, and these transfer to PV HOUSES OLD after a time delay, which accounts for model efficiency loss rates of the PV system. PV AND BATTERY HOUSES NEW represents households that have both a PV and battery system installed. These households also transition to PV AND BATTERY HOUSES OLD after a time delay. OFFGRID new represents households that have the capacity to leave the grid, these also transition to OFFGRID OLD after a time delay. This module represents the key dynamics of the SDM. Additionally, it represents the uptake behaviour of PV and battery observed in Queensland.

Baseload Supply Module – In Queensland the baseload supply is satisfied by predominately coal fired power stations. Base load supply is in reference to the minimum constant grid demand required.

Dispatchable Supply Module – Dispatchable supply satisfies real time demand, given that dispatchable generations can be switched on, off, and adjusted quickly. A problem with PV is that it is instantaneous, and consequently when it drops out, dispatchable generation is required to stabilise demand requirements.

Irradiance Module – Irradiance and temperature affects PV output, given that the higher the irradiance, the higher the output current, the more electricity generated. This module was a necessary inclusion, given that it directly effects the grid demand requirements from PV HOUSES and PV AND BATTERY HOUSES.

Electricity Household Monthly Demand Module – This module represents the five different demand requirements from the five different households. It marks a key dynamic, given that a significant issue with the rapid and strong PV uptake was a shift in demand times as well as demand volatility. STRANDED HOUSES and HOSUES require the most grid electricity, with PV HOUSES requiring less, PV AND BATTERY HOUSES requiring even less, and OFFGRID HOUSES having no grid requirements. A scalar was used to scale the NEW and OLD houses grid demand, given the efficiency of the PV and battery operating units.

Total Electricity Demand Module – The total electricity demand module represents the combined different electricity demand levels that the five different household types require.

Electricity Unit Price Module – Price is calculated through a fixed cost (Tariff 11) and a volumetric cost. The fixed cost is in reference to the capital investments and interest owed for the infrastructure of electricity generation. The volumetric cost is the cost associated with electricity demand and usage.

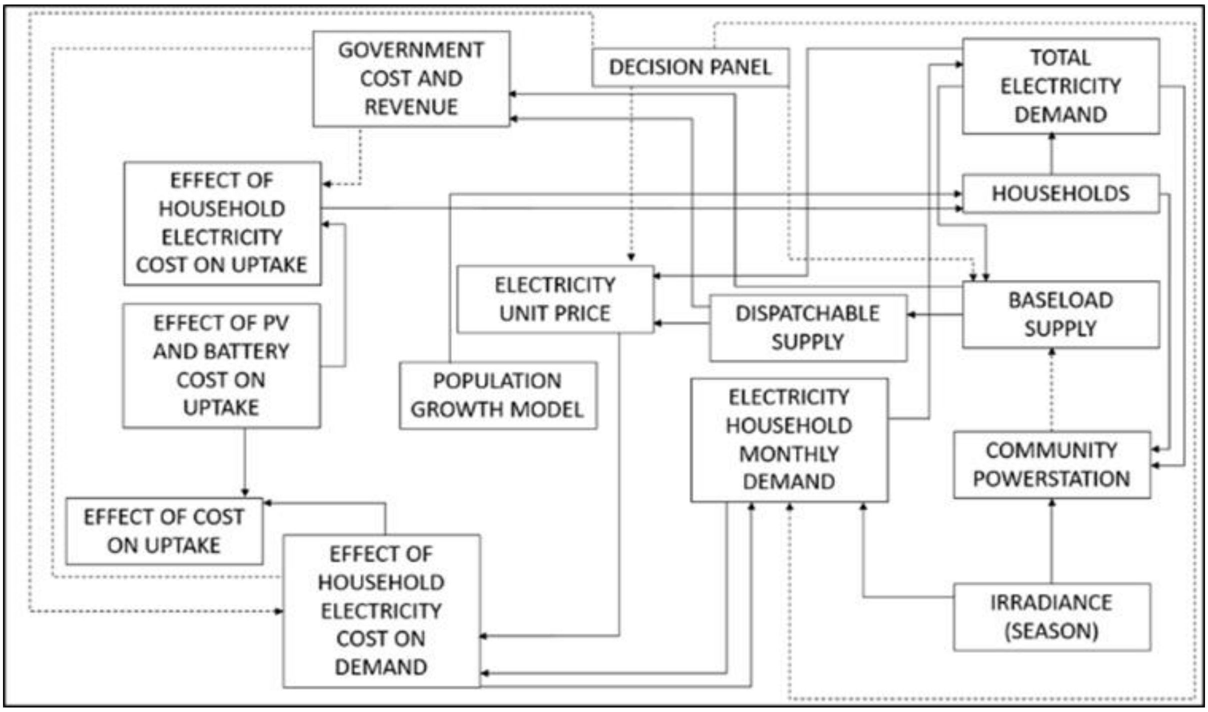

Figure 6. Electricity Model Design Architecture

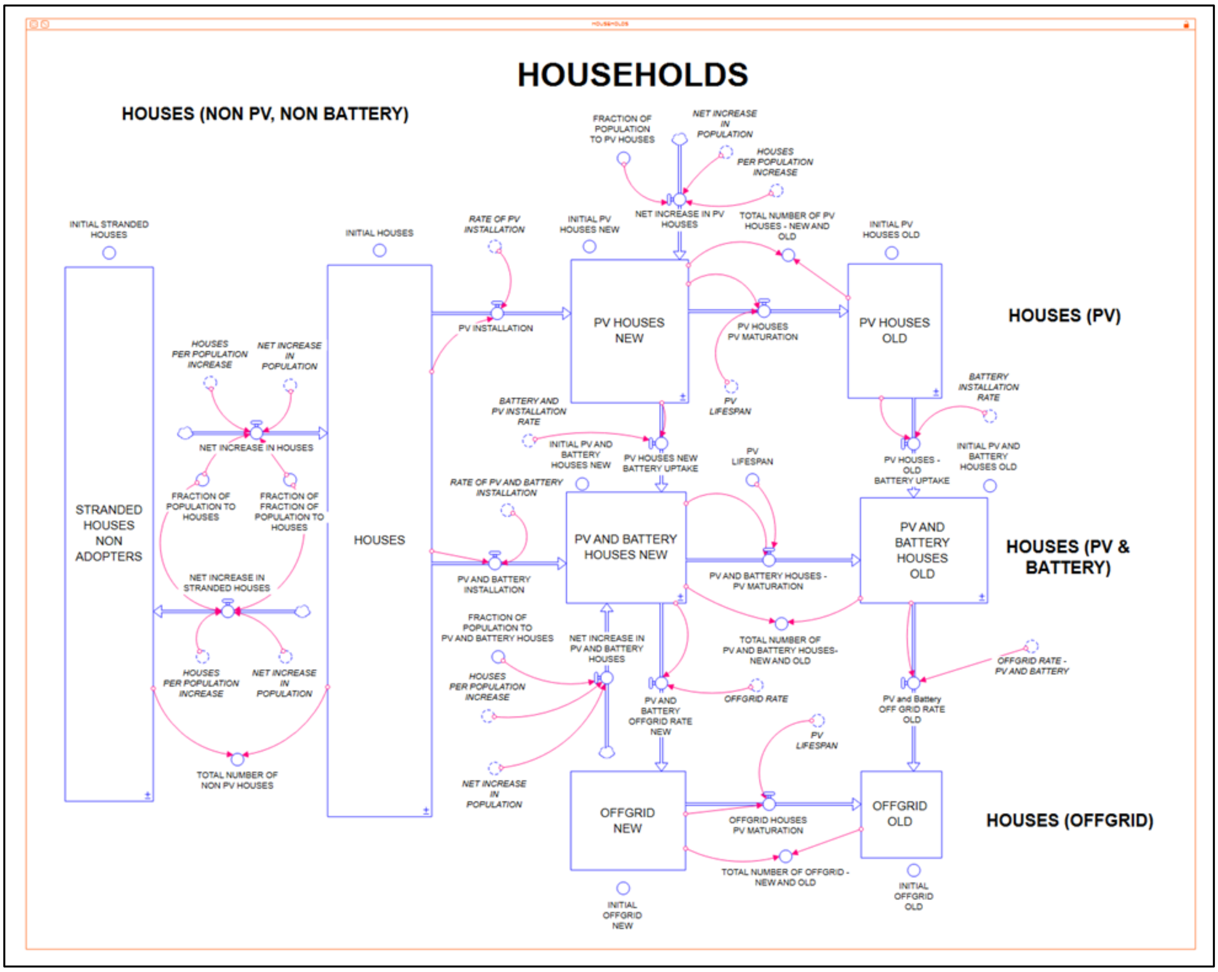

Figure 7. Household Module of the Stella Module

Effect of Household Electricity Cost on Uptake Module – This module factors price elasticity into the model, given that when electricity prices increase, the rate of uptake also correspondingly increases.

Effect of PV and Battery Cost on Uptake Module – This module represents the effect that the cost of initial PV and battery system installation has upon uptake rates. The SDM uses the bass diffusion model (Sterman, 2000) to represent the uptake behaviour of new, current, and late adopters.

Effect of Cost on Uptake Module – Uptake of PV from Non PV households, as well as battery uptakes from PV households and non-PV households, and transitioning off grid rates.

Decision Panel Module – The decision panel represents intervention points within the SDM. The intervention points controlled in the decision panel are: whether the communal power station should be switched on or off, the level of government enforcement attached to the communal power station, whether the electricity price should be manually adjusted, and the government subsidy level attached to PV and battery.

Government Cost and Revenue Module – This module represents the revenue and cost to government from the electricity sector. Revenue is in regards to income earned from the different house types through purchasing electricity, whereas the cost is in reference to the government's electricity infrastructure debt load, subsidy schemes, and enforcement.

Community Supply Module – The community supply module represents the most significant intervention point. This is a hypothetical intervention point that represents a communal supply, storage, and distribution of electricity. Households are generators and batteries that store and then export electricity back into the grid, whereupon they purchase the electricity.

Model Testing

The model was subjected to extreme conditioning testing, as well as mass balance testing. The extreme condition testing generated graphs that were consistent with behaviour observed and expected.

The mass balance test revealed that the model conserved matter.

Household Uptake and Price Diffusion

When assessing the different uptake rates from the different household types (Figure 8), it can be observed that PV AND BATTERY HOUSES have the most significant behaviour change after approximately 2029. This is consistent with Figure 3's predicted battery growth. The behaviour of Figure 8 can be explained by Figure 9's cost of PV and battery behaviour graphs. Figure 9 displays the rapid decrease in price for both PV and battery, with the decrease in price for PV occurring currently, while the decrease in battery will still occur.

Different Household Electricity Demands

Figure 10 displays the electricity demand profiles for the different household types. As was expected, the households that could not adopt PV or battery require constant grid electricity. PV houses required a significant less demand from the grid, with PV and Battery displaying similar behaviours, but lowered by a degree.

Demand for all the different households display seasonal affects – more electricity is demanded in summer as opposed to winter.

Household Uptake and Baseload and Dispatchable Profiles

The dispatchable power behaviour over time (Figure 11) results from the volatility of solar capacity. Given that there is projected significant uptake for both PV and battery, this behaviour was expected.

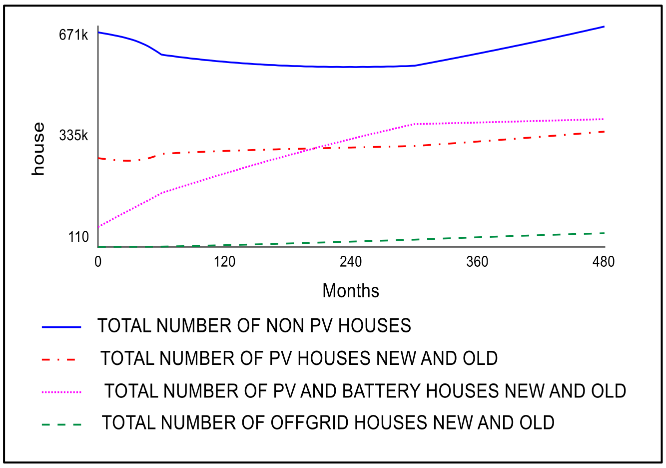

Figure 9. Different Household Uptakes over Time

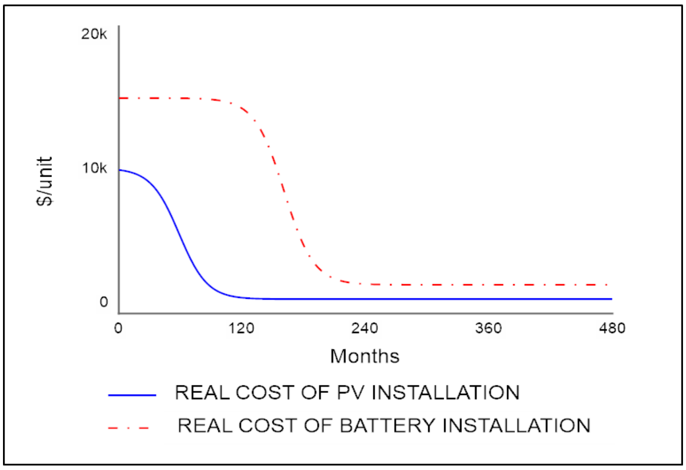

Figure 9. PV and Battery Cost Installation over Time

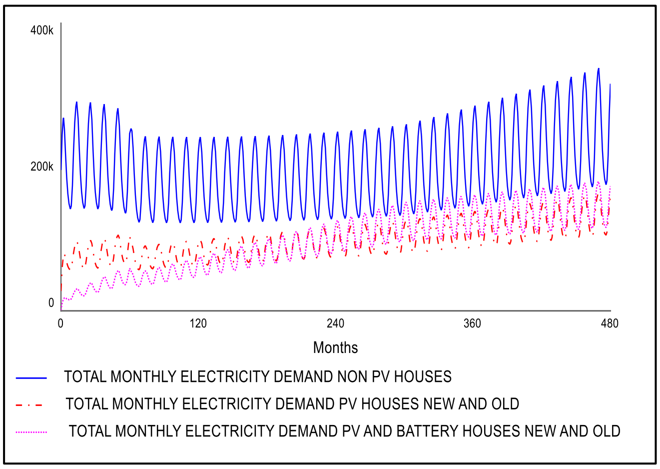

Figure 9. Total Monthly Electricity Household Demands

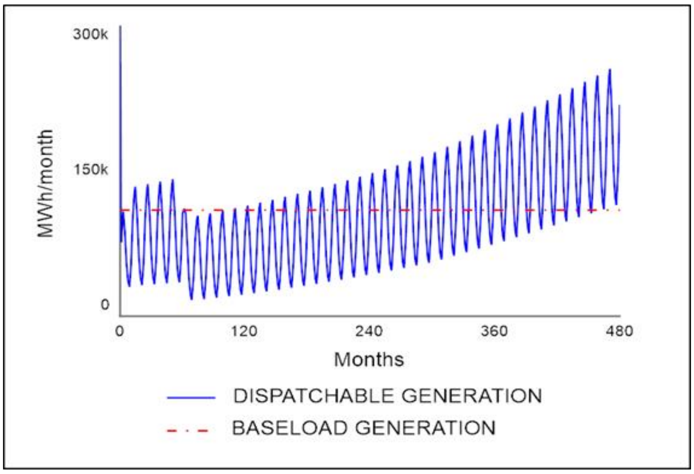

Figure 11. Baseload and Dispatchable Electricity Profile

ACKNOWLEDGMENTS

This work was supported by the University of Queensland Business School. We are grateful to Ninad Jagdish (BTN Pte Ltd) for his support in the preparation and construction of the Electricity Model.

References

ABC. (2018). *Chart of the day, something has gone terribly wrong with electricity prices*. Retrieved from: https://www.abc.net.au/news/2018-07-18/electricity-price-rises-chart-of-the-day/9985300

Abdullah, Agalgaonkar, & Muttaqi. (2014). Climate change mitigation with integration of renewable energy resources in the electricity grid of New South Wales, Australia. *Renewable Energy, 66*(C), 305-313.

AEMO. (2019a). Rooftop PV and Battery Storage. Retrieved from https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/NEM-Electricity-Demand-Forecasts/Electricity-Forecasting-Insights/2017-Electricity-Forecasting-Insights/Key-component-consumption-forecasts/PV-and-storage

AEMO. (2019b). *Quarterly Energy Dynamics Q2 2019.* Retrieved from https://www.aemo.com.au/-/media/Files/Media_Centre/2019/QED-Q2-2019.pdf

AER. (2019). Seasonal Peak Demand. Retrieved from https://www.aer.gov.au/wholesale-markets/wholesale-statistics/seasonal-peak-demand-region

AIP. (2019*). Kaboom – Tarong power station to close by 2018/19, with Stanewell and half Gladstone to Follow*. Retrieved from: https://aip.asn.au/2017/11/kaboom-tarong-power-station-to-close-by-2018-19-with-stanwell-and-half-gladstone-to-follow/

Berk, K. (2015). Modeling and Forecasting Electricity Demand A Risk Management Perspective. Wiesbaden: Springer Fachmedien Wiesbaden : Imprint: Springer Spektrum.

CS Energy. (2019). *Queensland Government to Establish a Third Energy Generator*. Retrieved from: https://www.csenergy.com.au/news/queensland-government-launches-third-energy-generator

Energex. (2018*). Distribution Annual Planning Report: 2018-19 to 2022-23*. Retrieved from:

https://www.energex.com.au/__data/assets/pdf_file/0016/720223/Distribution-Annual-Planning-Report-2018.pdf

Energy Synapse. (2018). QLD smashes electricity demand record during heatwave but narrowly avoids high pricing. Retrieved from: https://energysynapse.com.au/qld-smashes-electricity-demand-record-during-heatwave-but-narrowly-avoids-high-pricing/

Energy Synapse. (2019). National Electricity Market Year in Review Part ½: Wholesale Electricity Prices. Retrieved from: https://energysynapse.com.au/category/energy-markets/page/2/

Ergon Energy. (2016). *Distribution Annual Planning Report: 2016-17 to 2022-21*. Retrieved from: https://www.ergon.com.au/__data/assets/pdf_file/0017/720233/Ergon-DAPR-2016.pdf

Ergon Energy. (2019). Energy Supply Tariffs. Retrieved from: https://www.ergon.com.au/retail/residential/tariffs-and-prices/general-supply-tariffs

Fan, & Hyndman. (2011). The price elasticity of electricity demand in South Australia. *Energy Policy*, *39*(6), 3709-3719.

Green Energy Markets. (2018). Solar achieves new record. Retrieved from: http://greenmarkets.com.au

Maani, K. E., & Cavana, R. Y. (2007). *Systems Thinking, System Dynamics: Managing Change and Complexity* (2nd ed.). Auckland: Pearson Education New Zealand.

Parliament of Australia. (2019). Energy Prices – the story behind rising costs. Retrieved from: https://www.aph.gov.au/about_parliament/parliamentary_departments/parliamentary_library/pubs/briefingbook44p/energyprices

Powerlink, (2019). Annual Report and Financial Statement:2017/18. Retrieved from: https://www.powerlink.com.au/sites/default/files/2018-10/2017-2018%20Annual%20Report.pdf

Queensland Government. (2019). Electricity Prices and Supply. Retrieved from: https://www.qld.gov.au/housing/buying-owning-home/energy-water-home/electricity/electricity-prices/understand-electricity-system

Renew Economy. (2019a). Live Australia Electricity Generation Data. Retrieved from: http://reneweconomy.com.au

Renew Economy. (2019b). Duck! Solar charge puts energy market transition on the fast track. Retrieved from: https://reneweconomy.com.au/duck-solar-charge-puts-energy-market-transition-on-the-fast-track-39479/

Shahnia, F., Arefi, A., & Lich, G. (2018). Electric distribution network planning. Singapore: Springer.

Sterman, J. D. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston: Irwvin/McGraw-Hill.

Woody, T. (2013). Quartz:Most coal-fired power plants in the US are nearing retirement age. Retrieved from: https://qz.com/61423/coal-fired-power-plants-near-retirement/