THE UNIVERSITY OF NEW SOUTH WALES

SCHOOL OF PHOTOVOLTAIC AND RENEWABLE ENERGY ENGINEERING

Study of Battery Systems for Frequency Regulation in the Australian National Electricity Market

by

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Abstract

This study investigated the effects of battery systems for frequency regulation in the Australian National Electricity Market (NEM), with a main focus on the impacts to generator ramping requirements, transmission power flow congestion, and curtailment of renewable energy generation. PLEXOS Integrated Energy Model software was used to create a working model of the NEM, based on measured operational data, to evaluate current and forecasted generation portfolios at a resolution of 1-minute intervals.

Computer simulations generated by PLEXOS indicate that the NEM currently stands to reduce its generator ramping requirements by 49.24% during summer and 57.49% during winter with the addition of 7.5 MWh of fast-responding battery regulation capacity to the network. These same scenarios also demonstrated a reduction in the times transmission lines spent at maximum power congestion by 17.77% during summer and 13.50% during winter.

Thirty-six different scenarios were also investigated with regard to the curtailment of renewable energy generation that arises as a result of high intermittency. Results from these simulations invariably showed that energy curtailment can be reduced with the addition of battery regulation systems to the network. One scenario representing the NEM's current generation portfolio suggests that this reduction in curtailment can be as high as 94.34% when 7.5 MWh of battery regulation capacity is integrated within the network infrastructure.

The results of these simulations have implications for a number of benefits to the NEM, including: improved power quality, a more robust network, increased generator lifetimes, higher generator operating efficiencies, lower network emissions, reduced dependency on energy imports between regions, and improved economic performance of renewable energy generators.

Dedicated to my family and friends

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Glossary

AC	Alternating Current
AGC	Automatic Generator Control
Ah	Amp-Hour
AEMO	Australian Energy Market Operator
BREE	Bureau of Resources and Energy Economics
BESS	Battery Energy Storage System
BOM	Bureau of Meteorology
CCGT	Combined Cycle Gas Turbine
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CST	Concentrated Solar Thermal
FCAS	Frequency Control Ancillary Service
GWh	Gigawatt-Hour
LCOE	Levelised Cost of Electricity
MW	Megawatt
MWh	Megawatt-Hour
NEM	National Electricity Market
OCGT	Open Cycle Gas Turbine
O&M	Operations and Maintenance
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PSOC	Partial State of Charge
PV	Solar Photovoltaic
SOC	State of Charge
SOH	State of Health
SRMC	Short-Run Marginal Cost
STC	Standard Test Conditions
ROC	Rate of Change

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Introduction

Frequency regulation plays an important role in any power network and is used to continually correct minor deviations in the balance between electricity generation and demand. The frequency of an AC current also has implications for its power quality, which, if not maintained within certain tolerance limits, can cause damage to network infrastructure and end-use appliances.

In order to minimise the impacts of anthropogenic climate change, Australia must make significant reductions to the emissions that result from its electricity generation, presumably through transitioning towards renewable energy technologies. However, the intermittent nature of these technologies mean that operators of such systems are unable to fully control their output, which can cause technical difficulties in maintaining power system frequency – particularly when fluctuations in renewable energy generation exceed the ramping capabilities of generators that provide regulation services.

Battery systems have advantages over conventional generators which make them more flexible and faster to respond to control signals. Battery systems used for regulation services are therefore able to maintain system frequency in a power network much more accurately, which has already been demonstrated in a number of projects worldwide.

As the penetration level of renewable energy generation is expected to increase in the NEM, so too are the deviations in power system frequency. Some areas in Australia are already facing the situation where new installations of renewable energy generators has been stopped due to concerns about their impact on the health of the network. And although there are other countries that have higher levels of renewable energy generation and fast-responding battery regulation systems, these networks do not always provide a relevant reference to Australia's unique power network configuration and climatic conditions.

Taking a macroscopic view of the NEM, this thesis project aims to characterise the effects on grid stability - as indicated by generator ramping requirements and transmission power flows - when battery regulation systems are included in its power network infrastructure. The scope of this thesis will include current and forecasted generation portfolios of the NEM, with a main point of focus being on the installed capacity of renewable energy generators. Building upon measured data and mathematical approximations, PLEXOS Integrated Energy Model software will be used to construct a representation of the NEM to simulate these impacts.

Chapter 1

1 Background

1.1 The Australian National Electricity Market

THE Australian National Electricity Market (NEM) is the financial electricity market and physical transmission infrastructure that supplies electricity to the eastern and southern states of Australia: Queensland, New South Wales (including the Australian Capital Territory), Victoria, South Australia, and Tasmania. The NEM is the longest spanning power network in the world, comprising of about 40,000 km of cables/transmission lines and stretching over 5,000 km from Queensland to Tasmania (AEMO, 2010). The NEM supplies about 200 TWh of electrical energy annually to 19 million residents across its five regions, which are roughly defined by state lines, as shown in Figure 1 on the next page.

The Australian Energy Market Operator (AEMO) manages network planning and system operations in the NEM, and are responsible for maintaining power quality and ensuring that electricity demand is met in each region for a minimum of 99.998% of the time for each financial year, as outlined in the National Electricity Rules (AEMO, 2015). During normal operations, AEMO controls the dispatch of generators to minimise the cost of energy while maximising system stability. The supply of electricity is facilitated by a competitive spot market, where generators competitively submit bids based on their short-run marginal costs (SRMCs) in 5-minute intervals to supply energy at a certain price. Generating units are then committed and loaded in order to match the aggregated output of all generators to consumer requirements. Trading periods are 30 minutes in length and the average spot price for that period is then paid to all generators according to their energy provision.

Auxiliary energy provided by ancillary services is also reserved for unforeseen imbalances between generation and demand, and in cases of emergency which threaten the stability of the system. Ancillary services are used by AEMO to control the power quality and reliability of electricity in the NEM, and are facilitated in a similar manner to that of the electricity market, where generators bid their services into ancillary energy markets. Payments for ancillary services include payments for availability as well as the delivery of that service, and depending on the amount required at any particular time, can vary significantly from period to period.

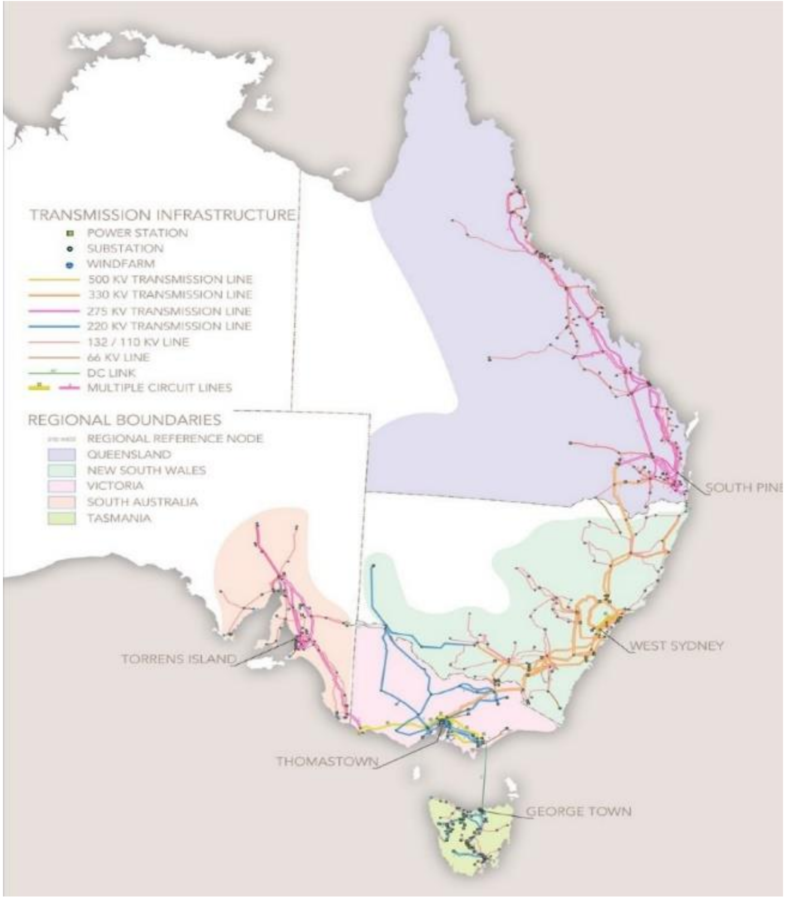

Figure 1: Transmission Infrastructure and Regional Boundaries of the NEM[1]

1.2 Frequency Regulation and FCAS Markets

Electrical power grids must maintain a constant balance between power generation and load demand in order to prevent power outages or damage to network elements and end-use appliances. The electrical frequency of an AC power network is used as an indicator of this balance and needs to be kept within certain tolerance limits at all times throughout the day in order to ensure power quality and reliability. This frequency is maintained by generators that are synchronised to the network. When electricity demand exceeds the rate of generation, the frequency in the network will begin to drop. Conversely, when generation exceeds demand, the frequency rises. Frequency regulation is similar but distinct to load following; used for the correction of unpredictable, minor disturbances in the generation and load balance, as opposed

[1] (Australian Energy Regulator, 2009)

to longer-timescale patterns that are highly correlated with time of day and seasonal change. This distinction is illustrated in Figure 2 below.

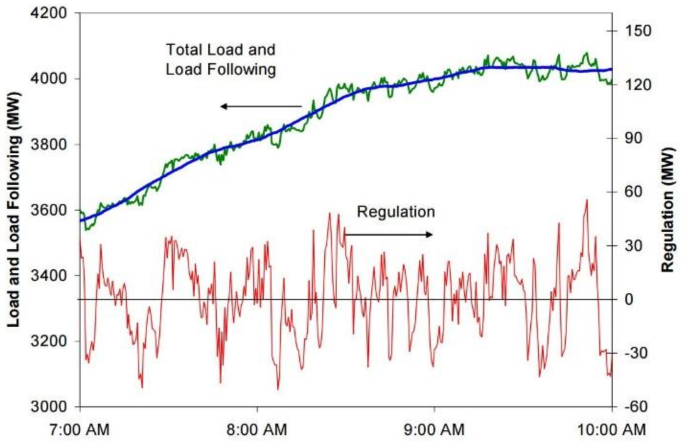

Figure 2: The Distinction Between Load Following and Frequency Regulation[2]

All regulation frequency services are provided by generators, storage units, or loads that are able to receive control signals from the network operator to adjust their output in such a way that maintains the total system frequency within its normal operating limits. Different power network have their own set of rules, system requirements, and market mechanisms that affect their generation dispatch. In New Zealand, for example, the under-frequency constraint is so stringent that, on occasion, there has been more capacity committed to reserve provision than to generation (Drayton-Bright, 1997). In the NEM, AEMO regulates system frequency through Frequency Control Ancillary Services (FCAS) in accordance with the Mainland Frequency Operating Standard[3] to maintain system frequency within the operating range of 49.85 – 50.15 Hz for at least 99% of the time during normal operation (Australian Energy Market Commission, 2009).

FCAS markets fall into one of two distinct categories: ‘Regulation’ and ‘Contingency’ markets. Services participating the in regulation market are used to continually correct the generation and load balance in response to minor deviations. Meanwhile, contingency services are only used occasionally and are reserved for the correction of the generation/load balance following a major contingency event, such as the failure of a generating unit or major transmission line. Both regulation and contingency services are categorised as either ‘Raise’ or ‘Lower’ services, while contingency services are further categorised according to their response times. Figure 3

[2] (Kirby, 2004)
[3] This does not include Tasmania, which abides by slightly more lenient standards due to having different technical characteristics (Australian Energy Market Commission, 2008)

on the following page shows the typical deployment of various contingency regulation services in electricity networks, which in the NEM are represented by the 6-second, 60-second, and 5-minute contingency services.

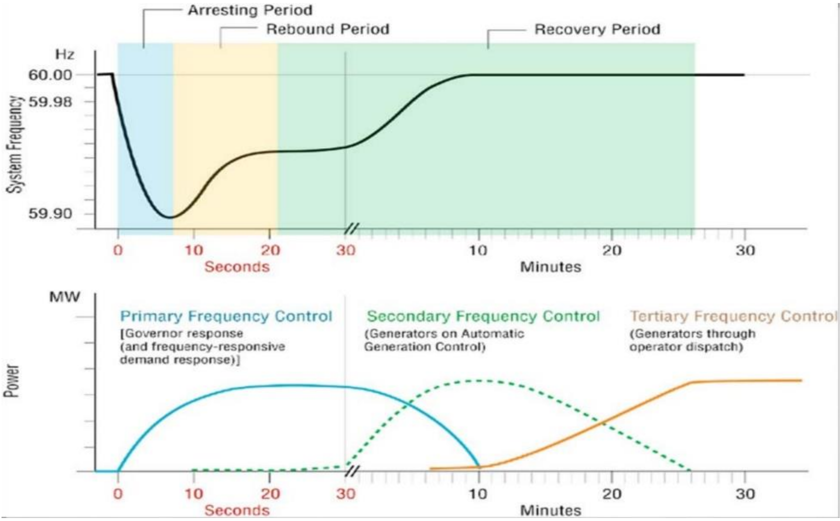

Figure 3: The Sequential Actions Of Primary, Secondary, And Tertiary Frequency Controls Following The Sudden Loss Of Generation And Their Impacts On System Frequency[4]

An example of a contingency frequency event that did not meet the NEM's Mainland Frequency Operating Standard occurred during September 2012, when the Kogan Creek Power Station suffered a trip from 731 MW. Figure 4 below shows that the mainland frequency fell below the normal operating band for 452 seconds, exceeding the maximum allowed 5 minute recovery period.

[4] (U.S. Department of Energy, 2013)

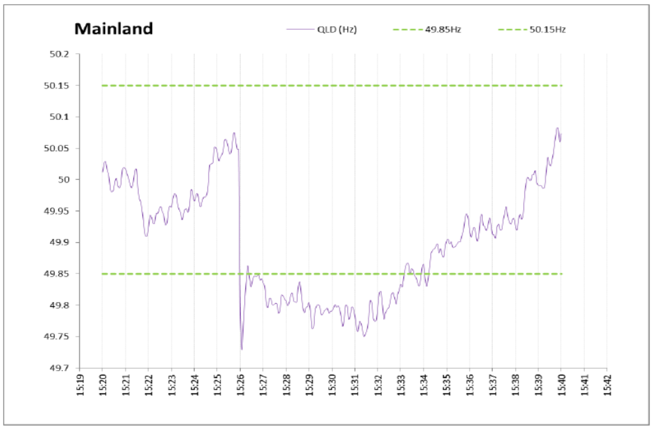

Figure 4: Under-Frequency Event In The NEM Mainland (26/09/2012)[5]

Power system frequency is seen at the system level, meaning that all mainland regions (i.e. all regions in the NEM excluding Tasmania) experience the same system frequency, and that AEMO can obtain global regulation FCAS from synchronised generators that are located anywhere within the mainland. The Basslink Interconnection which connects Tasmania to Victoria (and therefore to mainland Australia) does has the ability to provide FCAS transfers via its frequency controller, despite Tasmania operating at slightly more relaxed standards compared to the rest of the NEM. On the 2nd of August, 2015, an under-frequency event occurred in Tasmania, shown in Figure 5 below. This was caused by the trip of two transmission lines and the subsequent loss of 228 MW of generation that resulted in the disconnection of 225 MW of customer load for a brief period of time. Figure 6 on the following page shows the response of the Basslink Interconnector to the incident, which reduced its power flow to Victoria under the action of its frequency controller.

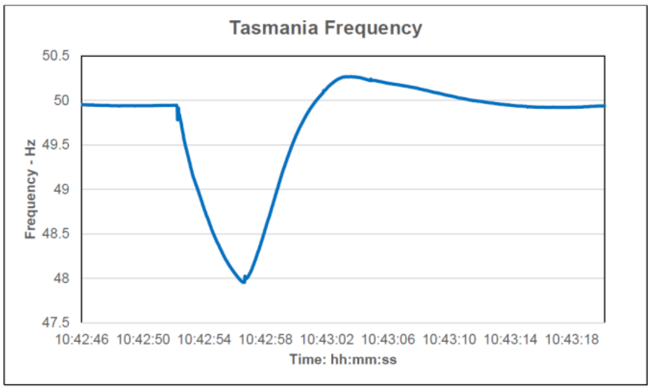

Figure 5: Under-Frequency Event in Tasmania (02/08/2015)[6]

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[5] (AEMO, 2012)
[6] (AEMO, 2015)

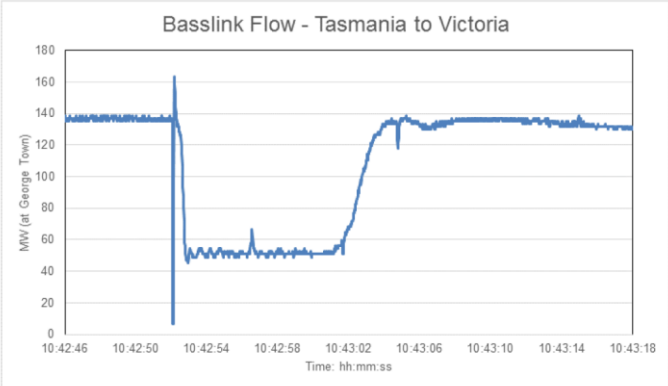


Figure 6: Basslink Response to Under-Frequency Event in Tasmania (02/08/2015)[7]

The reason that Tasmania's frequency operating standards are not as strict as those of the rest of the NEM are due to it having distinct technical characteristics. The Tasmanian power system is unique due to its relatively small load and installed generating capacity, resulting in a low power system inertia (Australian Energy Market Commission, 2008).

Power system inertia (also known as 'spinning reserve') is a measure of the energy stored in the rotating masses of generators that are synchronised to the power system and is directly related to system frequency. System inertia impacts the rate at which the frequency in an electricity network changes following a disturbance in the generation and demand balance, since such changes require all synchronous generators to speed up or slow down correspondingly. Network frequency is therefore most susceptible to changes during periods of low demand when the fewest generators are connected to the network. Conversely, when generation (and therefore power system inertia) is high, its frequency will not change as rapidly for a given disturbance.

Since power system inertia affects how rapidly the network frequency changes in response to a disturbance, there are implications for determining the amount of contingency FCAS required at any one time. However, AEMO does not regulate the amount of inertia in the NEM in any way – it is simply an observed characteristic of the system. Instead, AEMO assumes that the levels of inertia in the NEM are high enough to not affect the calculation of mainland contingency FCAS requirements (AEMO, 2013). Since regulation FCAS is not in response to any particular contingency, there is currently no analytical approach to calculating how much

[7] (AEMO, 2015)

is required at any given time, and AEMO’s approach to regulation FCAS has historically been based on empirical observations (ROAM Consulting, 2011).

1.3 Challenges in Maintaining System Frequency

Traditionally, in order to maintain the balance of power consumption and generation, electricity network operators must send out requests to generators to either ramp up or down their power output in order to maintain system frequency within normal operating limits.

However, as the configuration of electricity networks has evolved to deliver greater loads to wider populations, the introduction of distributed generators has increased the complexity in maintaining power quality and reliability, requiring more sophisticated control systems and algorithms. This challenge is compounded by the widespread growth of grid-connected renewable energy generation which presents an even greater range of challenges to network operators. In parts of Queensland and Western Australia, the installation of rooftop PV installations has already been stopped. This is an allegedly conservative approach to concerns surrounding network problems and a lack of information regarding the cost of the mitigation of such effects (CSIRO, 2012).

Under conventional frequency control techniques, this added variability in frequency is manageable for networks with low levels of renewable energy penetration. However, as the contribution of renewable energy generation is increased, so too is the magnitude of variability in power output and, consequently, frequency deviations in the electricity grid. Figure 7 below shows the 10-minute variability in power output as a function of total renewable energy production for three hypothetical scenarios with increasing levels of renewable energy penetration (2%, 14%, and 30%) in the PJM Interconnection (USA), as part of a study conducted by GE Energy Consulting (2014).

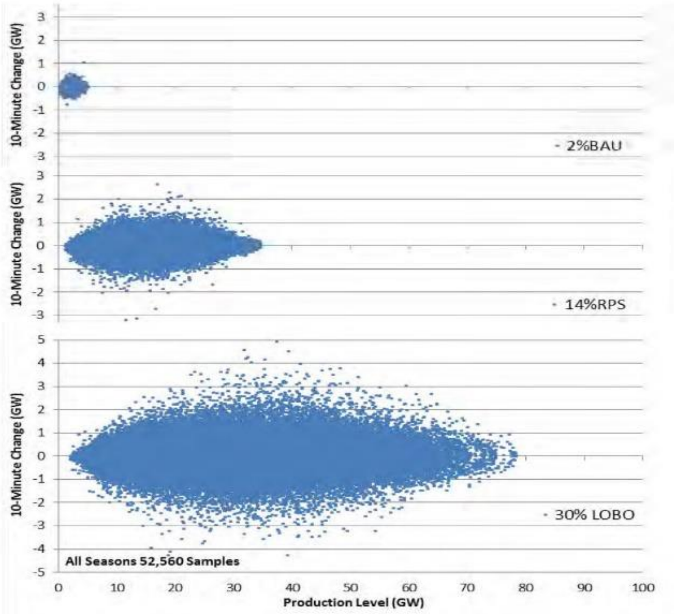


Figure 7: Ten-Minute Wind And Solar Variability As Function Of Production Level For Increasing Renewable Penetration[8,9]

According to results from the study, the 2%, 14% and 30% scenarios shown would require increases in regulation capacity of 1.5%, 30.1% and 108%, respectively[10]. Although these results are very much dependent on factors that are specific to the PJM Interconnection and its configuration of renewable energy generators, the analysis has relevance to other electricity networks by illustrating that the variability of renewable energy output is a function of the total production level.

The requirement for added frequency regulation capacity due to renewable energy generation will therefore vary significantly between regions depending on the various technologies used, network configurations, energy usage patterns, local climate types, and the sparsity of renewable energy resources. It should be well noted that existing grids with high penetration levels of renewable energy, such as those of Germany and Denmark, do not always provide a relevant reference for future power systems in Australia. (International Energy Agency, 2009). This is because the unique framework of the NEM presents contrasting technical challenges to those of the European electricity grid. The shape of the NEM is narrow and far-reaching, as opposed to being well-connected and serving a densely populated region. Despite delivering

[8] (GE Energy Consulting, 2014)

[9] Maximum variability occurs when production is around half of total capacity. This is partly due to wind generators operating above the knee in the wind-power curve where changes in wind speed do not affect electrical power output

[10] These values are dependent on the configuration of renewable energy generators. In one 30% scenario, it was found that the added variability required an increase in regulation capacity of 127.4%

electricity to a population that is only one quarter of that of Germany's, the NEM occupies an area that is roughly ten times its size (CSIRO, 2012). Furthermore, the Australian NEM operates as an 'island grid', unable to import/export electricity to neighbouring countries during periods of high/low electricity demand. The level of interconnection and capabilities of transmission lines within a power network is therefore a critical aspect of regulating frequency deviations.

There is currently very little published literature which discusses the observed system impacts of high penetrations of PV capacity. The majority of existing work focusses on modelling impacts rather than actual observations. However, there appears to be a general consensus that adequate system flexibility is a key requirement for managing high levels of intermittent renewable generation and that increasing this level of renewable energy adds strain on conventional generators, requiring them to be more flexible with their output.

There are two main reasons for this. Firstly, there are concerns that increased levels of wind and PV generation could result in the economic displacement of other forms of generation that would otherwise contribute inertia to the network. Although older wind turbine designs that are based on fixed-speed induction generators do add some limited amount of inertia to the system, this contribution is considered by AEMO to be negligible in calculations of power system inertia. Likewise, modern wind generators that are based on doubly-fed induction generators or full-rated power converters are also not considered to contribute inertia to the grid since the power electronics used in these designs essentially decouple the inertia of these generators from the network (AEMO, 2013). Rodriguez & Candela (2013) propose a method of utilising PV generators paired with synchronous power controllers in order to provide an inertial response to the grid, however this approach is not practical due to the complex electronics that must be implemented and, more importantly, a suboptimal operation which requires the PV generator to perform at a de-rated performance level, thereby resulting in a higher economic cost of the PV system (Wang, Yue, & Muljadi, 2014).

Secondly, unlike operators of conventional thermal generating units, renewable energy system operators have very little to no control over the flexibility and availability of their power outputs, as weather variations dictate the generation output of these units. The result is that PV generation is viewed as a 'negative load', and when combined with the actual system demand yields a 'net load', which corresponds to the power output that must be supplied by other generating units. Fluctuations in PV generation output for networks with high penetration levels of PV will result in proportionally high levels of variability in the net load. Consequently, conventional generating units will be required to vary their output rapidly, resulting in higher O&M costs, lower fuel efficiency, decreased lifetime, and a higher LCOE – and in some cases, possibly eliminating the economic value of PV.

However, is it suggested by Mills & Wiser (2010) that many studies which conclude the economic value of PV decreases at higher penetration levels are questionable, due to a lack of high time-resolution data from multiple PV sites. Instead, many of these results are based on overly simplified approximations, and that there currently does not exist any consensus on how to accurately characterise the aggregated variability of multiple PV sites. This suggests that there is a context-specific effect on power systems by PV generation which must therefore be considered on a case-by-case basis (CSIRO, 2012). Nevertheless, it is known from empirical observations that this variability is affected by both spatial and temporal domains, with the variability between sites decreasing as both geographic distance between sites and sampling frequency increases. Figure 8 below illustrates that the relative variability of solar irradiation is decreased when averaged over multiple locations, as compared to the variability at a single site.

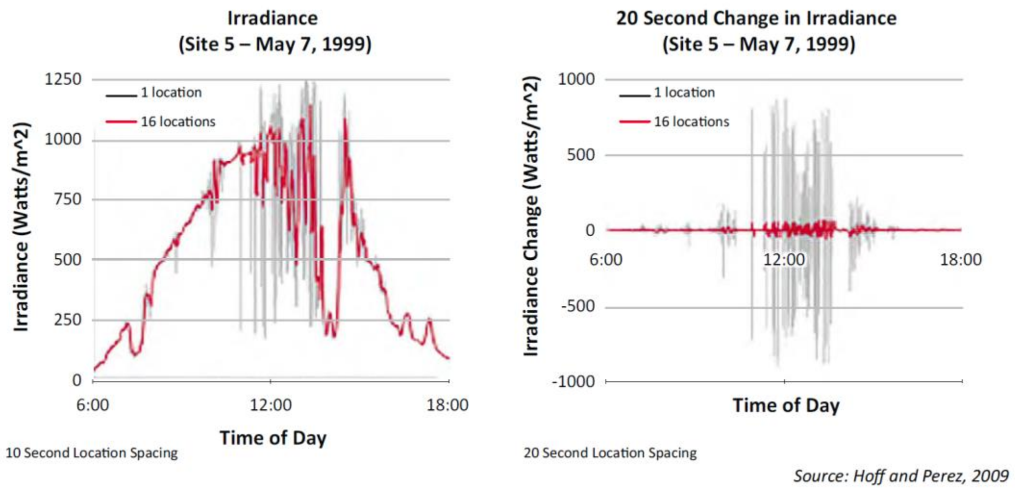


Figure 8: Relative Variability Of Solar Irradiance Is Reduced With Spatial Diversity[11]

[11] (Mills, et al., 2009)

The reason for this is because changes in the position of the sun affect the output of all PV plants in a highly correlated way, whereas cloud cover does not. Cloud cover is the main cause of short-term intermittency in PV generation, which, for a single site, can result in a large, abrupt drop in power output within seconds (Mills, et al., 2009). A good example of the variability that can be expected on a cloudy day for a large-scale PV system is shown in Figure 9 below, which shows the output of a 4.6 MW PV system located in Arizona, USA. Here it can be seen that sudden drops in power by as much as almost 4 MW can occur over very short timeframes. Therefore, when assessing the system impact of PV generation, careful consideration must be given for the configuration of PV generators as well as the timeframe over which forecasting will occur.

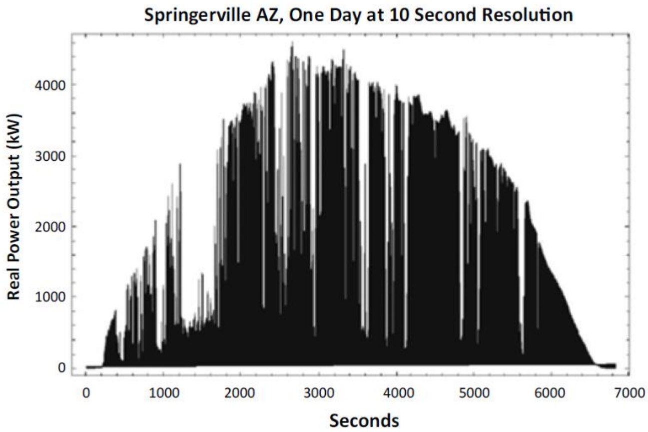


Figure 9: Power Output Of A Single PV Site On A Cloudy Day[12]

The power output of wind generators can also exhibit significant variability over short time periods. When operating below the knee in the wind-power curve, the power output of a wind turbine is proportional to the third power of wind velocity – meaning that a change in wind speed by a factor of 2 will correspond to a change in power output by a factor of 8. In reality, this is may not always be the case, as advancements in control methods such as blade pitch regulation and Automatic Generator Control (AGC) specifically designed for variable-speed wind turbines promise a better grid integration than the older fixed-speed wind turbine models (Rodríguez-Amenedo, Arnalte, & Burgos, 2002). Nevertheless, wind generation can rapidly change in such a way that cannot be fully predicted or controlled. Figure 10 shows the output of a single wind turbine over a 20 second period. It can be seen that there is a sudden drop in power output between times t = 8 seconds and t = 9 seconds, from about 1.5 MW to 0.9 MW, or roughly 40%, within a 1-second period.

[12] Taken from '*The Need for Electricity Storage*' http://www.megawattsf.com/gridstorage/gridstorage.htm

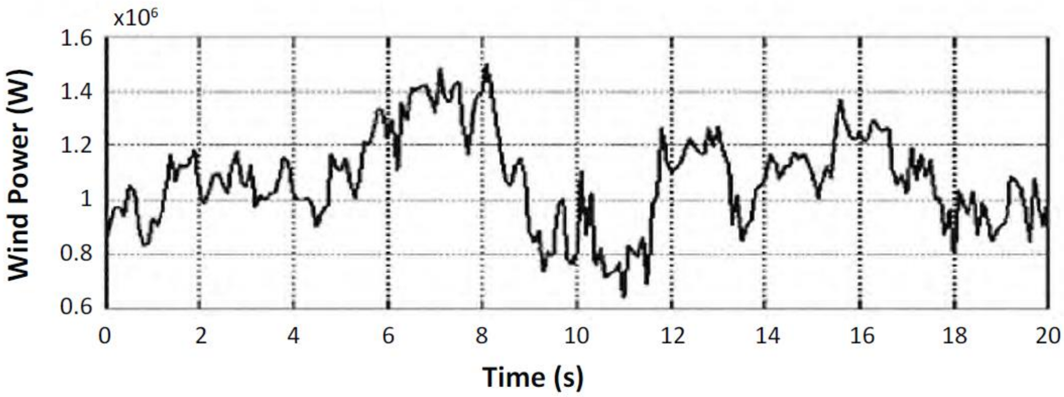


Figure 10: Wind Power Output For A Single Wind Turbine (Doubly Fed Induction Generator) [13]

As with PV generation, it has been observed that the relative intermittency of aggregated wind turbine power output decreases when generators are spaced further apart. However, the extent to which this variability decreases is difficult to quantify as different locations may have very peculiar and distinct wind resources. As such, there is currently no consensus on how to characterise the variability of aggregated wind generators. The figures on the following pages illustrate the distribution of 5-minute variability of individual and state-aggregated wind farms in South Australia, Victoria, and Tasmania, as well as the NEM-wide wind generation variability. Again, we can observe that the relative variability of wind power output is significantly decreased when aggregated over many sites. Nonetheless, these wind farms do experience a significant level of 5-minute variability, reaching as high as about ±10% for the total aggregated NEM wind production, representing a change of up to ±249.8 MW within a 5-minute period. When considering the impacts on power system frequency, these are conservative estimates of the total wind variability, since 1-minute variability can be expected to be much higher than this. According to Table 1 on the following page, the aggregated South Australian wind generation variability over a 5-minute period has been observed to be as high as 23%.

[13] (CSIRO, 2012)

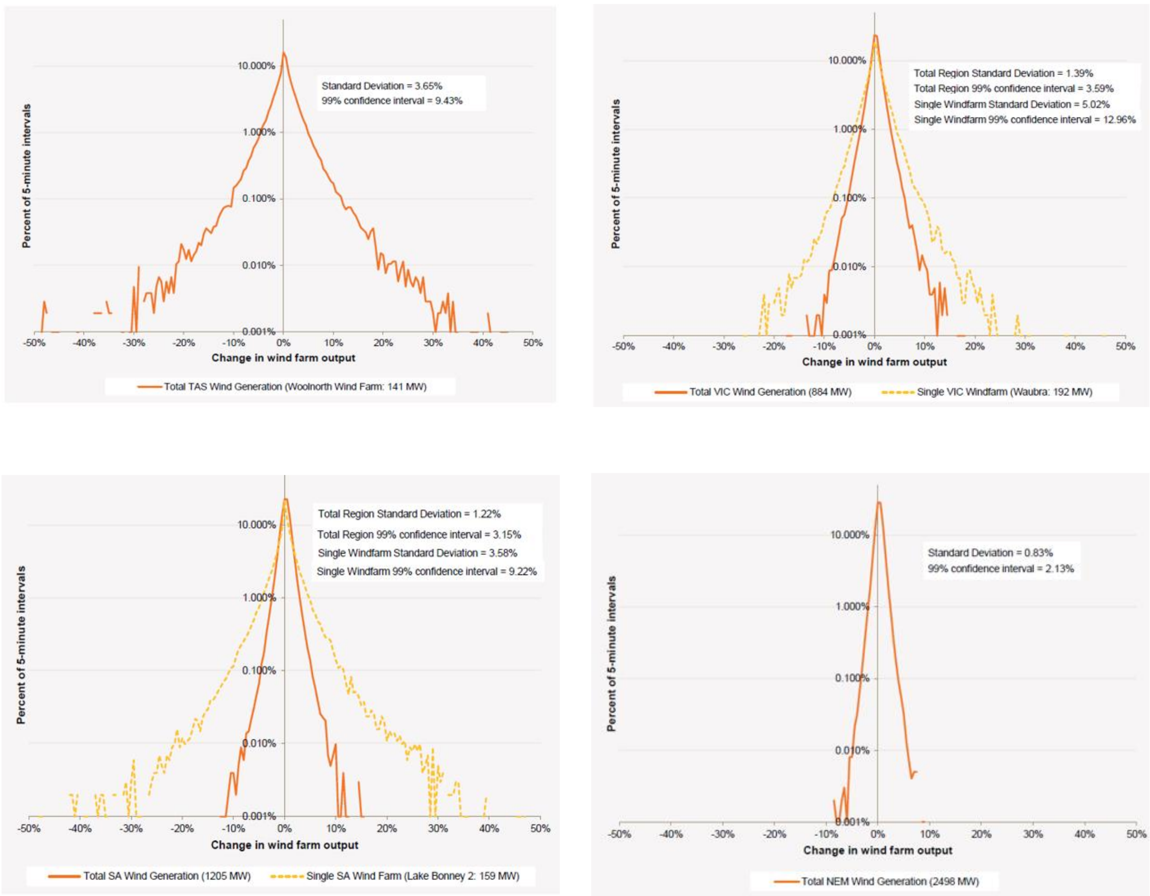


Figure 11: Probability Distribution Of 5-Minute Variability Of Wind Generation For 2013. Top Left: Tasmanian Wind Generation, Top Right: Victorian Wind Generation, Bottom Left: South Australian Wind Generation, Bottom Right: NEM-Wide Wind Generation[14]

	Mid-north region	South-east region	Coastal Peninsula region	Total South Australia
Existing installed capacity	618	325	192	1,205
Maximum 5-minute increase	275 (44%)	122 (38%)	131 (68%)	279 (23%)
Maximum 5-minute decrease	277 (45%)	140 (43%)	131 (68%)	294 (24%)

Table 1: Maximum recorded 5-minute Change In South Australian Wind Genration (MW)[15]

[14] (AEMO, 2013)
[15] (AEMO, 2013)

In order to ensure that electricity quality and reliability is not compromised, it is apparent that careful planning must take place if the NEM is to transition towards a low-carbon network. Although Australia is rich in wind and solar energy resources, particular consideration must be given to the mitigation of the intermittency that is inherent in renewable energy generation. This is most likely to occur through the uptake of fast-responding regulation services, such as those of battery systems, which are discussed in further detail in the following section of this report.

1.4 Batteries for Frequency Regulation

The idea of using grid-scale battery systems for frequency control is not a new concept, with several large battery demonstration projects having been built and operated in the past. In 1986, a 17 MW / 14 MWh lead acid battery was installed at the Bewag electric utility company in Berlin, which was designed to strengthen Berlin's island electricity network by providing frequency regulation and spinning reserve to the local grid (Künisch, Krämer, & Dominik, 1986). This project proved to be successful, however, when Berlin was connected to the wider electricity grid in 1993, the battery was no longer needed for frequency regulation and was decommissioned. Nonetheless, the operation of the project provided valuable information in demonstrating the role that batteries can play in stabilising island networks (Wagner, 1997).

For power grids that struggle to maintain system frequency, battery systems present a desirable solution to meeting the rapidly fluctuating signals that the network demands. The benefits of utilising battery systems for this application are twofold; firstly, this would free up existing generator regulation capacity to be used for other services such as energy provision or contingency reserve generation, thereby improving system stability and consequently allowing a greater amount of renewable energy generation to be contributed to the grid. Secondly, batteries exhibit a number of advantages over conventional thermal generators that allow them to better control system frequency. This is, of course, in addition to the vast number of other applications that batteries can serve to the grid, including peak load shaving, energy arbitrage, backup power, and renewable energy generation smoothing.

Batteries are not restricted by the mechanical and thermal constraints that limit the rate at which conventional generators can change their output, and are therefore able to respond to signals much more quickly and accurately to within the scale of milliseconds. This can be seen in

Figure 12, which is taken from operational data from the PJM Interconnection in the USA and shows the control signals and associated responses from a lithium-ion battery and a natural gas turbine. PJM regulates its frequency by sending out two separate control signals: a 'traditional' signal, for conventional generators, and a 'dynamic' signal for battery systems. It can be clearly seen that the battery response follows the regulation control signal much more tightly than the natural gas turbine, which lags behind by several seconds. This is despite the dynamic signal requiring a much faster fluctuation than the traditional signal.

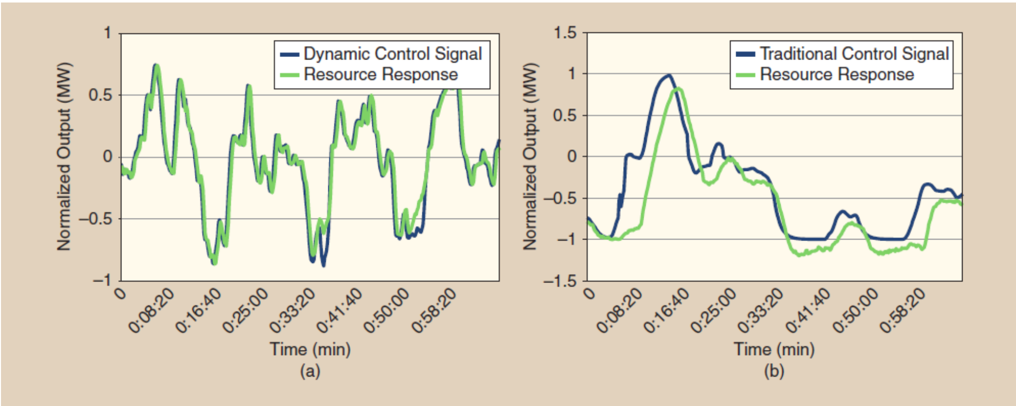


Figure 12: The Two PJM Regulation Control Signals. Left: A Lithium-Ion Battery That Follows The Dynamic Signal. Right: A CCGT Plant That Follows The Traditional Signal[16]

In addition to having a much faster response time, batteries are also capable of operating over a greater flexible range than conventional generators, being able to charge and discharge as required. Contrastingly, generators must often maintain some minimum stable level before being able to quickly adjust their output, resulting in ongoing standby costs and emissions. This is illustrated in Figure 13 below, which shows that the flexible range of a thermal generator is typically much lower than that of a battery system with the same power rating.

[16] (Boston & Baker, 2015)

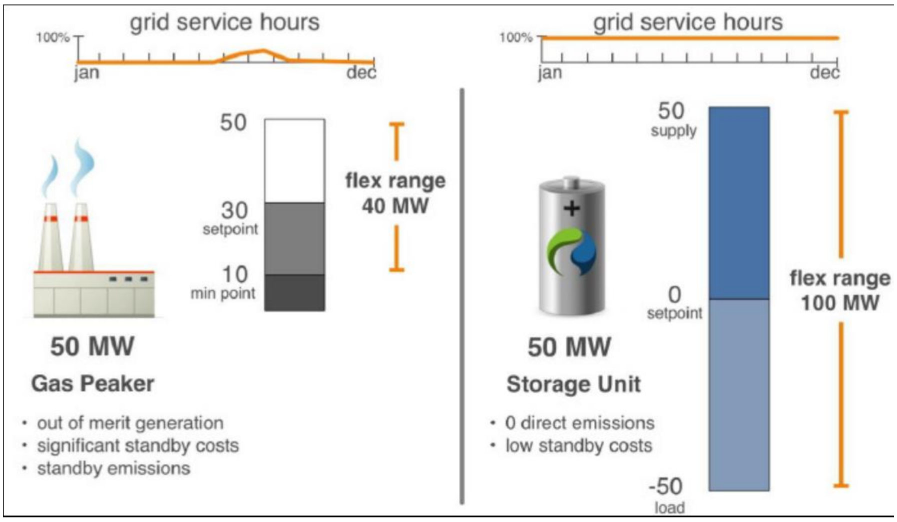


Figure 13: The Flexible Range Of A Typical 50 MW Gas Turbine And Energy Storage Unit[17]

Since implementing the dynamic and traditional regulation control scheme in 2012, PJM has been able to reduce the total amount of power procured for regulation from 1% of peak load[18] down to 0.7%, and then again to a fixed amount of 700 MW on-peak and 525 MW off-peak; resulting in an overall reduction in the cost of this service (Boston & Baker, 2015).

Although Australia has an opportunity to learn from international experiences, such as that of Berlin and the PJM Interconnection, careful consideration must be given for the type of battery technology used with regard to Australia's unique climate conditions. Lithium-ion batteries, for example, are particularly sensitive to temperature effects when cycled outside of their normal operating range, which can accelerate irreversible cell degradation if not tightly controlled. Furthermore, across Australia, extreme weather events typically correlate with peak demands in energy usage, potentially adding further stress on the battery system. Test results from a study conducted by Waldmann *et. al*. (2014) are shown in Figure 14 below, illustrating the effects of

[17] (Energy Storage Coalition, 2014)

[18] Where peak load in the PJM Interconnection is typically about 163,500 MW (Boston & Baker, 2015).

temperature on the state-of-health[19] (SOH) of a lithium-ion[20] battery when cycled at its 1C rate[21].

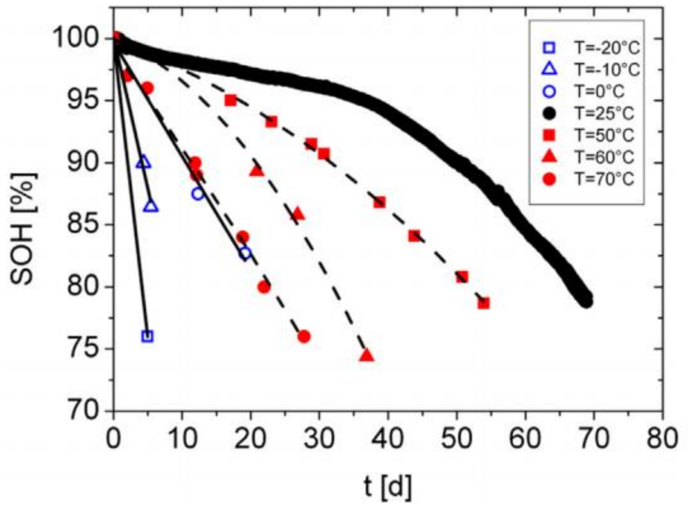


Figure 14: Measured SOH Curves As A Function Of Temperature For A Li-Ion Battery Cycled At Its 1C Rate[22]

The most suitable battery for frequency regulation will be able to operate over a wide range of temperatures, be capable of high charge and discharge rates, and will be able to operate in a partial state of charge (PSOC) regime. The advanced lead acid battery serves as a good candidate for this application, having been deployed for a number of demonstration projects in Australia, as well as providing frequency regulation to the PJM Interconnection since 2013 (East Penn Manufacturing Co, 2014).

The advanced lead acid battery, which was developed at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), combines a supercapacitor and a conventional lead acid battery within the battery cell. The supercapacitor enhances the specific power of the battery by acting as a buffer between the battery cell and terminals during charge and discharge. In this way, the battery is able to operate at very high charge/discharge rates in a PSOC.

[19] Where SOH is defined as the discharge capacity of an aged cell compared to the discharge capacity of the same cell when it was new. A SOH of less than 80% is usually regarded as the end of life criterion for a battery.
[20] Tests were done on a Lithium Nickel Manganese Cobalt Oxide battery.
[21] C ratings specify the discharge current of batteries in terms of time from full charge to depletion. For example, a battery discharged at its 1C rate would provide that current for 1 hour, and a battery discharged at its 2C rate would provide that current for ½ hour.
[22] (Waldmann, Wilka, Kasper, Fleischhammer, & Wohlfahrt-Mehrens, 2014)

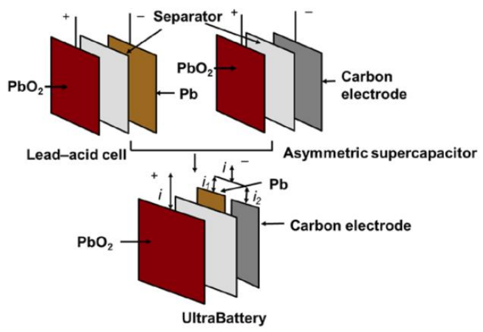


Figure 15: Advanced Lead Acid Battery Chemistry[23]

The high power capabilities and PSOC operation of the advanced lead acid battery make it particularly well-suited to grid-connected applications. Figure 16 and Figure 17 below show the response of Ecoult's advanced lead acid battery system to PJM's regulation control signal, as well as its state of charge (SOC) during this time. We can see that the advanced lead acid battery is able to charge and discharge very quickly in response to the control signal while operating in a PSOC regime.

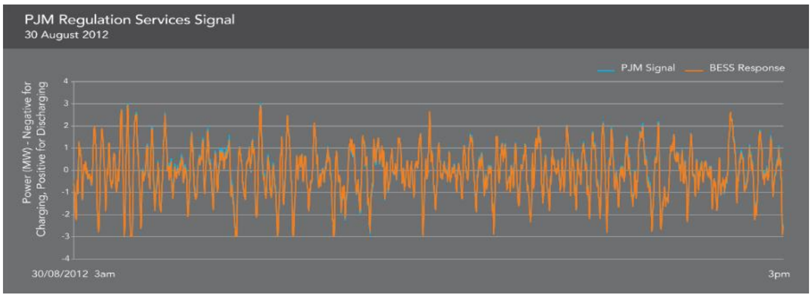


Figure 16: Advanced Lead Acid Battery Response To PJM Regulation Control Signal[24]

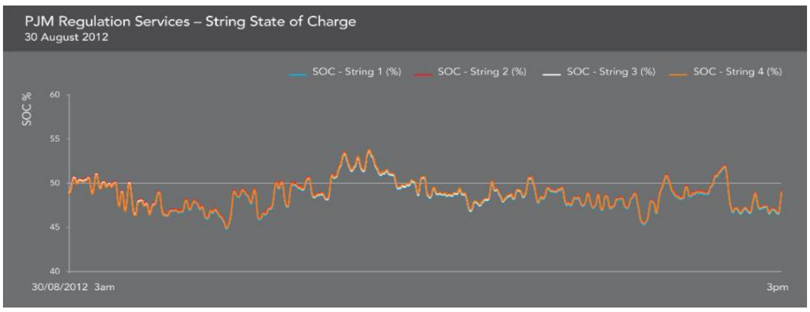


Figure 17: Advanced Lead Acid Battery State Of Charge During Frequency Regulation Provision To The PJM Interconnection[25]

[23] (CSIRO, 2015)
[24] (Ecoult, 2013)
[25] (Ecoult, 2013)

Chapter 2

2 Research Design

2.1 Aim

THE aim of this project was to investigate the effects of adding fast-responding battery regulation capacity on the stability of the NEM, as indicated by its generator ramping requirements and transmission power flows between regions. This project used computer simulations that were based on actual measured data as well as mathematical approximations in order to create a power system model that was representative of the NEM.

2.2 Methodology

2.2.1 PLEXOS Integrated Energy Model

The software being used to model the behaviour of the NEM is PLEXOS[26], which is a software package that has been specifically designed to simulate energy markets and power systems over both short and long timescales. PLEXOS was chosen for this project as it is capable of modelling complex power systems over a short timescale of 1-minute intervals, making it a very comprehensive package that is suitable for modelling regulation services.

PLEXOS was used to build a model of the NEM from the ground up, which included its five regions and their major transmission lines, generators, load profiles, and contributions from PV and wind generation. The NEM model was then adjusted according to different situations of varying generation portfolios (including battery regulation capacity), renewable energy variability, and climatic conditions, resulting in a total number of 36 scenarios. Each of these scenarios consisted of more than 250 network elements, 460 memberships, and 1,700 properties. All of these scenarios were run over 1-week periods at the 1-minute interval resolution, equating to 10,080 periods per scenario. A screenshot of the PLEXOS Graphical User Interface (GUI) is shown in Figure 18 on the following page.

[26] PLEXOS Integrated Energy Model is a product of Energy Exemplar (www.energyexemplar.com)

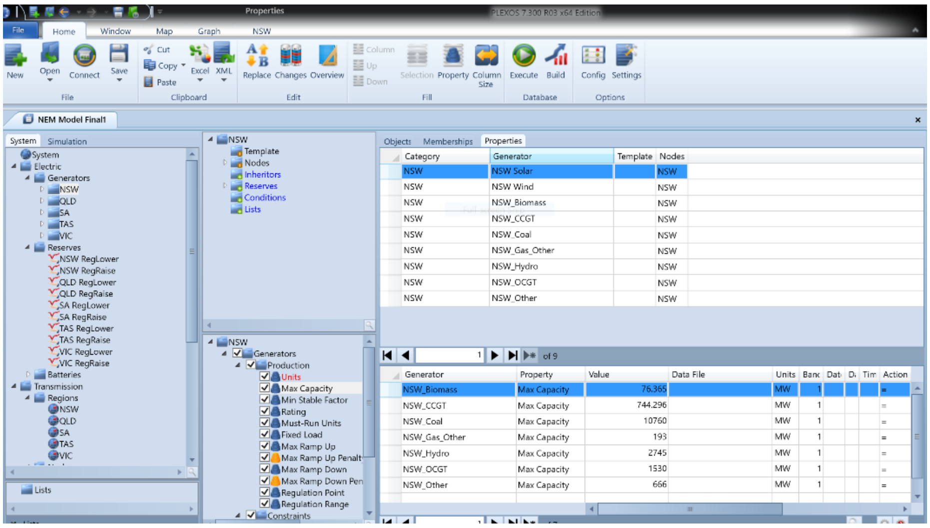


Figure 18: PLEXOS Graphical User Interface

2.2.2 Data Acquisition

Simulations in PLEXOS were modelled spanning 1-week periods representing both summer and winter loads. For consistency between datasets, the periods investigated were the weeks spanning the 13th-19th of January, 2015, and the 13th-19th of June, 2015.

Data used to generate the model of the NEM was acquired from a number of sources. Where data was unavailable or incomplete, mathematical approximations were made which will be discussed in further detail later in this report. The following dot points summarise the primary sources of datum that were used in the PLEXOS NEM model:

- Generator rated and maximum power output data was obtained from AEMO.
- Transmission line maximum rated power flow data was obtained from AEMO.
- Measured regional load data was obtained from Global-Roam[27]
- Measured regional wind generation data was obtained from Global-Roam.
- Solar irradiation data was acquired from the Australian Bureau of Meteorology (BOM).
- Data pertaining to installed capacity of large-scale and rooftop solar PV in Australia was obtained from the Australian PV Institute (APVI).
- Forecasted growths in load demand, wind energy generation, and PV generation were taken from the Australian Bureau of Resources and Energy Economics (BREE) and AEMO.

[27]Global-Roam Pty Ltd (home.global-roam.com)

2.2.3 Modelling the NEM

AEMO has a publicly available PLEXOS model of the NEM, known as the National Transmission Network Development Plan (NTNDP). This model was, however, not used in this project as it was found to be unsuitable for the purposes of this study, having been designed specifically for long-term planning. The maximum data resolution in this model is presented in 1-hour interval periods which is not sufficient to accurately simulate the short-term fluctuations in generation and load that require regulation provision. Furthermore, consideration needed to be taken for the computational requirements of this project. While each simulation was to be run at a very fine time resolution of 1-minute intervals, the NTNDP contains over 30,000 objects, memberships and properties, which would have added unnecessary computing time. Therefore, a more simplified model of the NEM was created from the ground up, in order to obtain results that were relevant to this study. The following section outlines how the NEM was modelled and some of the assumptions that were made.

2.2.4 Transmission Characteristics

Regions within the NEM were simulated as having a single reference node. These reference nodes are transmission buses which are required to connect generators and loads. Transmission lines then connect regions via these nodes, forming the overall framework of the NEM. There are 6 major transmission lines in the NEM which connect each of its regions. Table 2 below details the power flow ratings of these interconnectors in the NEM whose values were used in the modelling for this project:

Name	Direction	Forward Flow Rating (MW) [28]	Reverse Flow Rating (MW) [29]
Terranora	NSW → QLD	107	210
NSW1-QLD1	NSW → QLD	300-600	1078
VIC1-NSW1	VIC → NSW	700-1600	400-1350
Basslink	TAS → VIC	594	478
Heywood	VIC → SA	460	460
Murraylink	VIC → SA	220	220

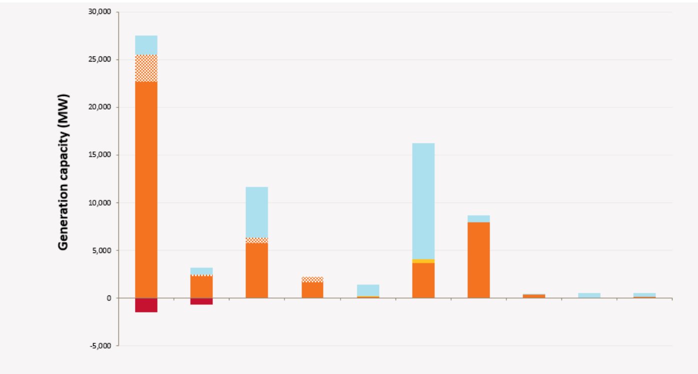
Table 2: Interconnector Rated Power Flows[30]

[28, 28] Transmission lines were assumed to be able to operate at their maximum power rating at all times

[30] (AEMO, 2015)

2.2.5 Modelling Generation Portfolios

There are over a hundred generators in the NEM that supply electricity to each of its regions. In order to reduce the amount of time required for calculations, the generators in each region were categorised according to their technology type, and their outputs aggregated. In this way, each generator technology type was modelled as a single generator providing services to its respective region. The technologies that generators were categorised by were: Coal, Combined Cycle Gas Turbine (CCGT), Open Cycle Gas Turbine (OCGT), 'Other Gas', Solar, Wind, Hydroelectric, Biomass, and 'Other'. These categories align with information given in AEMO's Generation Information Datasheets (AEMO, 2016), from which the figures for regional generator rated capacity were taken. (Note that there is some ambiguity here surrounding the distinction between solar PV and solar thermal technology. Hence, solar PV data was sourced elsewhere, as discussed later in this report). Further details of generators' maximum power ratings were obtained from AEMO's Current Registration and Exemption Lists (AEMO, 2016), which was cross-referenced with the Generation Information Datasheets in order to verify the rated capacities of each generator technology. In instances where conflicting rated capacities were stated, the maximum power output was calculated as a percentage of the rated capacity from the Current Registration and Exemption List, and then re-calculated based on the figures given in the Generation Information Datasheets. Shown below is the NEM-wide aggregated generator rated capacity by technology type, as stated on the AEMO Generator Information web page (AEMO, 2016).



	Coal	CCGT	OCGT	Gas other	Solar	Wind	Water	Biomass	Geo-thermal	Other
Committed	-	-	-	-	56	362	-	-	-	-
Proposed	2,000	715	5,315	-	1,174	12,194	666	22	510	365
Withdrawn	-1,489	-624	-	-	-	-	-	-	-	-
Announced Withdrawals	2,786	171	578	510	-	-	-	-	-	-
Existing less announced withdrawals	22,716	2,299	5,806	1,696	176	3,688	7,987	423	-	169
In Service*	**25,502**	**2,470**	**6,384**	**2,206**	**176**	**3,688**	**7,987**	**423**	-	**169**

* "In service" capacity includes "Announced withdrawals".

Figure 19: NEM-Wide Aggregated Rated Capacity Of Existing, Withdrawn, Committed And Proposed Generating Units, By Fuel Source & Technology Type[31]

[31] (AEMO, 2016)

Hydroelectricity minimum generation level and maximum ramp rates were taken from AEMO's Current Registration and Exemption Lists. However, due to incomplete data, values for other generator technologies were not taken from this same source. Values pertaining to Coal, CCGT, and OCGT generator ramp rates and minimum generation levels were extrapolated from values stated by Vithayasrichararreon & MacGill (2014). The values for ramp rates were calculated as a percentage change per minute, relative to rated capacity, and then re-calculated as a MW/min ramping rate. The percentage change per minute values for Coal, CCGT, and OCGT were found to be 1.33%/min, 2.40%/min, and 6.66%/min, respectively. A percentage change of 6.66%/min for 'Gas Other' was also applied as a conservative approximation.

Table 3 below summarises the operating characteristics of generators in NSW as modelled in PLEXOS (a complete list of generator properties for each state can be found in the Appendix of this report). To avoid speculation, some values have been omitted due to a lack of reliable information. However, these exclusions are not expected to have a major impact on the final result due to these generators' relatively small contribution to total generation capacity, and also because frequency regulation services were modelled to be only provided by Coal, CCGT, OCGT, and Hydroelectric generators, as discussed later in this report.

New South Wales Scheduled Generation Portfolio					
Generator Type	**Rated Power (MW)**	**Maximum Power (MW)**	**Minimum Stable Level (% Rated Power)**	**Maximum Ramp-Up (MW/min)**	**Maximum Ramp-Down (MW/min)**
Coal	10,240	10,760	50	136.53	136.53
CCGT	598	744.30	40	14.35	14.35
OCGT	1,530	1,530	0	101.90	101.90
Hydro	2,745	2,745	20	880.72	880.72
Biomass	72	76.37	-	-	-
Gas Other	193	193	-	12.85	12.85
Other	666	666	-	-	-

Table 3: New South Wales Generator Operating Characteristics

2.2.6 Modelling FCAS Capabilities

The Reserve Class in PLEXOS is a powerful tool that enables the simulation of various ancillary services including both regulation and contingency provision. PLEXOS is able to integrate user-defined reserve constraints into its mathematical framework for the dispatch and co-optimisation of energy and regulation provision in the same way as in the Australian electricity market (Energy Exemplar, 2013).

This project does not take into account the modelling of contingency events and therefore only FCAS Regulation Raise and Lower services will be considered. Each reserve service is connected to a region via its associated generators and battery systems (if applicable). According to AEMO's Current Registration and Exemption Lists (AEMO, 2016), regulation services in the NEM are provided only by Coal, Hydroelectric, CCGT, and OCGT generators. This detail was modelled in PLEXOS by specifying which generators are linked to reserve services.

AEMO calculates the amount of regulation FCAS required on the mainland based on time error, with a minimum regulation set point of 130 MW and 120 MW for raise and lower services, respectively, and an upper limit of 250 MW for both. In PLEXOS, reserve services are attributed to a particular region. Since FCAS services can be obtained from anywhere on the mainland, it was assumed that reserve services are shared equally amongst regions. Therefore, each region's minimum and maximum regulation raise provisions were set to 32.5 MW and 62.5 MW, respectfully; while each region's minimum and maximum regulation lower provisions were set to 30 MW and 62.5 MW– making sure that the 'Sharing Enabled' setting was implemented so that regions can import and export regulation services to each other. An example of the PLEXOS inputs for New South Wales are shown in Table 4 below. These requirements do not apply to Tasmania, whose regulation requirements were set to a nominal value of 50 MW for both raise and lower services, as outlines in the National Electricity Rules (AEMO, 2014). A summary of these values can be found in the Appendix of this report.

Reserve	Property	Value	Units
NSW RegLower	Sharing Enabled	Yes	Yes/No
NSW RegLower	Min Provision	30	MW
NSW RegLower	Max Provision	62.5	MW
NSW RegRaise	Sharing Enabled	Yes	Yes/No
NSW RegRaise	Min Provision	32.5	MW
NSW RegRaise	Max Provision	62.5	MW

Table 4: NSW Regulation Property PLEXOS Inputs

2.2.7 Modelling Battery Regulation Capacity

Battery operating characteristics that were used in this PLEXOS model are approximate values that were based on a 1.5 MWh advanced lead acid battery system. Battery systems were assumed to have an initial SOC of 55% (midway between its minimum and maximum SOC). These values are summarised in Table 5 below.

Advanced Lead Acid Battery Assumed Operating Characteristics	
Max Power	1.4 MW
Charge Efficiency	95%
Discharge Efficiency	95%
Minimum State of Charge	30%
Maximum State of Charge	80%

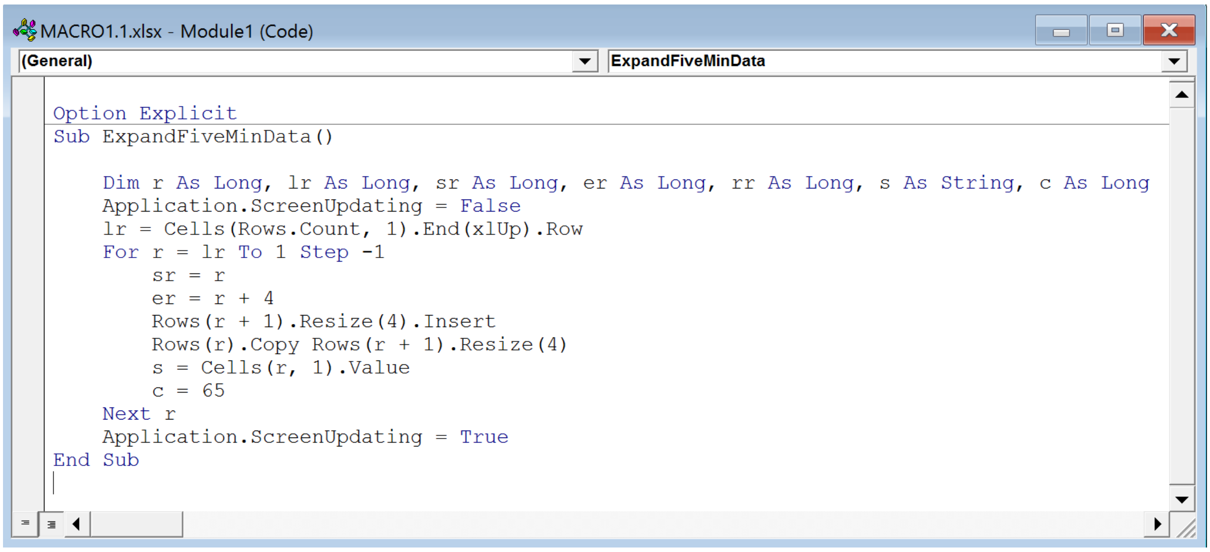
Table 5: Regulation Battery Operating Characteristics As Modelled In PLEXOS[32]

2.2.8 Modelling Random Variability in PLEXOS

The Variable Class in PLEXOS is a powerful tool that can be used to set conditions on objects, introduce a user-defined change to some datum over a given time, or define stochastic and expected profile data. This function was used in this model to introduce 1-minute random variability into datasets that were only available in 5-minute intervals, as opposed to other studies which have relied on linear interpolation in order to approximate contiguous values in a sequence. In this way, it is possible to generate a realistic dataset of 1-minute resolution from a dataset that has been sampled in 5-minute interval periods.

The first step was to create a Microsoft Excel macro script which was able to expand a dataset by repeating each sequential value five times. The Excel macro script that was used is shown in Figure 20**Error! Reference source not found.** on the following page.

[32] (Wood, 2016)


MACRO1.1.xlsx - Module1 (Code)

(General) | ExpandFiveMinData

```
Option Explicit
Sub ExpandFiveMinData()

    Dim r As Long, lr As Long, sr As Long, er As Long, rr As Long, s As String, c As Long
    Application.ScreenUpdating = False
    lr = Cells(Rows.Count, 1).End(xlUp).Row
    For r = lr To 1 Step -1
        sr = r
        er = r + 4
        Rows(r + 1).Resize(4).Insert
        Rows(r).Copy Rows(r + 1).Resize(4)
        s = Cells(r, 1).Value
        c = 65
    Next r
    Application.ScreenUpdating = True
End Sub
```

Figure 20: Screenshot Of Microsoft Excel VBA Macro Script Used For Dataset Expansion

The next step was to then introduce some level of variability to the newly expanded datasets. The approach used in this model was to set the expected chronological values according to the newly expanded datasets and then define parameters specifying the magnitude and distribution of how stochastic values would be generated around the datasets.

This was performed by employing the Endogenous Sampling method, in which the data has an expected value that varies on a period-to-period basis and whereby the stochastic variable then applies a differential equation to create an error function for each period (Energy Exemplar, 2015). For this model, the errors were set to be normally distributed around the expected values while also following the Simple Autocorrelation Model, whose equation is shown below.

$$e_t = \left[a \times r_{t-1} + (1-a) \times r_t\right] \times P_t \times S$$

where:

e_t is the error for time period t

a is the autocorrelation parameter (between 0 and 1)

r_t is a normal distributed random number

P_t is the expected value (profile value) in period t

S is the error standard deviation

Equation 1: Differential Equation Used in PLEXOS Simple Autocorrelation Model[33]

[33] (Energy Exemplar, 2015)

We can see from the above equation that the two input parameters are the Autocorrelation and Error Standard Deviation values, both of which are expressed as percentages in PLEXOS. According to the equation, a high autocorrelation results in a smoother curve with dampened randomness, whereas a higher standard deviation increases the volatility of these errors.

2.2.9 Modelling PV Generation

Since measured PV generation data was not available, the behaviour of PV systems in in the NEM was modelled based on a number of approximations. The first step was to determine the installed nameplate generation capacity of PV generation in the NEM. The Australian PV Institute (APVI) has compiled a 'solar map' of Australia which is the most comprehensive account of PV systems in Australia, including both large-scale and residential systems. The table below summarises the installed capacity[34] of PV generation in each state, as modelled in the PLEXOS NEM model. It should also be noted that solar thermal generators were not considered in the modelling for this project, since solar thermal technologies do not exhibit the same characteristics as PV in terms of short-term variability (CSIRO , 2012). Furthermore, solar thermal generators are most commonly used for water heating, displacing natural gas rather than electricity, therefore contributing a very small amount to the NEM.

State	**Total PV Capacity (MW)**
NSW[35]	1,263.038
QLD	1,524.942
VIC	905.411
SA	659.069
TAS	92.473

Table 6: Current Installed PV Capacity By State[36]

[34] As of May 22nd, 2016
[35] Includes the Australian capital Territory
[36] (APVI, 2016)

Ignoring the effects of temperature on solar cells, the output of a PV system has a linear relationship with the amount of solar irradiation it is exposed to. Solar irradiation measurements taken from the Bureau of Meteorology (BOM) were used to gauge the approximate solar irradiation in each state, despite irradiation data only being collected at a limited number of station across Australia. The sites from which data was used were selected based on close proximity to regions of high concentration of PV generation, as well as for consistency between dates, since many sites had missing data for the periods investigated. These sites were: Melbourne (Victoria), Adelaide (South Australia), Rockhampton (Queensland), Wagga Wagga (New South Wales), and Cape Grim (Tasmania). Since measurements from these sites were taken using ground-based equipment, the datasets were at times highly variable due to cloud cover and therefore not representative of the overall solar irradiation in each of the regions. Instead, a 'smooth' solar irradiation profile was used which was then scaled according to the daily maximum readings at each site. Again, this was not entirely representative of the solar irradiation in each state, but because power system frequency is affected by short-term fluctuations in PV generation, such as those caused by cloud cover, daily variability in solar irradiation was not expected to have a major impact on the end results. Furthermore, since solar PV installations are most concentrated in capital cities across the NEM, as seen in Figure 21 below, it is reasonable to assume that PV systems in these regions will be exposed to roughly the same daily maximums in solar irradiation. From the solar irradiation maps in Figure 22 and Figure 23 on the following page, we can also see that there is some correlation in the daily average solar irradiation between weather stations and capital cities within the same state.

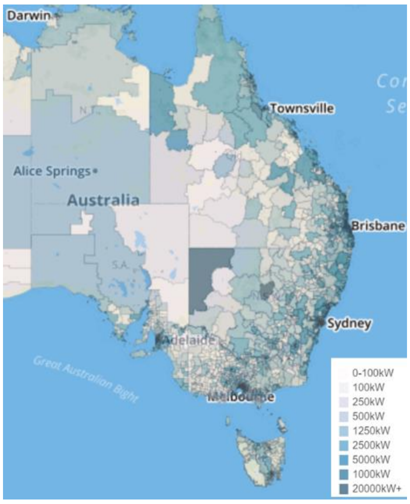


Figure 21: Solar Map Of Australia Showing PV Capacity By Postcode Area[37]

[37] Taken from The Australian PV Institute (APVI), funded by the Australian Renewable Energy Agency, available at pv-map.apvi.org.au

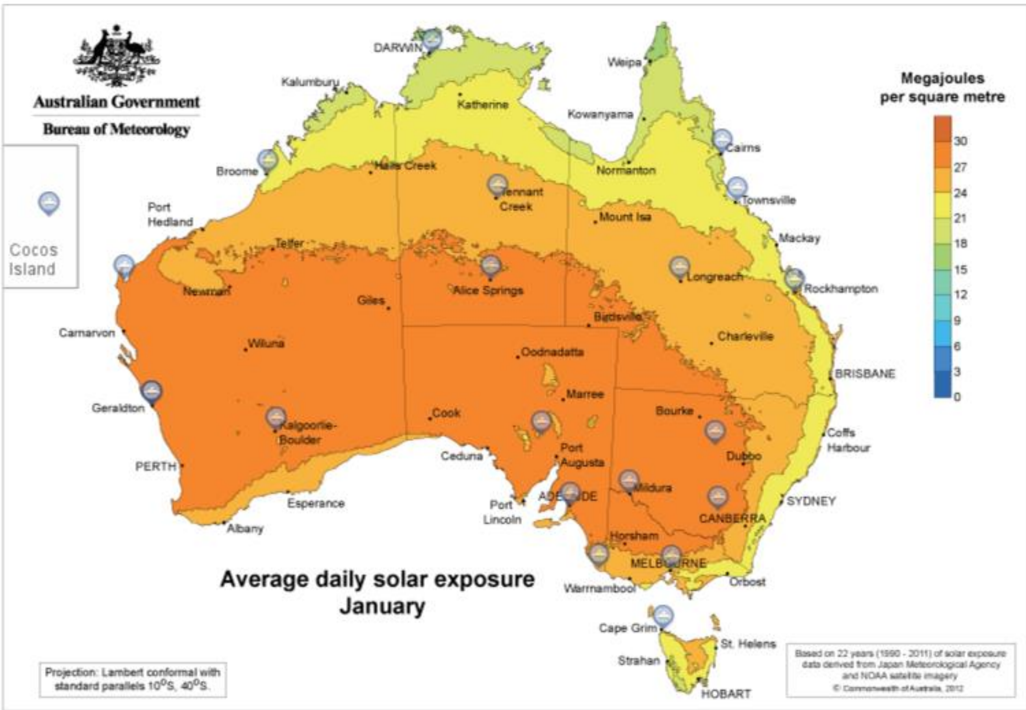


Figure 22: Average Daily Solar Exposure In January[38]

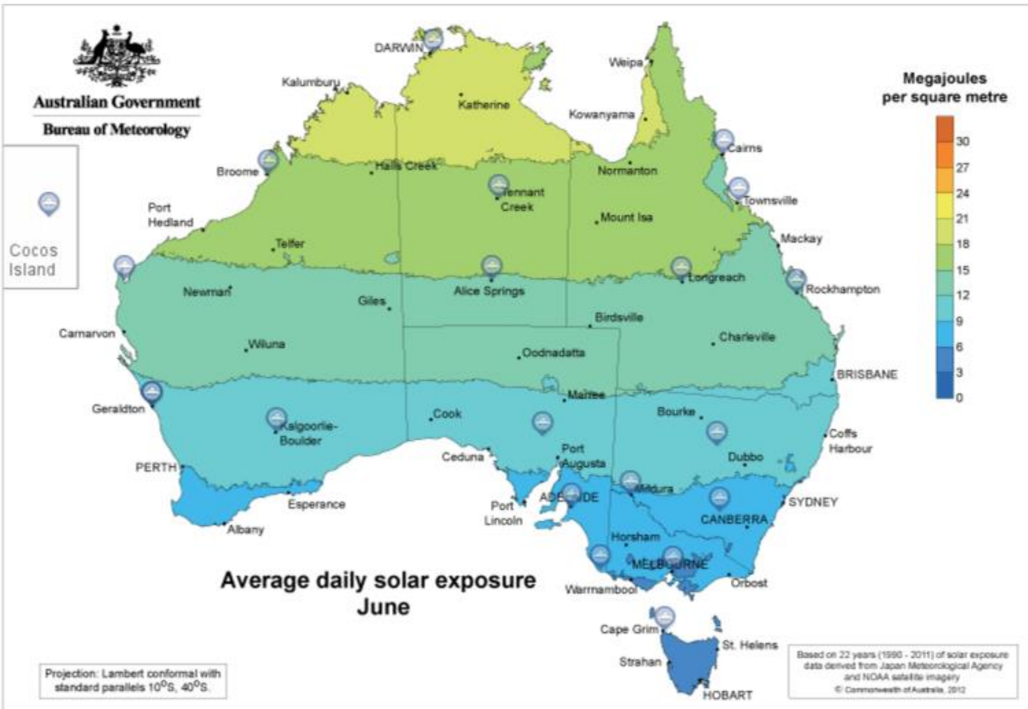


Figure 23: Average Daily Solar Exposure In June[39]

[38] (Bureau of Meteorology, 2016)
[39] (Bureau of Meteorology, 2016)

Modelling the output of PV generators was based solely on incoming solar irradiation. The capacity of PV generators is rated based on their output at standard test conditions (STC). One of the key assumptions for STC is that the incoming solar irradiation is 1,000 W/m^2. Therefore, a 1 MW rated PV array receiving 900 W/m^2 will generate 0.9 MW, ignoring temperature effects, module degradation, manufacturer derating, cable losses, inverter constraints, or any other limiting factors. Another key assumption was that all PV modules are fixed in a horizontal orientation, since this is how solar irradiation is measured at BOM's weather stations.

The final step, given solar generation for each state, was to introduce variability using the PLEXOS Variable Class. As previously discussed, the variability of aggregated PV generators is difficult to characterise, and there doesn't current exist any consensus on the best approach. Therefore, each scenario was modelled under three different levels of renewable energy variability, as measured by the percentage error of standard deviations: 5%, 10%, and 15% variability, with a 90% autocorrelation for each. In this way, these three levels of variability represent different configurations of PV generation under high levels of variability.

2.2.10 Modelling Wind Energy Generation

Measured wind generation data, aggregated by state, was used in the modelling for this project. Wind generation data included data from all wind farms in the NEM whose rated capacity is over 30 MW. Wind generation in Queensland is therefore assumed to be negligible as it only has one wind farm, the Windy Hill Wind Farm, which is rated at 12 MW. Since this data was only available in 5-minute intervals, it was necessary to expand the datasets using the aforementioned Microsoft Excel macro script. Variability at the 1-minute level was then introduced using the PLEXOS Variable function. As with PV generation, wind variability was set to 5%, 10%, and 15% error standard deviation in order to represent varying configurations of wind generation with high levels of variability. Since there are fewer wind generators than PV generators in the NEM, an autocorrelation of 75% (as opposed to 90%) was applied to the wind generation variable in PLEXOS.

2.2.11 Modelling Electricity Demand

This model used measured electricity demand data which was available in 5-minute intervals and aggregated by state. As with PV and wind generation data, this dataset was also expanded using Microsoft Excel to generate 1-minute interval data. Once again, the PLEXOS variable function was used in order to introduce some level of variability to the dataset. Characterising the amount of variability that is inherent in electricity demand is difficult to verify. However, a nominal value of 1% error standard deviation was applied to all scenarios with a 75% autocorrelation value.

2.2.12 Projected Growth Rates And Forecasts

This project analysed three scenarios of varying generation mix in the NEM. The first scenario was the 'Base' scenario which was based on currently installed generation. The second 'Proposed' scenario was modelled on existing generation mix with proposed withdrawals and installations of generator technologies, as well as being loosely based on renewable energy forecasts to the year 2035. The third 'High RE' scenario was based on forecasted installed renewable energy generation up to the year 2050. In order to model the latter two scenarios, it was necessary to take into account the forecasted growth in load demand, which were also based on 2035 and 2050 predictions, as outlined by the Australian Bureau of Resources and Energy Economics (BREE). Each scenario also included hypothetical installed capacities of battery regulation. The following sections outline the main assumptions that were made in order to form the basis of these future scenarios:

2.2.12.1 Base Scenario

The aim of the base scenario was to, as accurately as possible, model existing infrastructure and generation portfolio in the NEM. Modifications were then made to the base scenario to analyse the effect of adding 1.5 MWh battery regulation capacity in each state (or, a global network capacity of 7.5 MWh). Table 7 summarises the installed capacity of PV generation that was used in the Base Scenario, as well as the assumed wind generation capacities which were used as the basis for projected growth rates in the Proposed and High RE scenarios.

Base Scenario Renewable Energy Capacity		
	PV Capacity (MW)	**Wind Generation Capacity (MW)**
NSW	1,263.038	265
QLD	1,524.942	0
VIC	905.411	884
SA	659.069	1,205
TAS	92.473	308

Table 7: Base Scenario Modelled PV Capacity And Assumed Wind Capacity

2.2.12.2 Proposed Scenario

The proposed scenario incorporated many changes to the base scenario, and is loosely based on various forecasted projections for 2035. The generation mix has been modified to include proposed generator additions and withdrawals, as outline in AEMO's Generation Information Datasheets (AEMO, 2016). Further details on changes to generation mix can be found in the Appendix of this report. PV generation was also based on AEMO's 2035 projection of PV capacity in each state, which includes both large-scale and residential PV systems. Wind generation was based on AEMO's 2020 projection of installed wind generation capacity in each state (AEMO, 2013). Since wind generation was modelled from measured output data, these datum were scaled according to growth rates relative to the 2013 installed wind generation capacity. Finally, electricity load was based on BREE's 2035 projection of demand growth for each state (BREE, 2014), which was assumed to be uniform across winter and summer loads. The following table outlines

Proposed Scenario Modelling Assumptions			
	PV Capacity (MW)	Wind Generation Capacity (MW) / [Relative to Base Model]	Total Electricity Demand Relative to 2015
NSW	5,511	2,382 / [8.99]	1.36
QLD	6,910	266[40]	1.28
VIC	5,401	4,974 / [5.63]	1
SA	2,749	2,555 / [2.12]	1.33
TAS	584	1,368 / [4.44]	1

Table 8: Proposed Scenario Modelling Assumptions And Growth Rates

2.2.12.3 High RE Scenario

The High RE scenario builds on from the Proposed scenario, increasing the installed capacity of PV and wind generators to keep in line with 2050 projections. However, to avoid speculation about conventional generator technologies, these related valued have been unchanged from the Proposed case. The growth in PV generation was modelled from forecasted projections for 2050 from the Australian Bureau of Resources and Energy Economics, which are predicted to grow

[40] Since there was no reference profile for QLD wind generation in the Base scenario, QLD wind generation was modelled as a steady output with an assumed 50% capacity factor and some introduced variability as previously discussed. This was not expected to have a major impact on the end result since QLD wind generation is relatively small.

by 47.8% between 2035 and 2050. Wind generation growth was also based on BREE's projections, which foresees a growth of 17.2% from 2035 to 2050 (BREE, 2014). For both PV and wind generation, it was assumed that forecasted growth rates are uniform across individual states. Finally, 2050 figures of electricity demand for each state were also taken from BREE (BREE, 2014). These values are summarised in the Table 9 below.

High RE Scenario Modelling Assumptions			
	PV Capacity	Wind Generation Capacity	Total Electricity Demand (Relative to 2015)
NSW	8,147	2,792	1.36
QLD	10,215	312*	1.04
VIC	7,984	5,830	1.33
SA	4,064	2,994	1.33
TAS	863	1,603	1.21

Table 9: High RE Scenario Modelling Assumptions And Growth Rates

2.2.13 Summary of Scenarios Modelled

Thirty-six different scenarios were modelled with each spanning one week of one-minute intervals. Table 10 below summarises the key differences between these scenarios.

Number	**Generation Mix**	**One-Minute Variability Error Percentage Standard Deviation**	**Season**	**Total Battery Capacity (MWh)**
1	Base	5%	Summer	0
2	Base	5%	Summer	7.5
3	Base	5%	Winter	0
4	Base	5%	Winter	7.5
5	Base	10%	Summer	0
6	Base	10%	Summer	7.5
7	Base	10%	Winter	0
8	Base	10%	Winter	7.5
9	Base	15%	Summer	0
10	Base	15%	Summer	7.5
11	Base	15%	Winter	0
12	Base	15%	Winter	7.5
13	Proposed	5%	Summer	0
14	Proposed	5%	Summer	30
15	Proposed	5%	Winter	0
16	Proposed	5%	Winter	30
17	Proposed	10%	Summer	0
18	Proposed	10%	Summer	30
19	Proposed	10%	Winter	0
20	Proposed	10%	Winter	30
21	Proposed	15%	Summer	0
22	Proposed	15%	Summer	30
23	Proposed	15%	Winter	0
24	Proposed	15%	Winter	30
25	High RE	5%	Summer	0
26	High RE	5%	Summer	45
27	High RE	5%	Winter	0
28	High RE	5%	Winter	45
29	High RE	10%	Summer	0
30	High RE	10%	Summer	45
31	High RE	10%	Winter	0
32	High RE	10%	Winter	45
33	High RE	15%	Summer	0
34	High RE	15%	Summer	45
35	High RE	15%	Winter	0
36	High RE	15%	Winter	45

Table 10: Summary of modelled scenarios

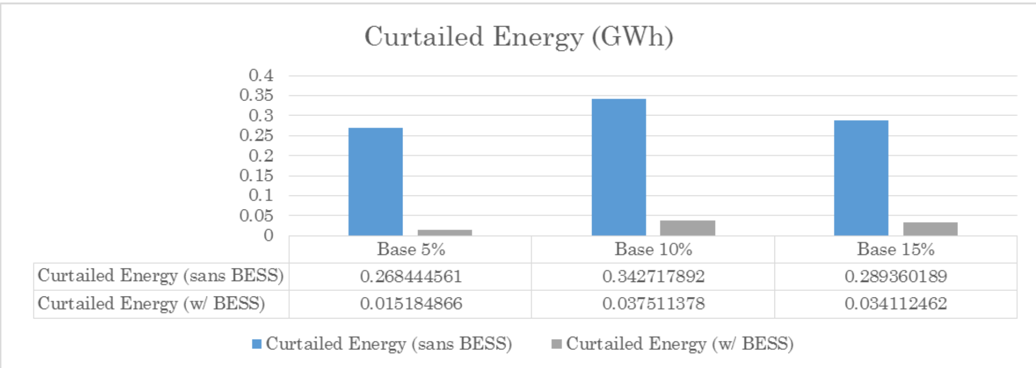
3 Results

The following sections summarise the results of the simulations of this study. Due to time constraints and with consideration for the length of this paper, not all results are analysed in this report; instead, only the 10% variability scenarios are presented with regard to generator ramping rates and transmission power congestion. Evaluation of energy curtailment, however, does include an assessment of all thirty-six scenarios.

3.1 Base Scenario, Summer Load

3.1.1 Energy Curtailment

From Figure 24 below, we can see that there is a sharp decrease in the amount of curtailed energy for the week of the 13th-19th January, 2015, after the addition of 7.5 MWh of global battery regulation capacity to the network. The reductions in energy curtailment for the 5%, 10%, and 15% scenarios are 253.26 MWh, 305.21 MWh, and 255.25 MWh, respectively, representing relative reductions of 94.34%, 89.05%, and 88.21%.

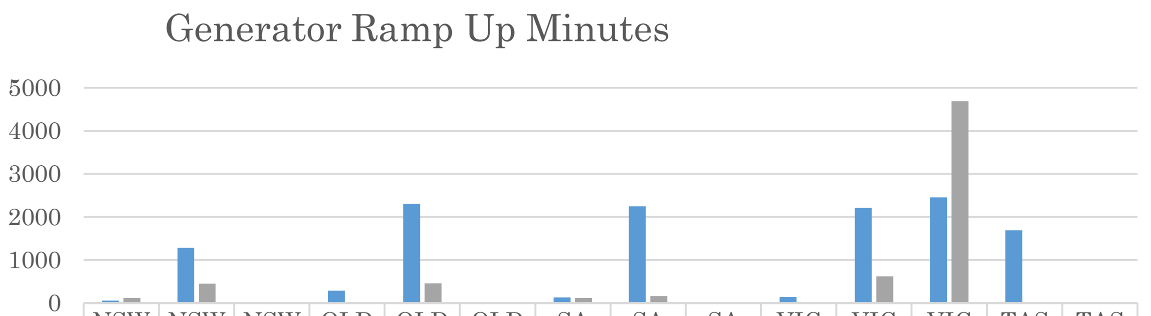


	Base 5%	Base 10%	Base 15%
Curtailed Energy (sans BESS)	0.268444561	0.342717892	0.289360189
Curtailed Energy (w/ BESS)	0.015184866	0.037511378	0.034112462

Figure 24: Curtailed Energy, Base Scenario Summer Load

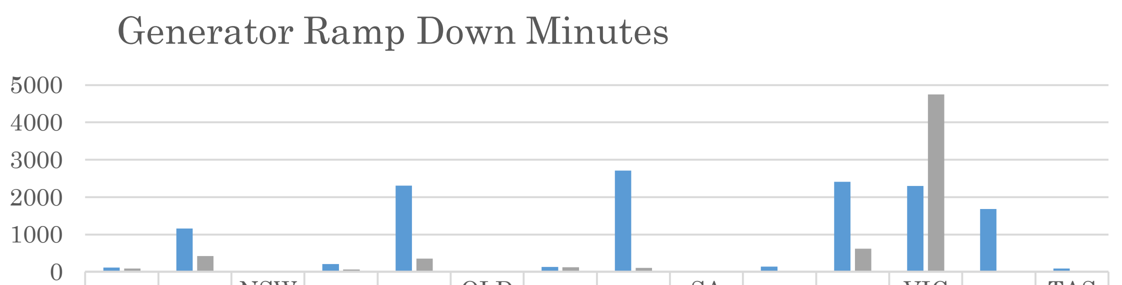
3.1.2 Generator Ramping Requirements

A summary of the effects on generator ramp up and ramp down times are shown Figure 25 and Figure 26 on the following page. From these graphs we can see that there is a significant decrease in the overall ramping requirements of generators when battery systems are utilised for regulation capacity. The total time spent ramping by the aggregate of all generators has decreased by 49.24% after the addition of the battery system. It is also interesting to observe here that the Victorian hydroelectric generators have increased their ramping times by 98.42%.



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Coal	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	58	1281	0	285	2305	0	131	2245	4	138	2208	2453	1692	11
Ramp Up Minutes (w/ BESS)	121	452	1	6	456	4	118	164	3	1	623	4689	15	14

Figure 26: Generator Ramp-Up Minutes, Base Scenario Summer Load



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Coal	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	114	1163	1	212	2305	3	130	2712	10	137	2408	2302	1682	94
Ramp Down Minutes (w/ BESS)	90	424	2	64	357	2	126	109	5	2	620	4746	15	12

Figure 25: Generator Ramp-Down Minutes, Base Scenario Summer Load

The figures on the following pages present more detailed generation/load profiles for each of the states in the NEM. We can see that there is some difference between generation profiles after the addition of battery regulation capacity. South Australia in particular shows a stark difference in its generator behaviour when battery regulation capacity is included, exhibiting much greater fluctuations in its generation before battery capacity is added. Other notable differences in generation profile include that of Victoria’s, which now relies less on coal and more on hydroelectric generation, and Queensland, which has greatly reduced the amount of gas generation it uses in its generation mix. Generation profiles for other scenarios examined can be found in Appendix B of this report.

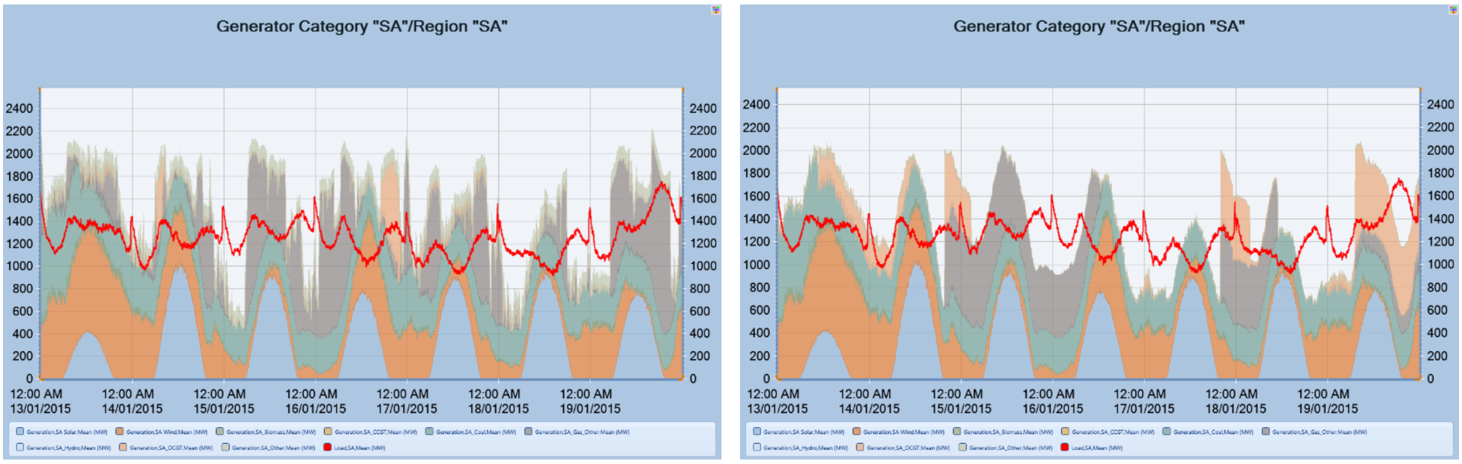


Figure 28: South Australian Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

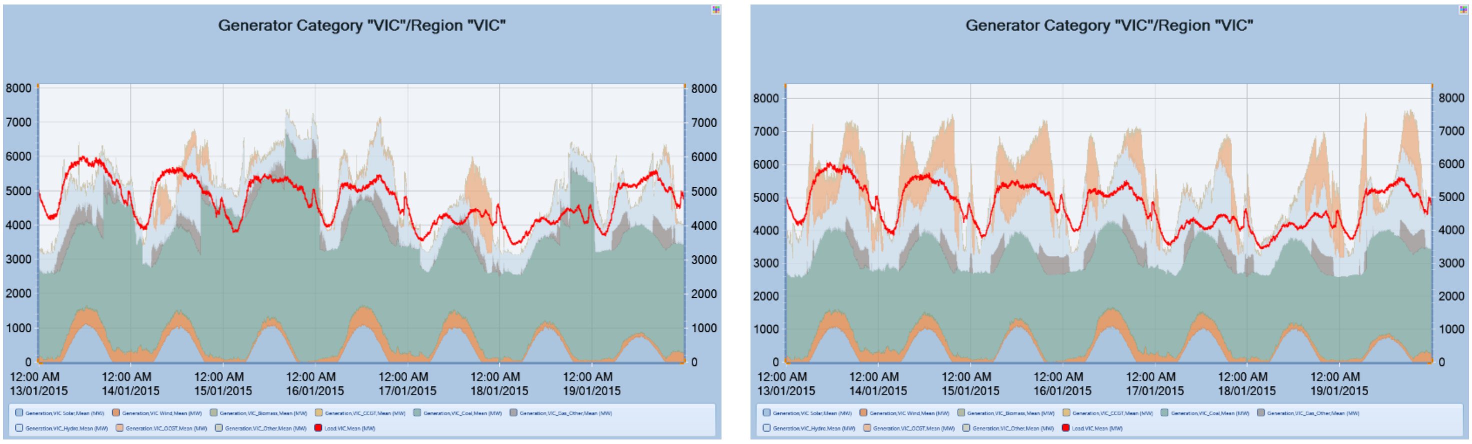


Figure 27: Victorian Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

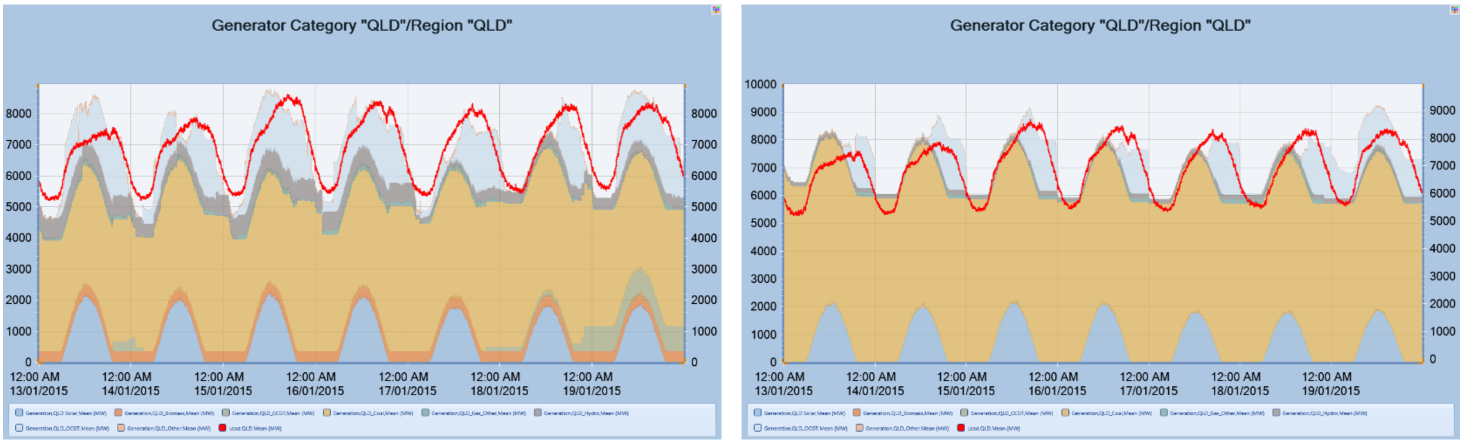


Figure 29: Queensland Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

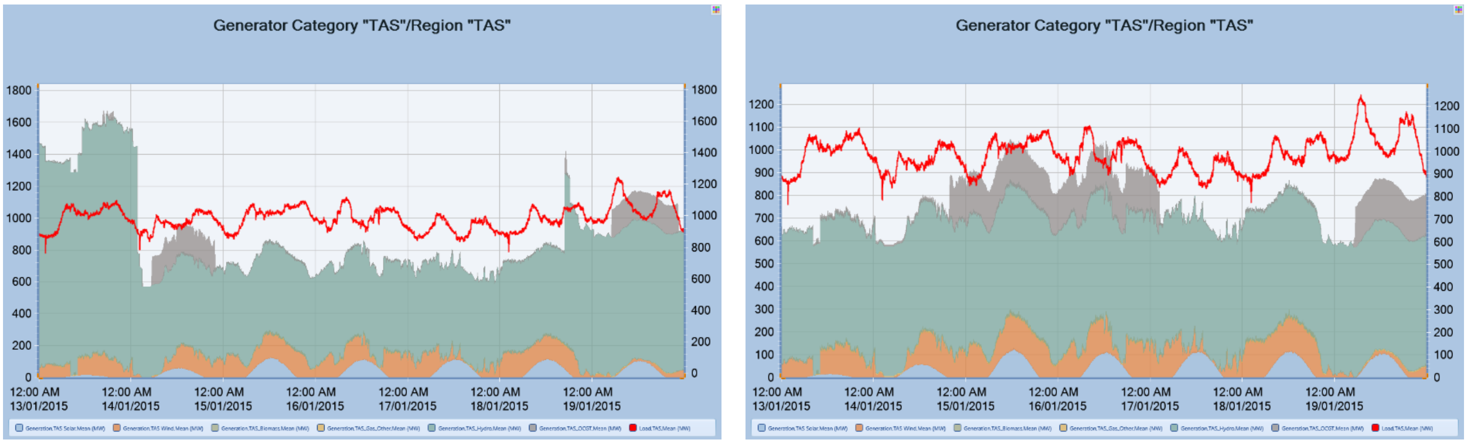


Figure 31: Tasmanian Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

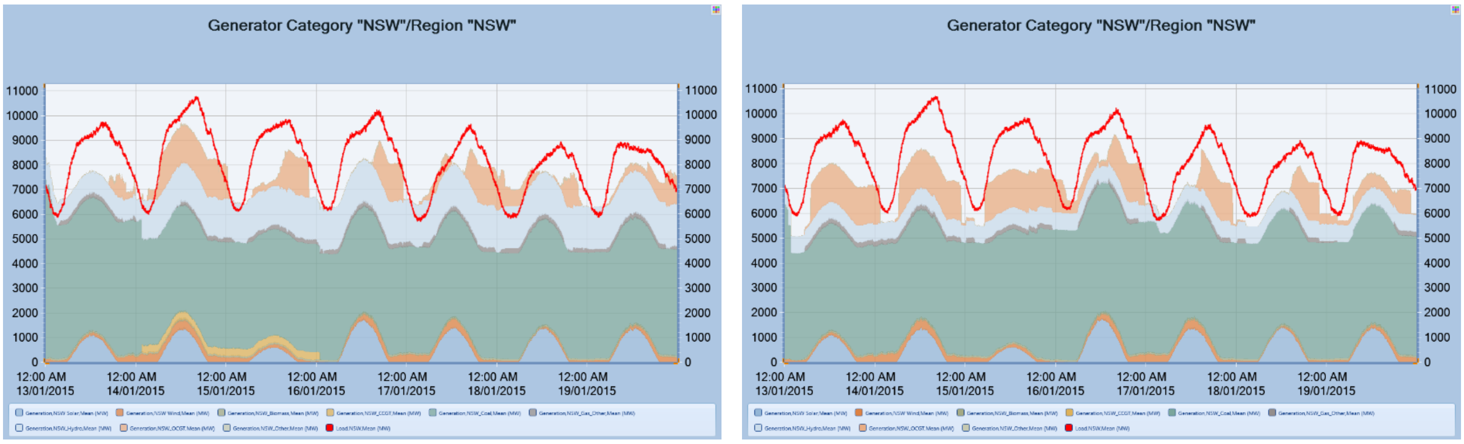


Figure 30: New South Wales Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

3.1.3 Effect of Battery Regulation on Transmission Congestion

Figure 32 and Figure 33 on the following page summarise the effect of battery reserve capacity on the amount of time that each transmission line spends operating at it maximum rated forward and reverse capacity. After the addition of 7.5 MWh of battery regulation to the NEM, the total number of aggregate congestion hours has decreased from 228.15 hours to 187.7, representing a relative reduction of 17.77%.

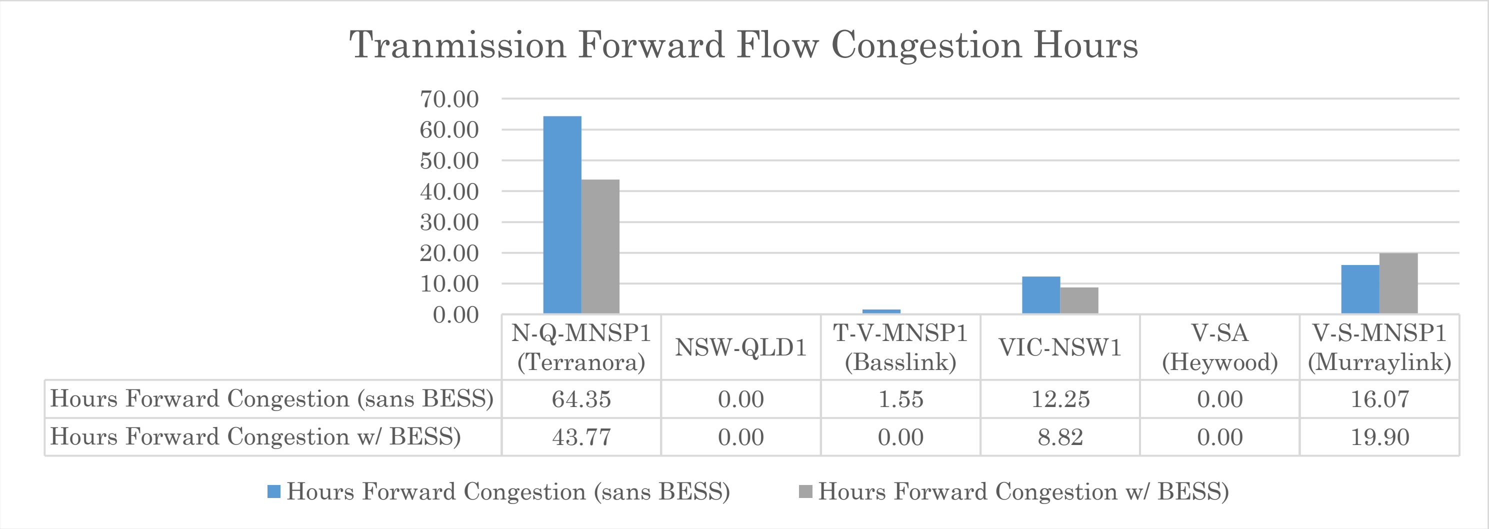


Figure 32: Transmission Forward Power Congestion Time, Base Scenario Summer Load

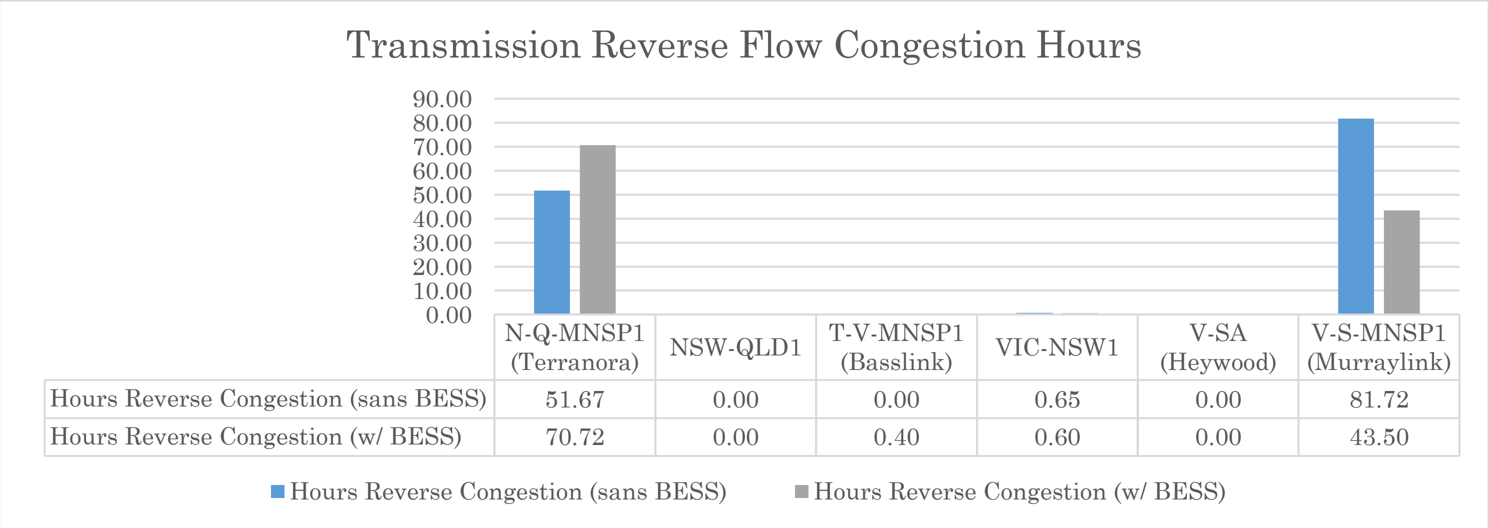


Figure 33: Transmission Reverse Power Congestion Time, Base Scenario Summer Load

Shown on the following pages are heat maps detailing the power flows between regions on a minute-by-minute basis, as well as the cumulative probability distributions of power flows on transmission lines. It can be seen from the probability distribution curves in Figure 34 that the distribution of power flow rates become smoother after the inclusion of battery regulation capacity, indicating a more even distribution of power flows. We can also see that the NSW-QLD and Murraylink lines cross the 50% mark closer to their midway points, which are -239 MW and 0 MW, respectively. It should be noted here that the Terranora and Heywood lines are not represented in these graphs, due to them having the same operating characteristics as the NSW-QLD1 and Murraylink, respectively.

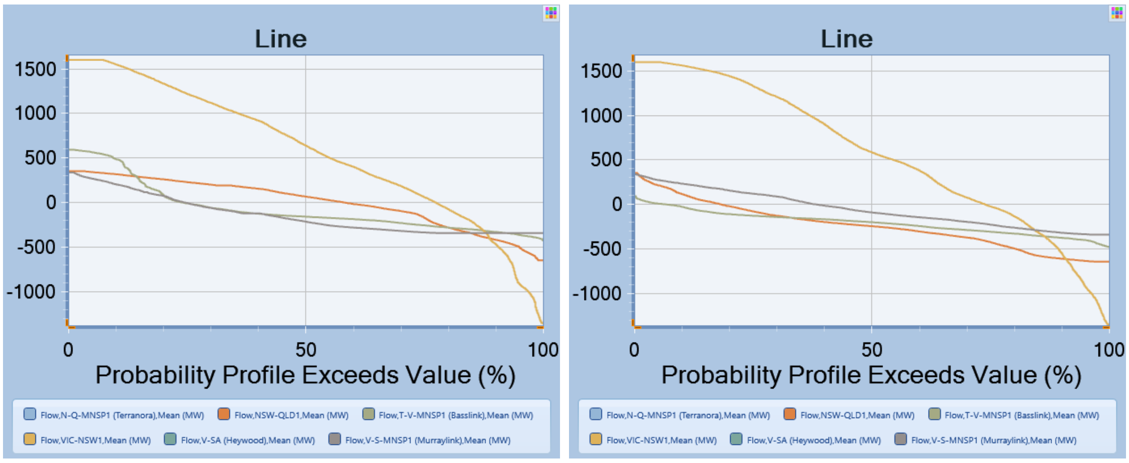


Figure 34: Cumulative Probability Distribution Profile Of Transmission Power Flows, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

The following heat maps also provide a good visualisation of the period-to-period variability on these transmission lines, which we can see undergo reductions in their period-to-period variability. (Note well that the Basslink heat maps do not follow the same colour scale, with the range of colours on the right-side graph representing a much tighter range of values).

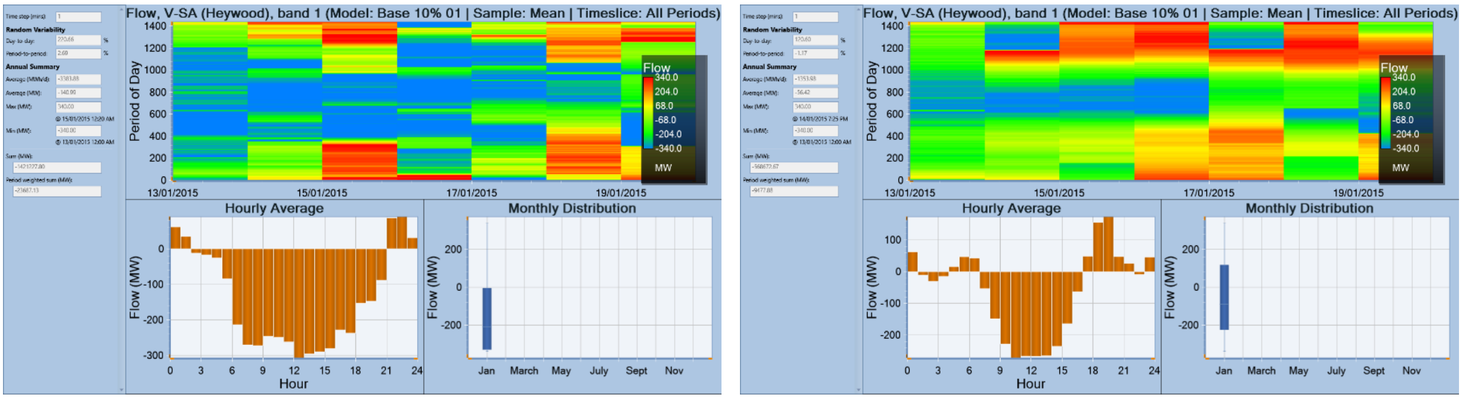


Figure 35: Heat Maps And Statistical Summary of Transmission Power Flow. On Heywood Line, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

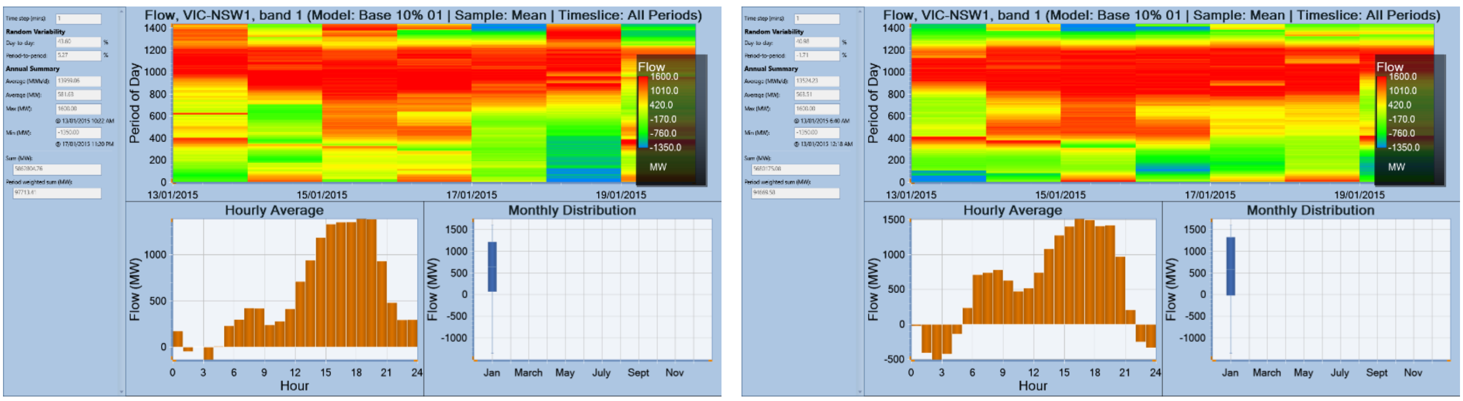


Figure 36:Heat Maps And Statistical Summary of Transmission Power Flow. On VIC-NSW1 Line, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

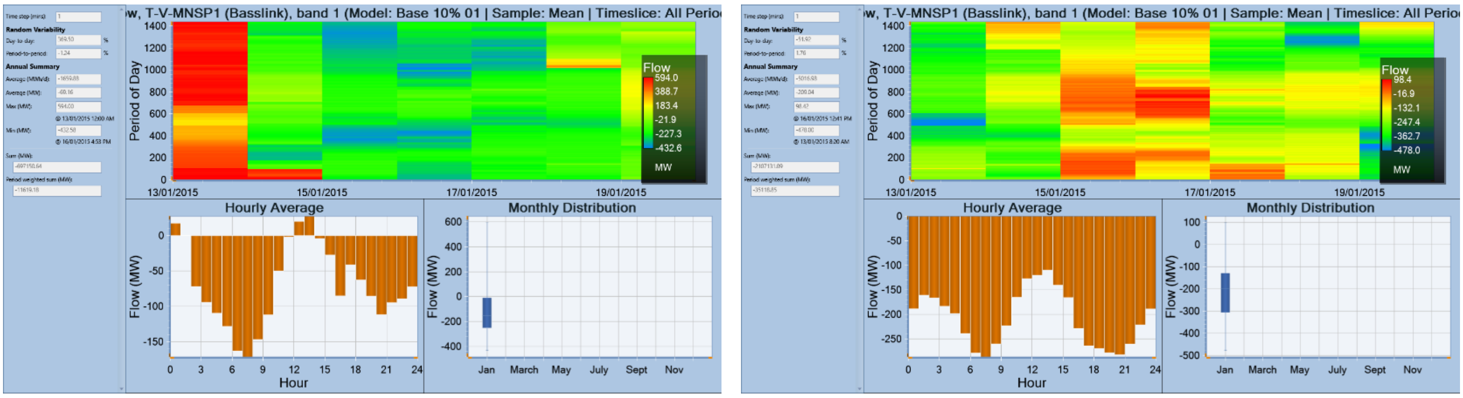


Figure 37: Heat Maps And Statistical Summary of Transmission Power Flow. On Basslink Line, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

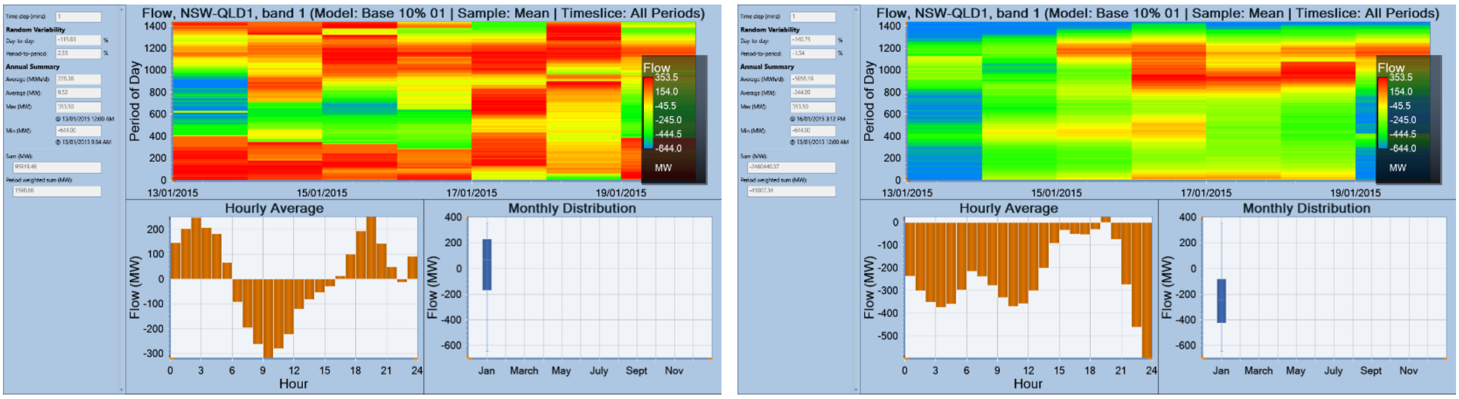
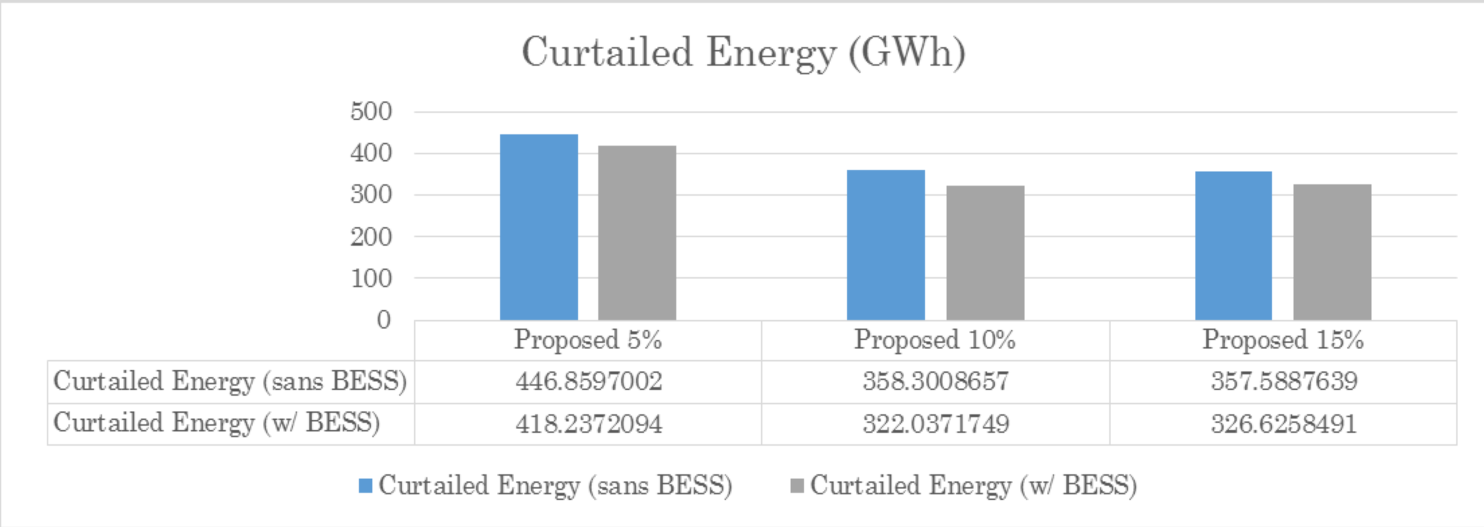


Figure 38: Heat Maps And Statistical Summary of Transmission Power Flow. On NSW-QLD1 Line, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

3.2 Proposed Scenario, Summer Load

3.2.1 Energy Curtailment

Again in Figure 39 we see a decrease in the amount of curtailed energy, this time with the inclusion of 30 MWh of battery regulation capacity. Although the *relative* reduction in energy curtailment after the inclusion of battery regulation capacity is not as significant here as it was in the Base scenario, the addition of battery regulation resulted in reductions of 28, 622 MWh, 36,264 MWh, and 30,963 MWh for the 5%, 10%, and 15% scenarios, respectively. These figures represent a total relative reduction in energy curtailment of 6.41%, 10.12%, and 8.66%.

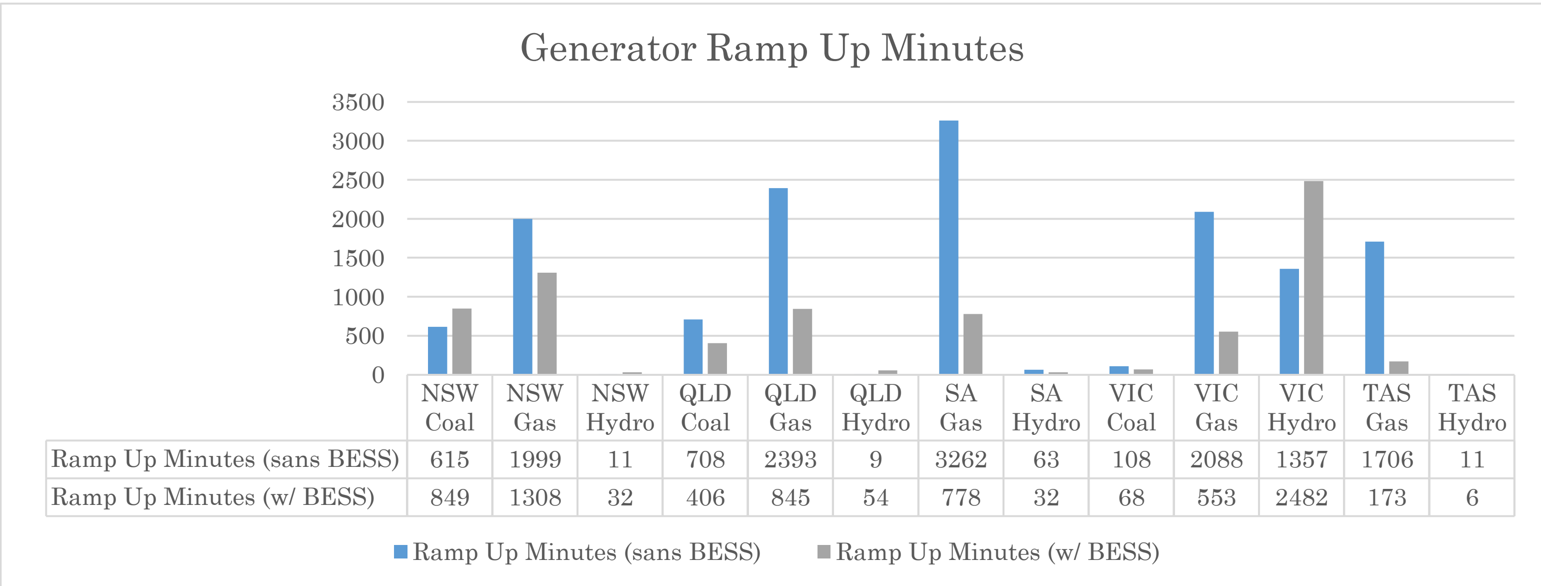


	Proposed 5%	Proposed 10%	Proposed 15%
Curtailed Energy (sans BESS)	446.8597002	358.3008657	357.5887639
Curtailed Energy (w/ BESS)	418.2372094	322.0371749	326.6258491

Figure 39: Curtailed Energy, Proposed Scenario Summer Load

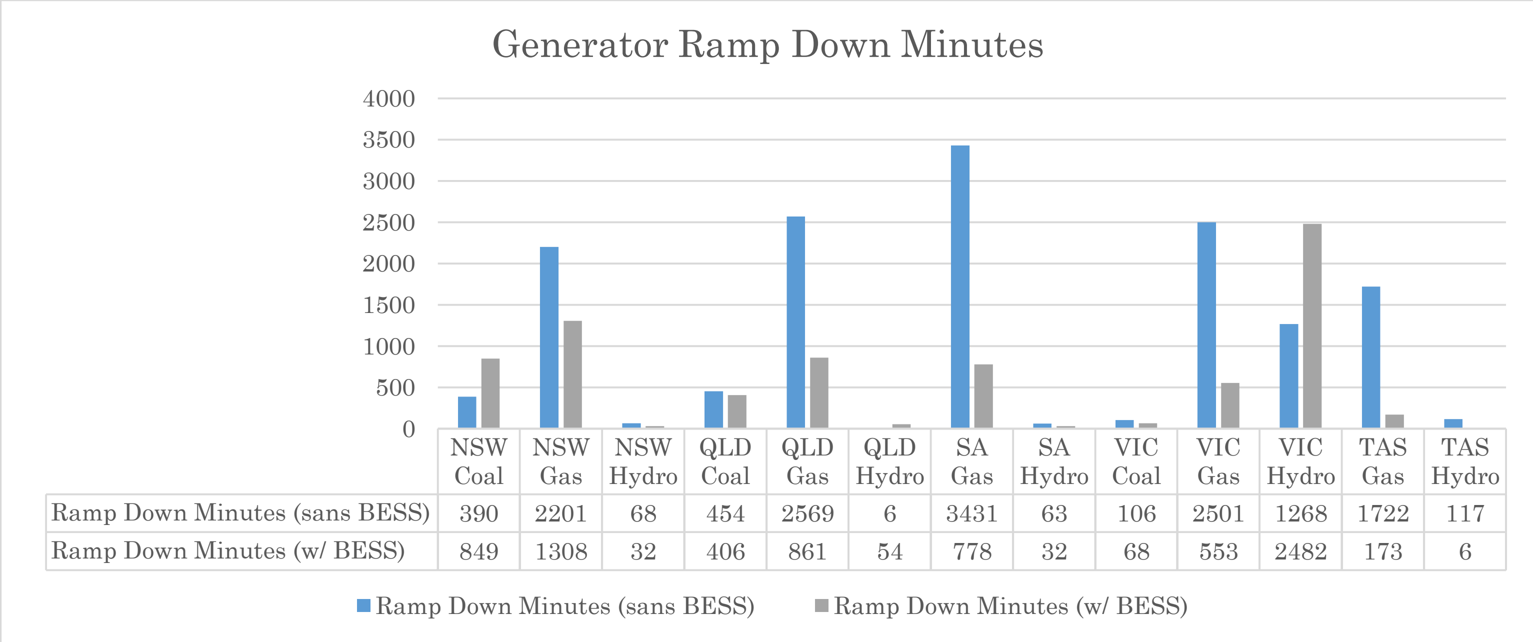
3.2.2 Generator Ramping Requirements

Again we can observe from the following graphs that all generator ramping times decreases with the exception of Victorian hydroelectricity and this time as well with the exception of New South Wales Coal generation. The relative reduction in aggregated generator ramping times is 48.03%, despite Victorian hydroelectricity increasing its ramping times.



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	615	1999	11	708	2393	9	3262	63	108	2088	1357	1706	11
Ramp Up Minutes (w/ BESS)	849	1308	32	406	845	54	778	32	68	553	2482	173	6

Figure 40: Generator Ramp-Up Minutes, Proposed Scenario Summer Load



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	390	2201	68	454	2569	6	3431	63	106	2501	1268	1722	117
Ramp Down Minutes (w/ BESS)	849	1308	32	406	861	54	778	32	68	553	2482	173	6

Figure 41: Generator Ramp-Down Minutes, Proposed Scenario Summer Load

3.2.3 Effect of Battery Regulation on Transmission Flow

It is interesting to see below that the changes to transmission behaviours are not repeated following the Base scenario. Instead, the Terranora line increases in its forward flow congestion and the Murraylink also increases in its reverse flow congestion. Meanwhile, the VIC-NSW line sees a slight increase in its reverse flow congestion. The change in probability distribution curves are more profound in the Proposed scenario than in the Base scenario, and once again we see the curves taking on a more S-shaped resemblance – an indication of a normally distributed range. The 50% crossings for the NSW-QLD and VIC-NSW lines are much closer to their midway points (-239 MW and 125 MW, respectively), while the Basslink line actually deviates further from its midway point. The overall reduction in congestion time was 13.25%.

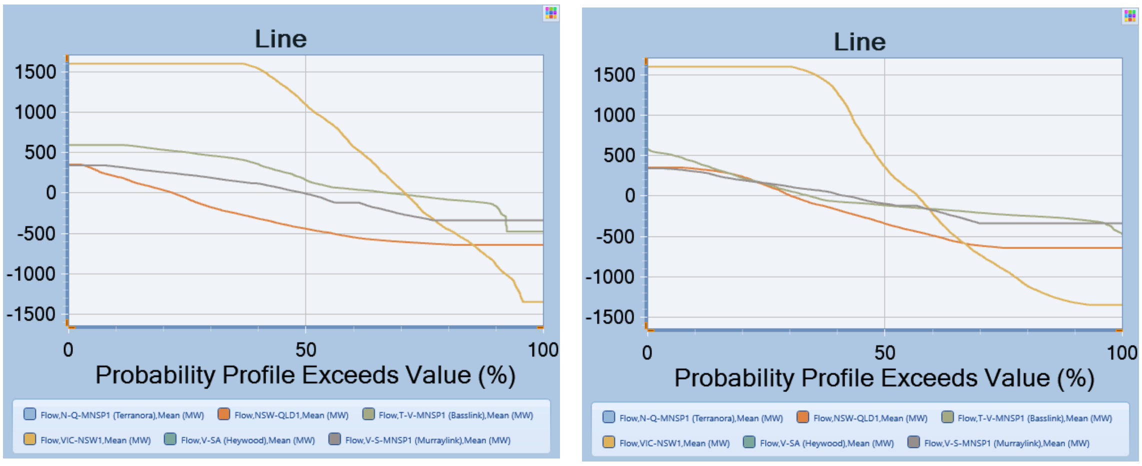
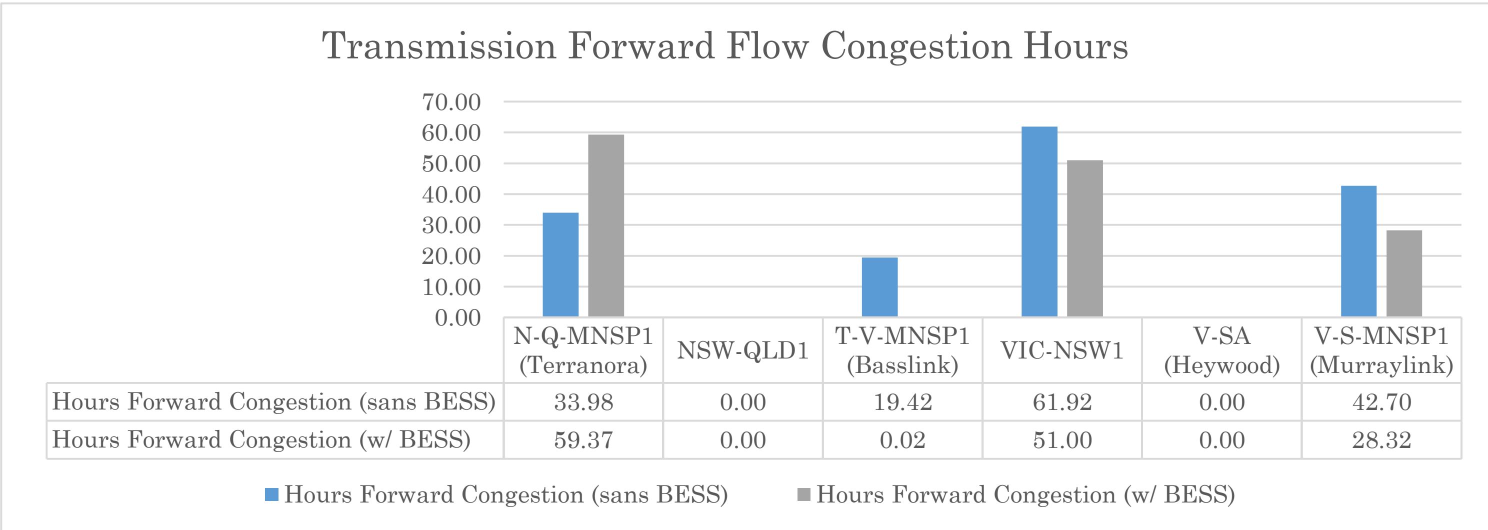
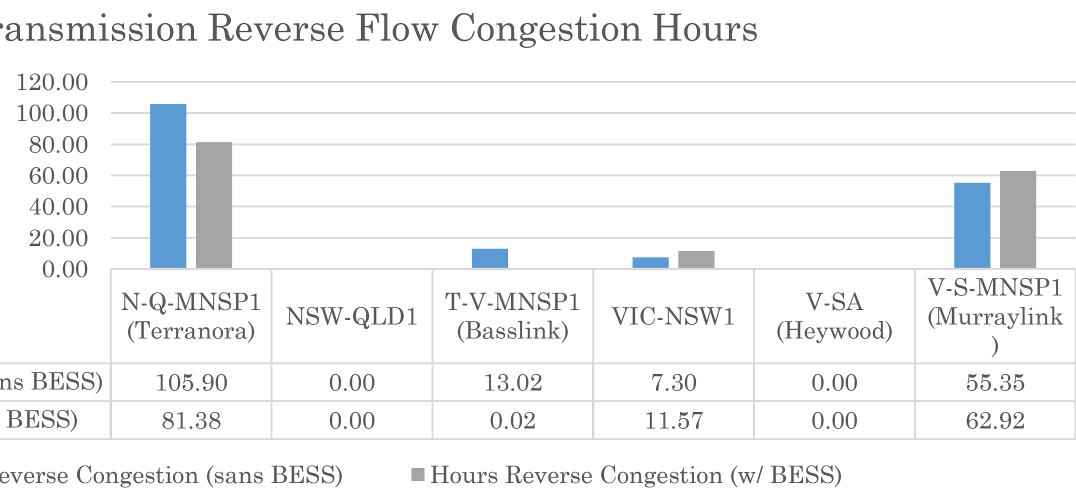


Figure 42: Cumulative Probability Distribution Profile Of Transmission Power Flows, Proposed Scenario Summer Load. Left: Sans Battery Regulation, Right: 30 MWh Global battery Regulation Capacity



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Forward Congestion (sans BESS)	33.98	0.00	19.42	61.92	0.00	42.70
Hours Forward Congestion (w/ BESS)	59.37	0.00	0.02	51.00	0.00	28.32

Figure 43: Transmission Forward Power Congestion Time, Proposed Scenario Summer Load



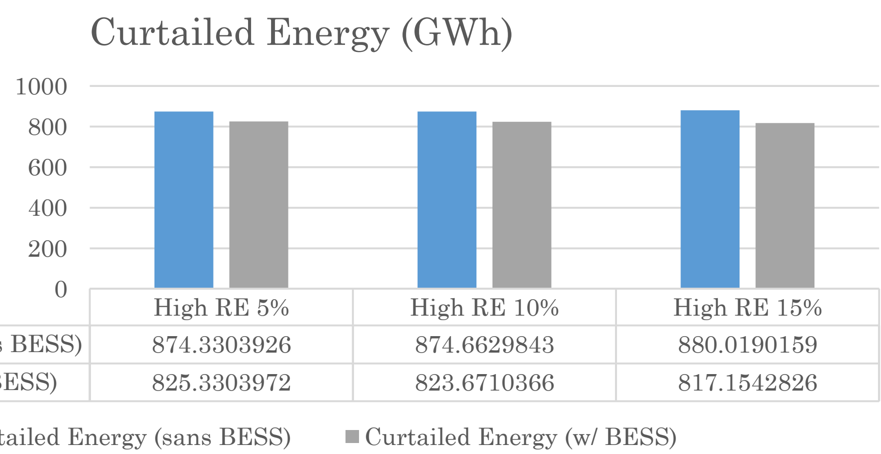
	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Reverse Congestion (sans BESS)	105.90	0.00	13.02	7.30	0.00	55.35
Hours Reverse Congestion (w/ BESS)	81.38	0.00	0.02	11.57	0.00	62.92

Figure 44: Transmission Reverse Power Congestion Time, Proposed Scenario Summer Load

3.3 High RE Scenario, Summer Load

3.3.1 Energy Curtailment

A higher amount of over-generation by renewable energy resources has again led to a large curtailment which has resulted in a lower relative reduction than the previous Proposed scenario. The reductions in the three scenarios of 49,000 MWh, 50,992 MWh, and 62,864 MWh represent percentage reductions of 5.60%, 5.83%, and 7.14%, respectively, for the 5%, 10%, and 15% scenarios. This was achieved through the inclusion of 45 MWh of global battery regulation capacity.

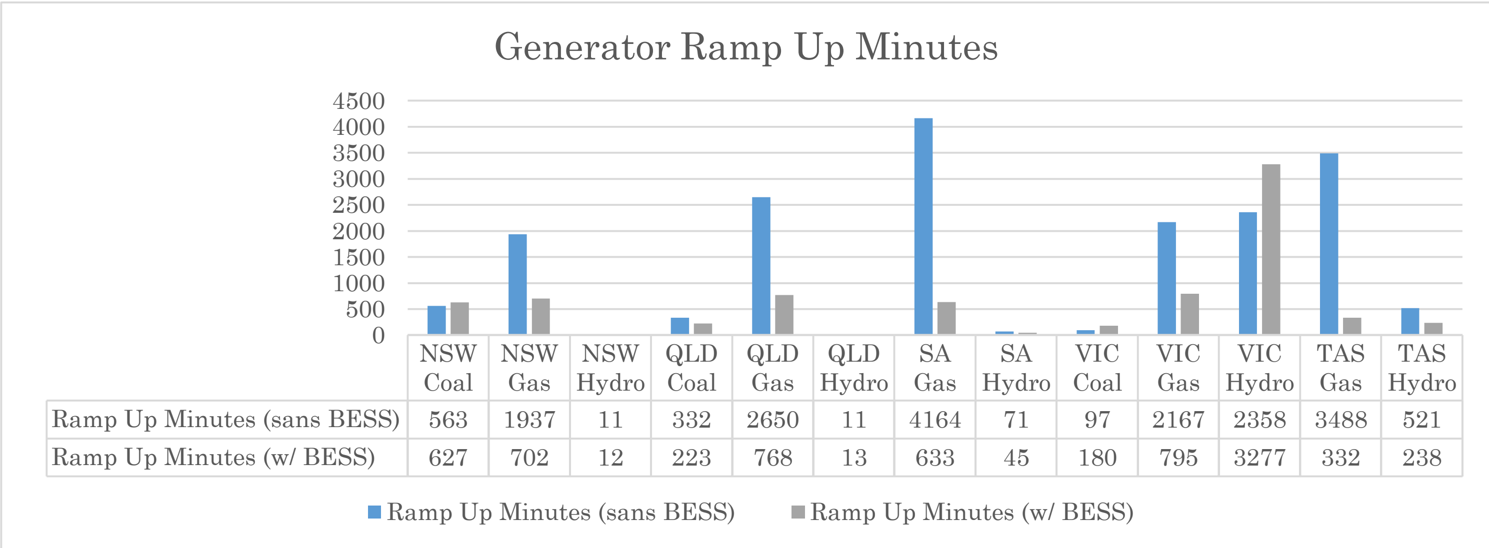


	High RE 5%	High RE 10%	High RE 15%
Curtailed Energy (sans BESS)	874.3303926	874.6629843	880.0190159
Curtailed Energy (w/ BESS)	825.3303972	823.6710366	817.1542826

Figure 45: Curtailed Energy, High RE Scenario Summer Load

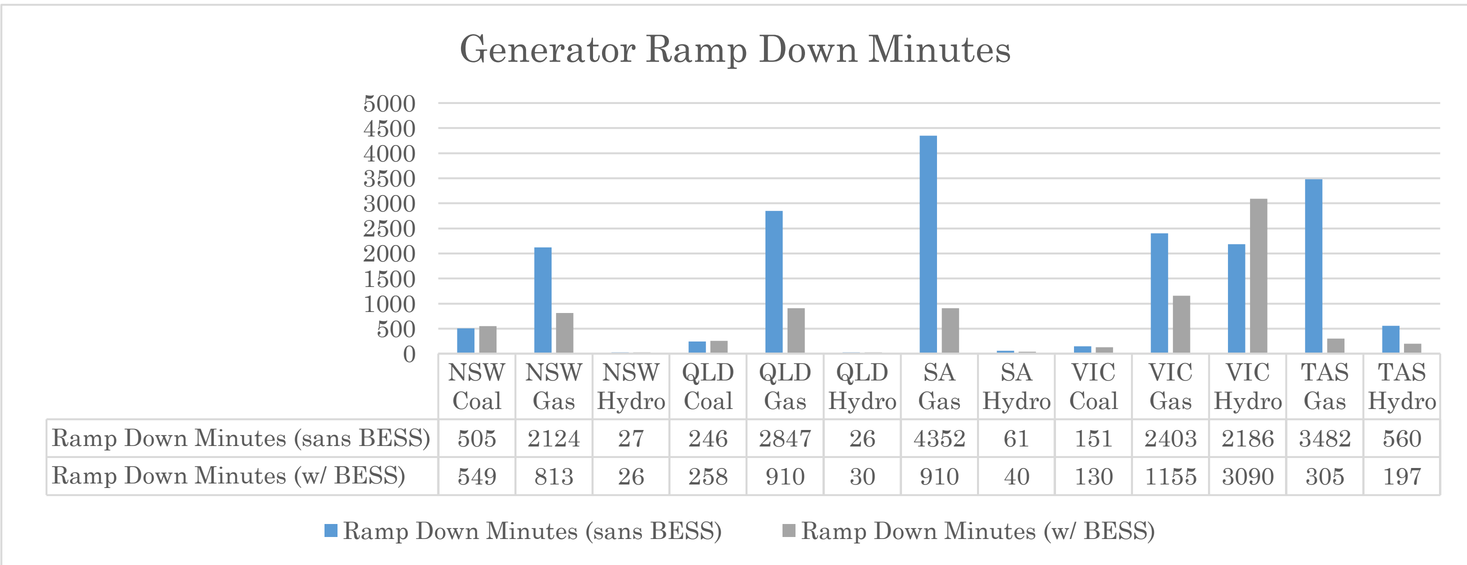
3.3.2 Generator Ramping Requirements

As expected we can again see a sharp decrease in generator ramp rates, however it appears that the relative reduction in ramping requirements is even greater in the High RE scenario as in the Proposed case. The reduction in aggregated ramping minutes has decreased by 49.56% .



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	563	1937	11	332	2650	11	4164	71	97	2167	2358	3488	521
Ramp Up Minutes (w/ BESS)	627	702	12	223	768	13	633	45	180	795	3277	332	238

Figure 46: Generator Ramp-Up Minutes, High RE Scenario Summer Load

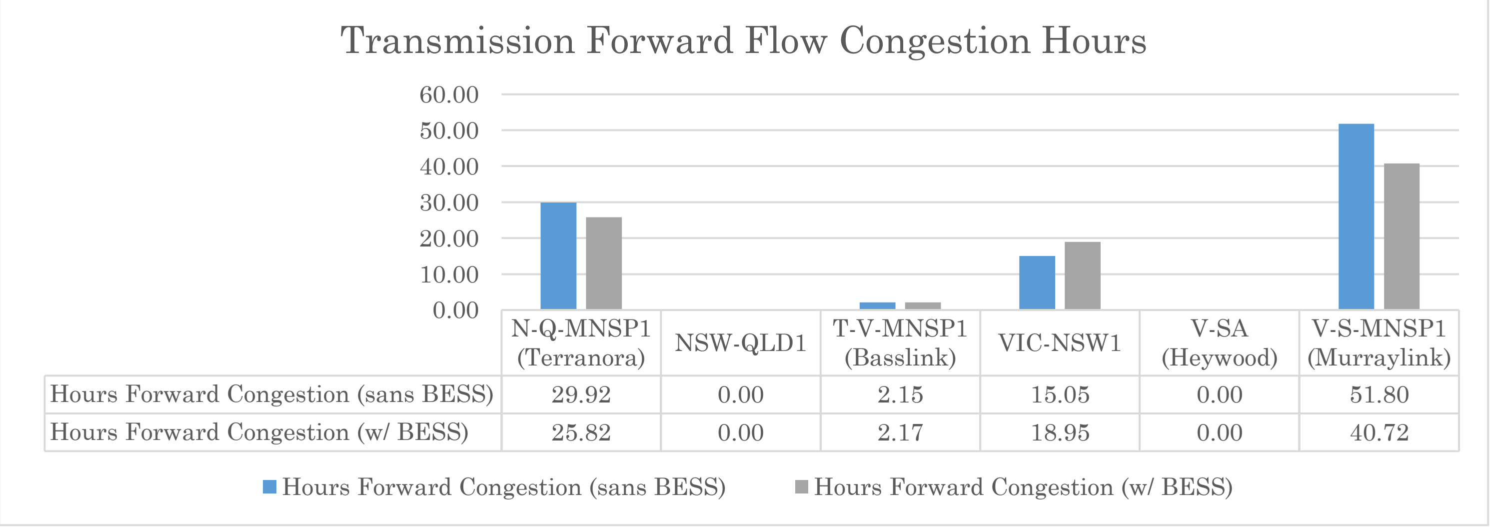


	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	505	2124	27	246	2847	26	4352	61	151	2403	2186	3482	560
Ramp Down Minutes (w/ BESS)	549	813	26	258	910	30	910	40	130	1155	3090	305	197

Figure 47: Generator Ramp-Down Minutes, High RE Scenario Summer Load

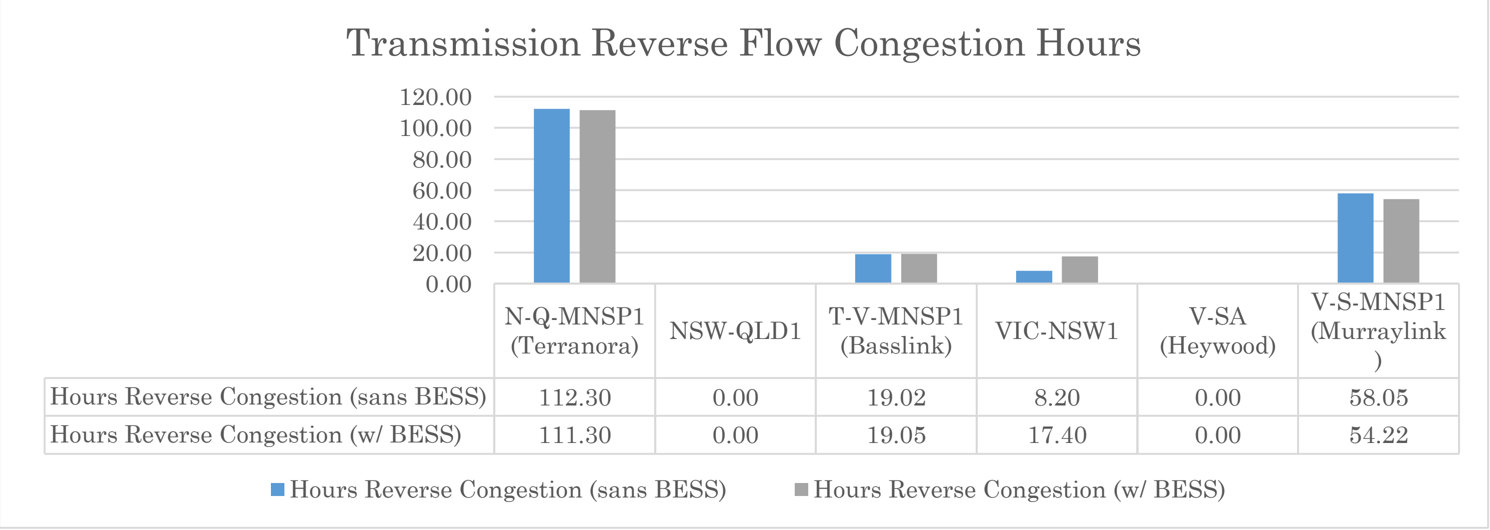
3.3.3 Effect of Battery Regulation on Transmission Flow

It is interesting to observe that, although there was a significant reduction in the requirements of generator ramping, the reduction in the amount of time of congestion on the major transmission lines is not as apparent, judging from ___ and ___ below. Observing the probability distribution functions in ____ we can again see that the NSW-QLD and VIC-NSW lines become much more S-shaped, despite the VIC-NSW deviating further from its midway point at the 50% crossing. Meanwhile, the Basslink and Muraylink probability distribution curves seem to be almost unchanged. We also observe from the heat maps that there is an improvement in the variability of power flows through the transmission lines, particularly in the Basslink and the VIC-NSW lines. The overall reduction in congestion time was 7.01%.



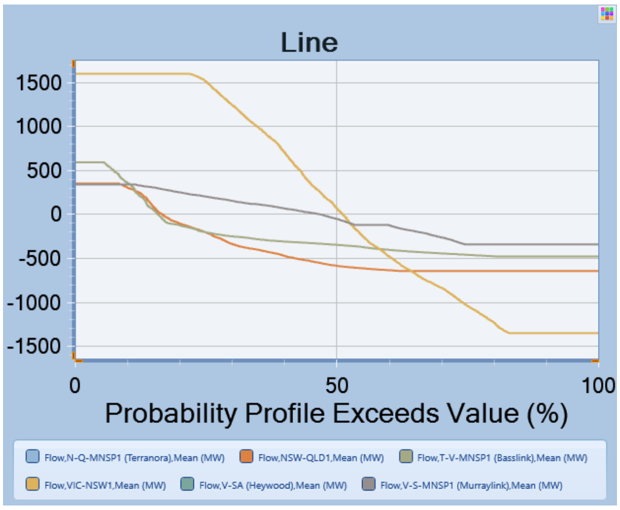
	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Forward Congestion (sans BESS)	29.92	0.00	2.15	15.05	0.00	51.80
Hours Forward Congestion (w/ BESS)	25.82	0.00	2.17	18.95	0.00	40.72

Figure 49: Transmission Forward Power Congestion Time, High RE Scenario Summer Load



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Reverse Congestion (sans BESS)	112.30	0.00	19.02	8.20	0.00	58.05
Hours Reverse Congestion (w/ BESS)	111.30	0.00	19.05	17.40	0.00	54.22

Figure 48: Transmission Reverse Power Congestion Time, High RE Scenario Summer Load



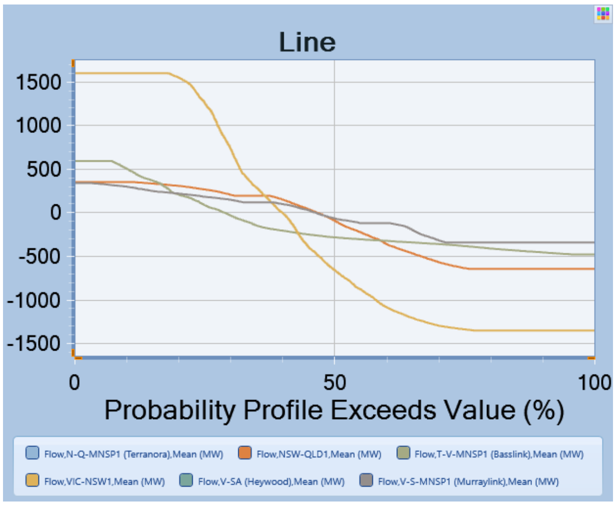


Figure 50: Cumulative Probability Distribution Profile Of Transmission Power Flows, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global battery Regulation Capacity

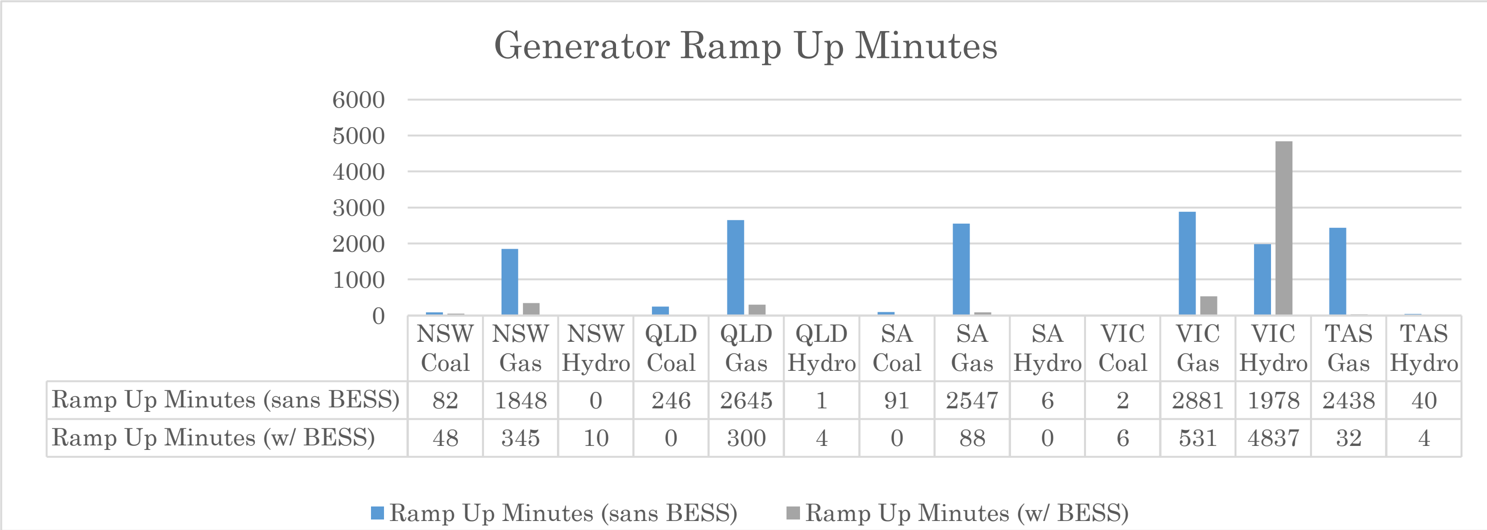
3.4 Base Scenario, Winter Load

3.4.1 Energy Curtailment

The winter Base scenario did not experience any curtailment of energy that was a result of high fluctuations or over-generation from renewable resources.

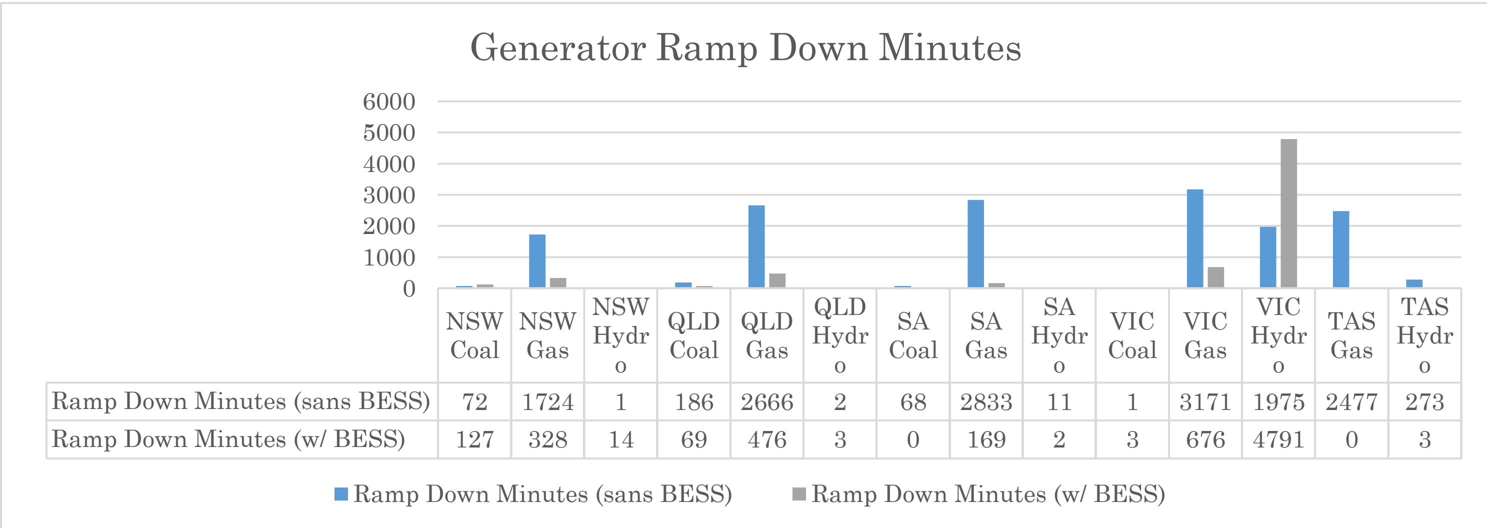
3.4.2 Generator Ramping Requirements

The reduction in generator ramping requirements after the addition of battery regulation in the winter scenario was higher than that in the summer, a decrease of 57.49%. Meanwhile, the Victorian hydroelectric generators saw a sharp increase in their ramp-up and ramp-down requirements, increasing by 143.56%.



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Coal	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	82	1848	0	246	2645	1	91	2547	6	2	2881	1978	2438	40
Ramp Up Minutes (w/ BESS)	48	345	10	0	300	4	0	88	0	6	531	4837	32	4

Figure 51: Generator Ramp-Up Minutes, Base Scenario Winter Load

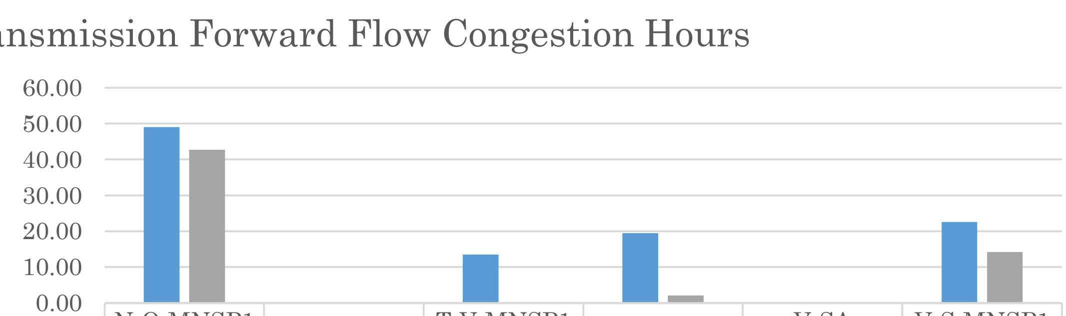


	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Coal	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	72	1724	1	186	2666	2	68	2833	11	1	3171	1975	2477	273
Ramp Down Minutes (w/ BESS)	127	328	14	69	476	3	0	169	2	3	676	4791	0	3

Figure 52: Generator Ramp-Down Minutes, Base Scenario Winter Load

3.4.3 Effect of Battery Regulation on Transmission Flow

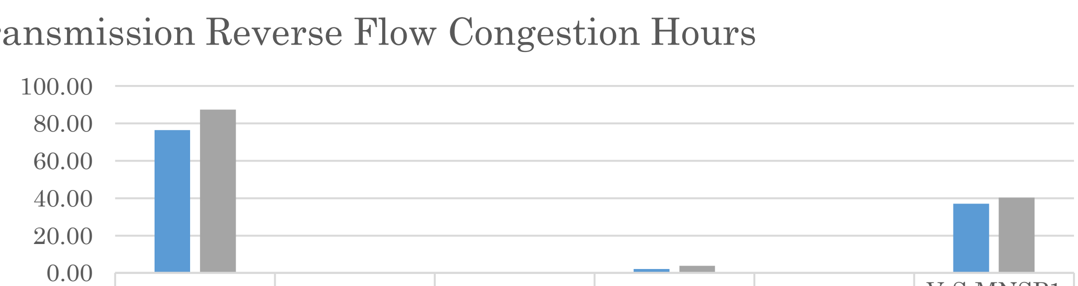
We can observe from ___ that transmission congestion hours increase in the reverse direction on all transmission lines, and decrease in the forward direction, resulting in an overall decrease in congestion time. When compared to the Base summer scenario, 13.50%.When looking at the probability distribution functions, we observe that, once again, the 50% of the Basslink and the Vic-NSW lines are much closer to their midpoints.



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Forward Congestion (sans BESS)	49.03	0.00	13.50	19.52	0.00	22.58
Hours Forward Congestion (w/ BESS)	42.67	0.00	0.00	2.13	0.00	14.22

■ Hours Forward Congestion (sans BESS) ■ Hours Forward Congestion (w/ BESS)

Figure 55: Transmission Forward Power Congestion Time, Base Scenario Winter Load



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Reverse Congestion (sans BESS)	76.40	0.00	0.00	2.08	0.00	37.07
Hours Reverse Congestion (w/ BESS)	87.43	0.00	0.00	3.77	0.00	40.23

■ Hours Reverse Congestion (sans BESS) ■ Hours Reverse Congestion (w/ BESS)

Figure 54: Transmission Reverse Power Congestion Time, Base Scenario Winter Load

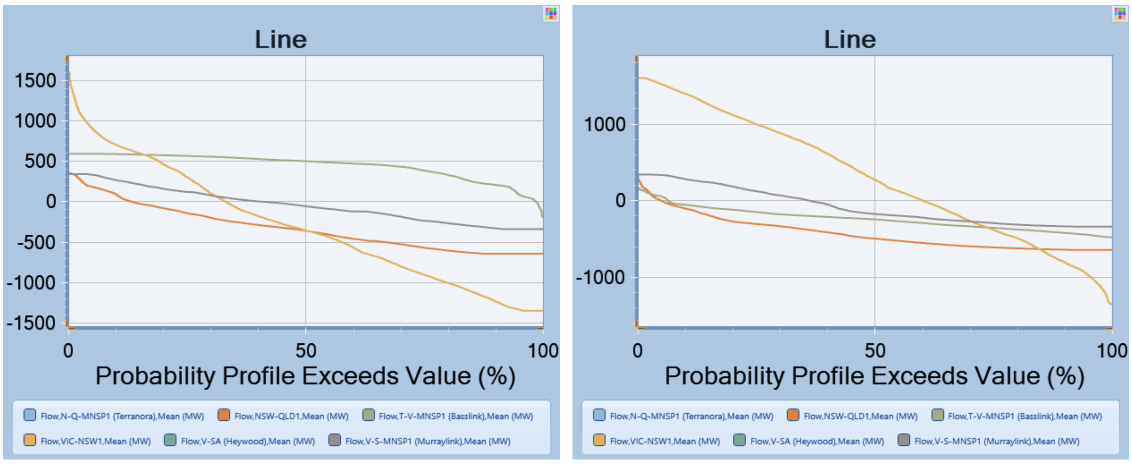
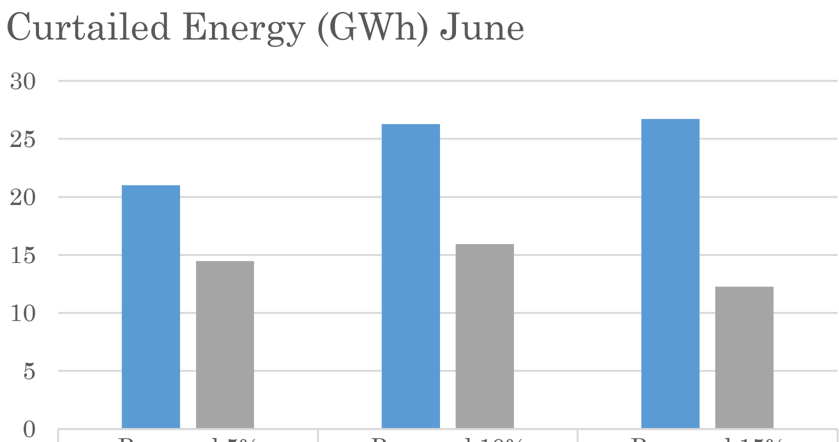


Figure 53Cumulative Probability Distribution Profile Of Transmission Power Flows, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global battery Regulation Capacity

3.5 Proposed Scenario, Winter Load

3.5.1 Energy Curtailment

Comparing winter and summer Proposed scenarios, we see that there is far less curtailed energy during the period of 13th-19th June, 2015. The relative reduction in curtailment is therefore much higher, at 31.09%, 39.36%, and 54.15% for the 5%, 10%, and 15% scenarios, respectively. This represents an absolute reduction of 6,535 MWh, 10,344 MWh, and 14,472 MWh for the three cases.



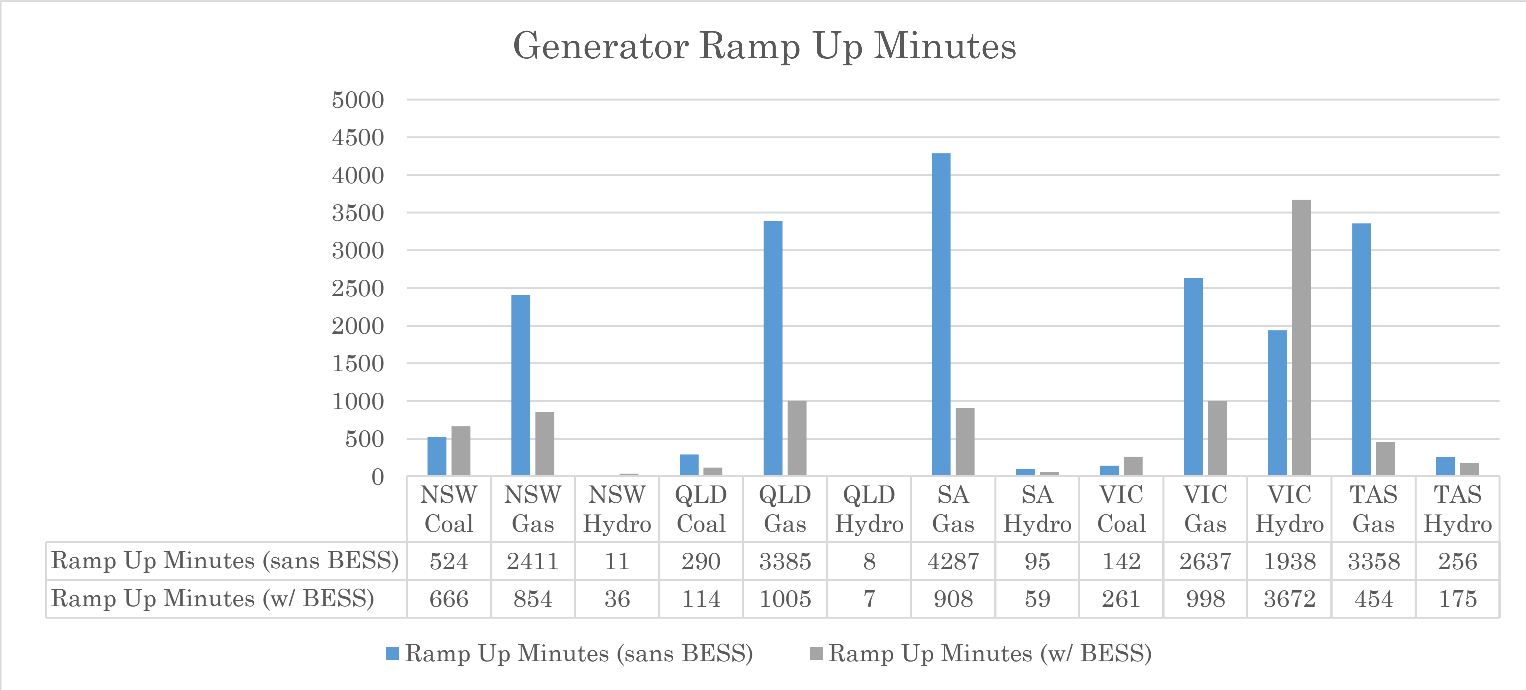
	Proposed 5%	Proposed 10%	Proposed 15%
Curtailed Energy (sans BESS)	21.02176847	26.28176962	26.7283888
Curtailed Energy (w/ BESS)	14.48616072	15.93825587	12.2562271

■ Curtailed Energy (sans BESS) ■ Curtailed Energy (w/ BESS)

Figure 56: Curtailed Energy, Proposed Scenario Winter Load

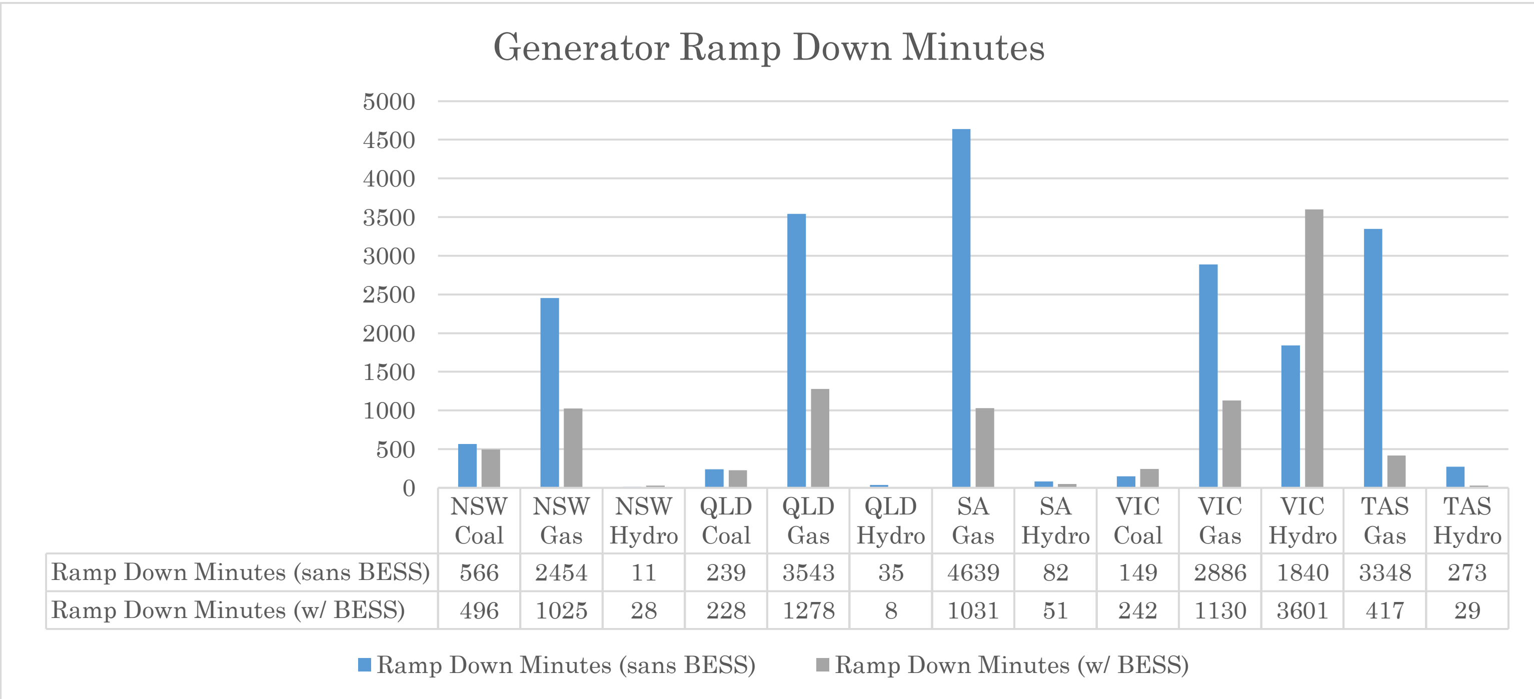
3.5.2 Generator Ramping Requirements

As was seen with the Base scenarios, the relative reduction in generator ramping requirement for the Proposed scenario is greater in winter than in summer, with a relative reduction in ramping time of 52.36%, compared to 48.03% for the summer. Again we can observe a sharp increase in the ramping times of the Victorian hydroelectric generators, as well as slight increase in NSW Coal ramping. This is summarised in Figure 58 and Figure 57 on the following page.



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	524	2411	11	290	3385	8	4287	95	142	2637	1938	3358	256
Ramp Up Minutes (w/ BESS)	666	854	36	114	1005	7	908	59	261	998	3672	454	175

Figure 58: Generator Ramp-Up Minutes, Proposed Scenario Winter Load

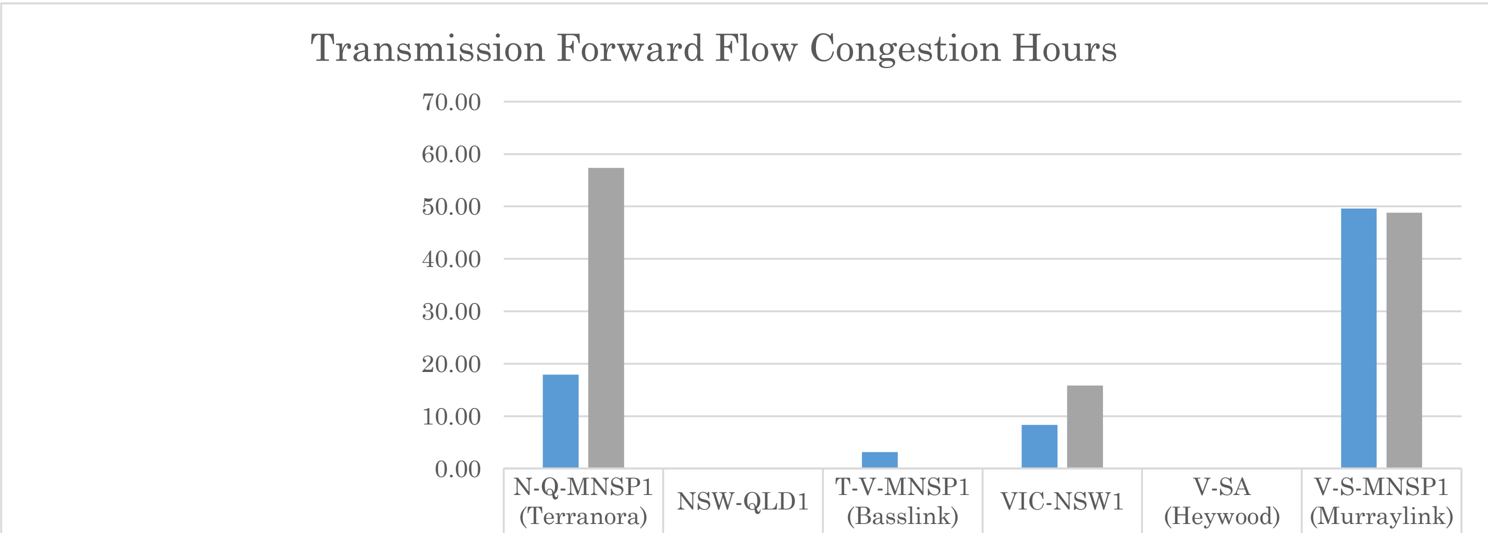


	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	566	2454	11	239	3543	35	4639	82	149	2886	1840	3348	273
Ramp Down Minutes (w/ BESS)	496	1025	28	228	1278	8	1031	51	242	1130	3601	417	29

Figure 57: Generator Ramp-Down Minutes, Proposed Scenario Winter Load

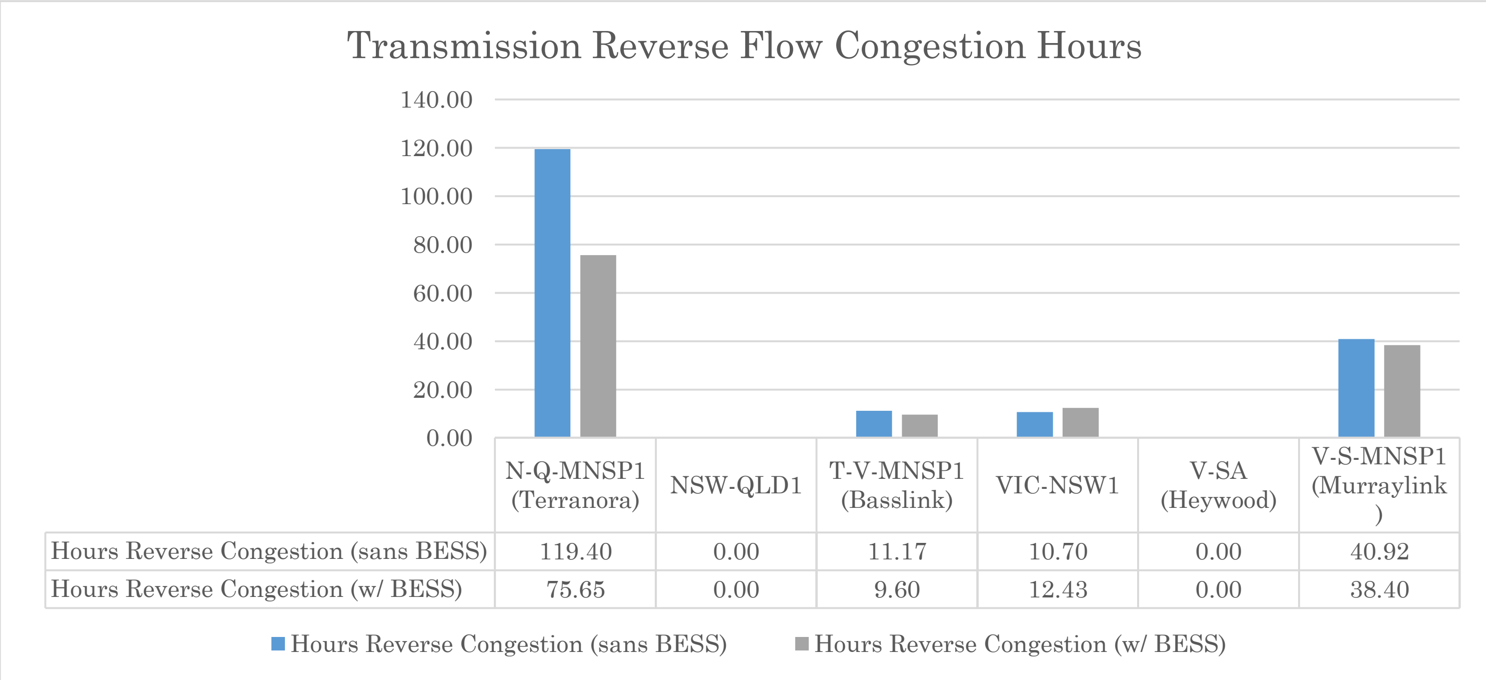
3.5.3 Effect of Battery Regulation on Transmission Flow

The Proposed winter case produced some alarming results which saw a significant increase in transmission congestion – particularly on the Terranora line, whose forward congestion hours were nearly trebled. However, this increase in congestion in the forward direction was also outweighed by the decrease in reverse congestion on the same line. Other transmission lines only saw slight changes to their transmission congestion hours after the addition of battery regulation capacity. This scenario saw the lowest decrease in total relative transmission congestion hours, at a 1.19% reduction after the addition of the 30 MWh of battery regulation capacity. A summary of these results are shown in Figure 59 below and Figure 60 on the following page.



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Forward Congestion (sans BESS)	17.93	0.00	3.15	8.30	0.00	49.58
Hours Forward Congestion (w/ BESS)	57.33	0.00	0.00	15.83	0.00	48.80

Figure 59: Transmission Forward Power Congestion Time, Proposed Scenario Winter Load



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Reverse Congestion (sans BESS)	119.40	0.00	11.17	10.70	0.00	40.92
Hours Reverse Congestion (w/ BESS)	75.65	0.00	9.60	12.43	0.00	38.40

Figure 60: Transmission Reverse Power Congestion Time, Proposed Scenario Winter Load

From Figure 61 below we can see again that the probability distribution function is much smoother with added battery regulation, with the NSW-QLD line trending much closer to its midway point at the 50% crossing and the VIC-NSW line much more closely resembling an S-shape, despite the basslink deviating further from its midway point at the 50% crossing..

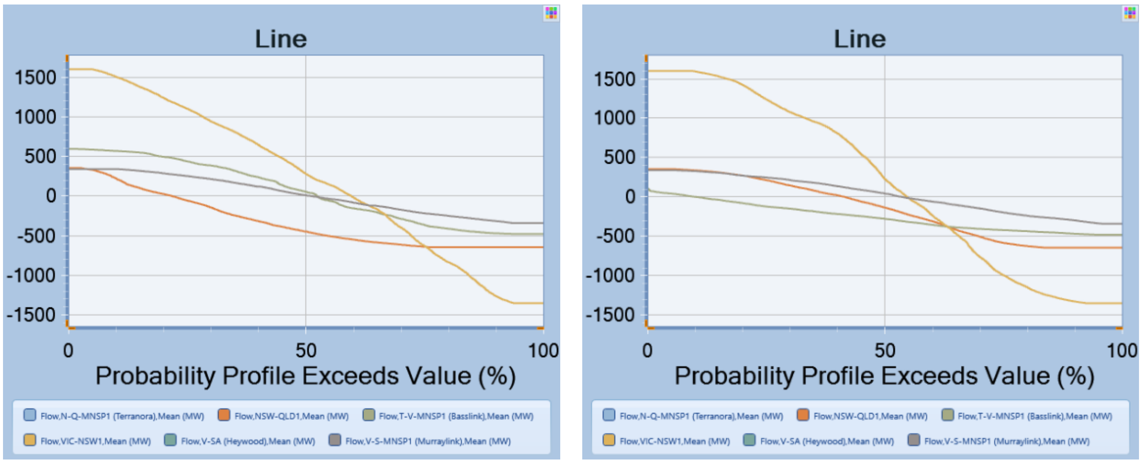


Figure 61: Cumulative Probability Distribution Profile Of Transmission Power Flows, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global battery Regulation Capacity

3.6 High RE Scenario, Winter Load

3.6.1 Energy Curtailed

The added 45 MWh battery regulation capacity in the High RE scenario resulted in a decrease in renewable energy curtailment of 21,965 MWh, 24.115 MWh, and 15,312 MWh in the 5%, 10% and 15% scenarios, representing a relative reduction of 14.61%, 16.17%, and 10.63%, respectively, as shown in Figure 62 below

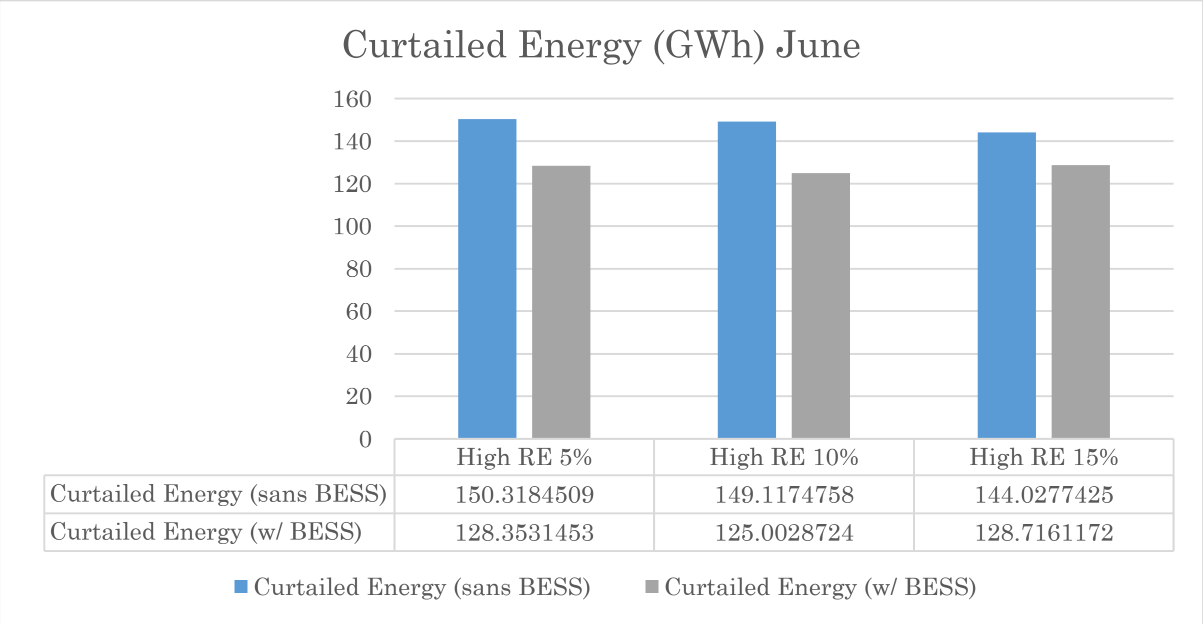
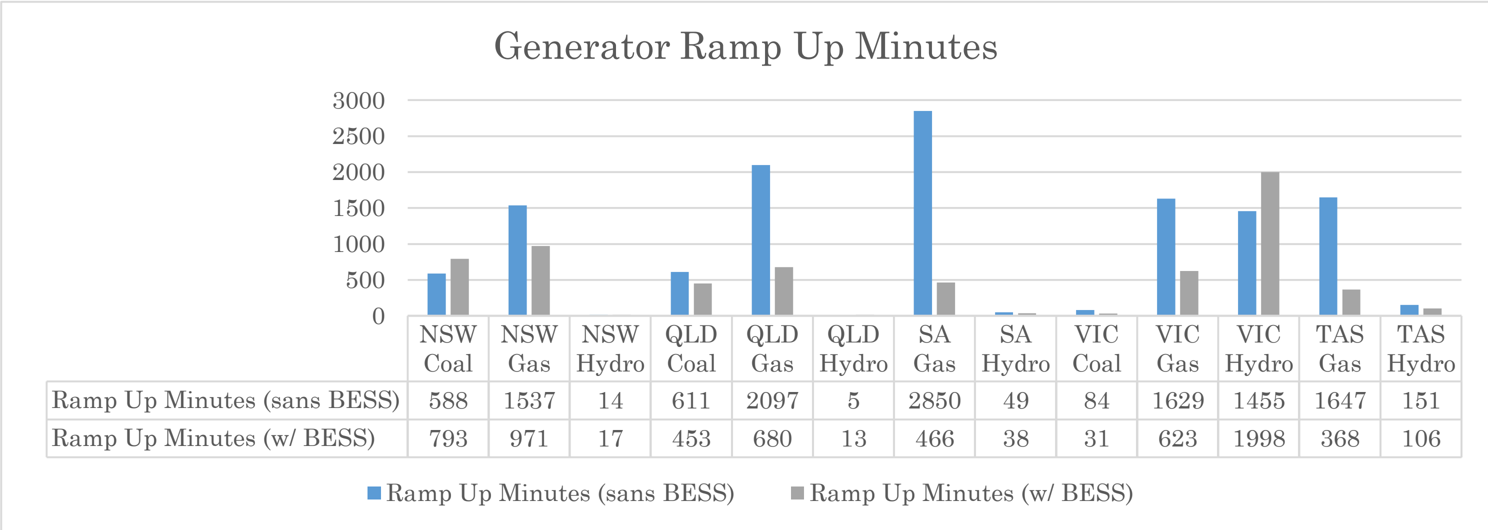


Figure 62: Curtailed Energy, High RE Scenario Winter Load

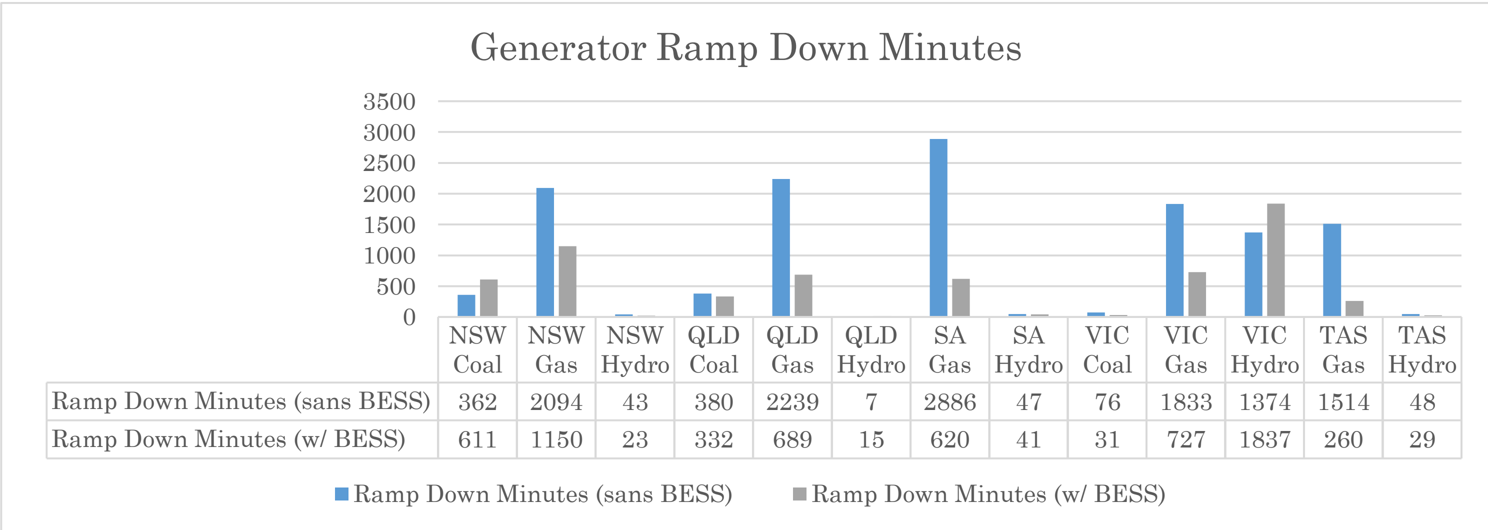
3.6.2 Generator Ramping Requirements

As was seen in the summer scenario, we see that all generators experience a decrease in their ramping requirements, with the exception of Victorian hydroelectricity and New South Wales Coal generation. The time spent ramping was reduced by 56.46%,, while the Victorian hydroelectric generators increased their ramping times by 37.32% and 33.7% in the upward and downward directions.



	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Up Minutes (sans BESS)	588	1537	14	611	2097	5	2850	49	84	1629	1455	1647	151
Ramp Up Minutes (w/ BESS)	793	971	17	453	680	13	466	38	31	623	1998	368	106

Figure 63: Generator Ramp-Up Minutes, High RE Scenario Winter Load



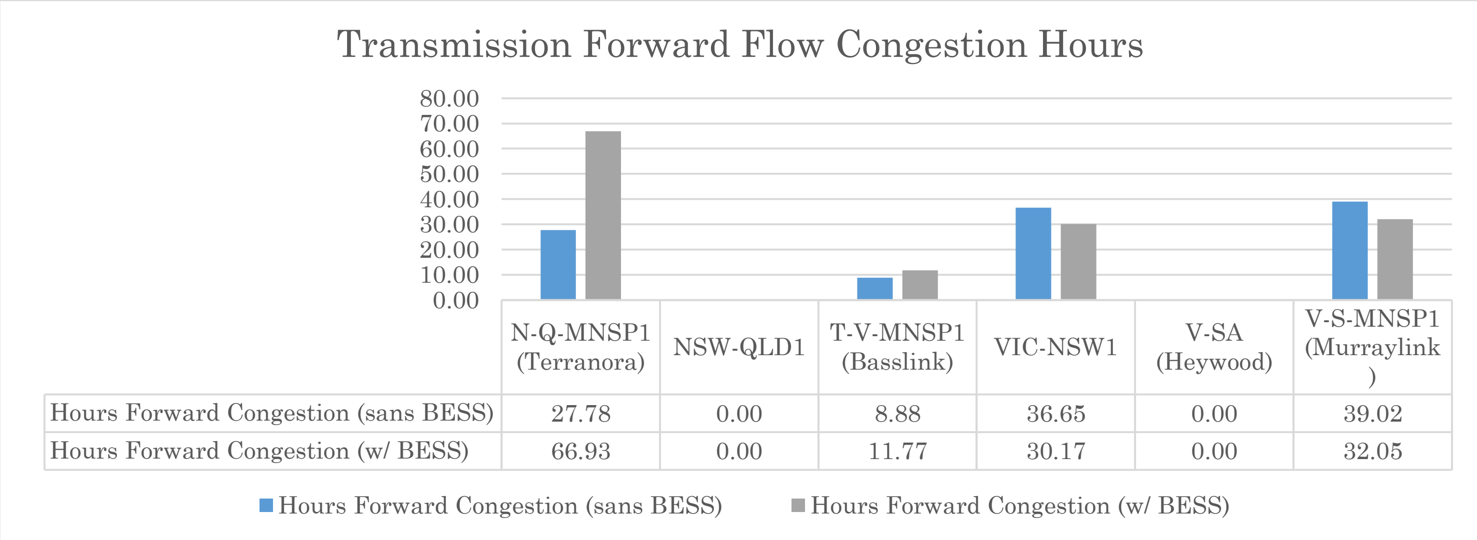
	NSW Coal	NSW Gas	NSW Hydro	QLD Coal	QLD Gas	QLD Hydro	SA Gas	SA Hydro	VIC Coal	VIC Gas	VIC Hydro	TAS Gas	TAS Hydro
Ramp Down Minutes (sans BESS)	362	2094	43	380	2239	7	2886	47	76	1833	1374	1514	48
Ramp Down Minutes (w/ BESS)	611	1150	23	332	689	15	620	41	31	727	1837	260	29

Figure 64: Generator Ramp-Down Minutes, High RE Scenario Winter Load

3.6.3 Effect of Battery Regulation on Transmission Flow

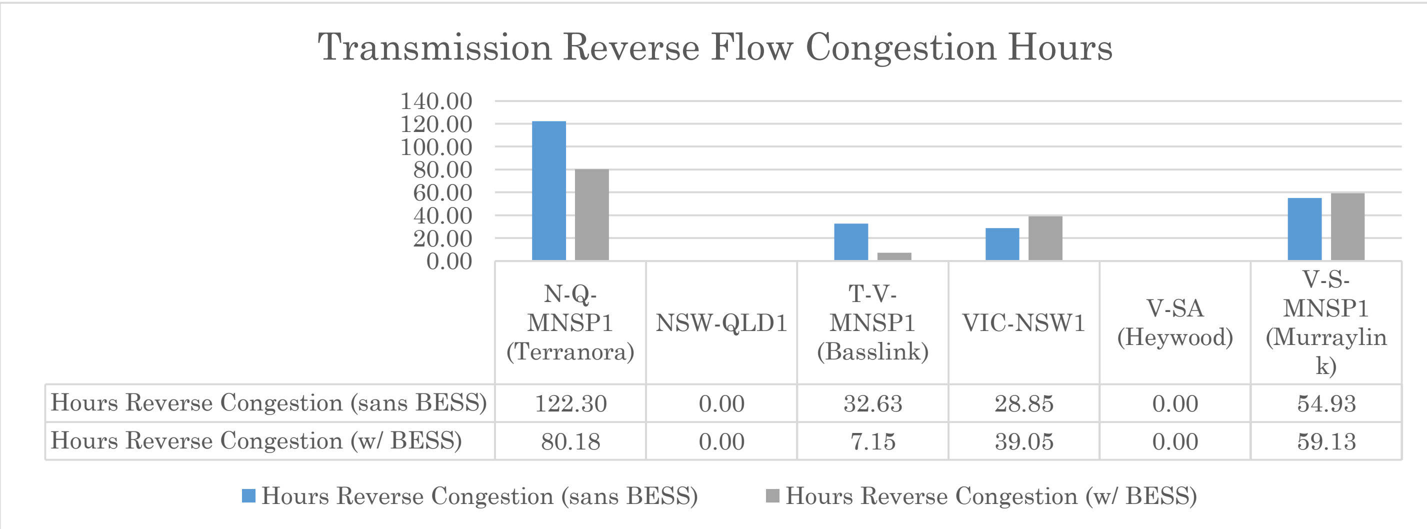
When looking at Figure 65 and Figure 66 on the following page can see that the addition of battery regulation capacity to the network has once again resulted in an overall decrease of the aggregated transmission congestion hours, representing a total decrease of 2.32%

It can also be observed in the probability distribution profiles from Figure 67 on the following page that the distribution of power flows becomes slightly more normalised, despite the Basslink deviating further from its midpoint at the 50% crossing.



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Forward Congestion (sans BESS)	27.78	0.00	8.88	36.65	0.00	39.02
Hours Forward Congestion (w/ BESS)	66.93	0.00	11.77	30.17	0.00	32.05

Figure 65: Transmission Forward Power Congestion Time, High RE Scenario Winter Load



	N-Q-MNSP1 (Terranora)	NSW-QLD1	T-V-MNSP1 (Basslink)	VIC-NSW1	V-SA (Heywood)	V-S-MNSP1 (Murraylink)
Hours Reverse Congestion (sans BESS)	122.30	0.00	32.63	28.85	0.00	54.93
Hours Reverse Congestion (w/ BESS)	80.18	0.00	7.15	39.05	0.00	59.13

Figure 66: Transmission Reverse Power Congestion Time, High RE Scenario Winter Load

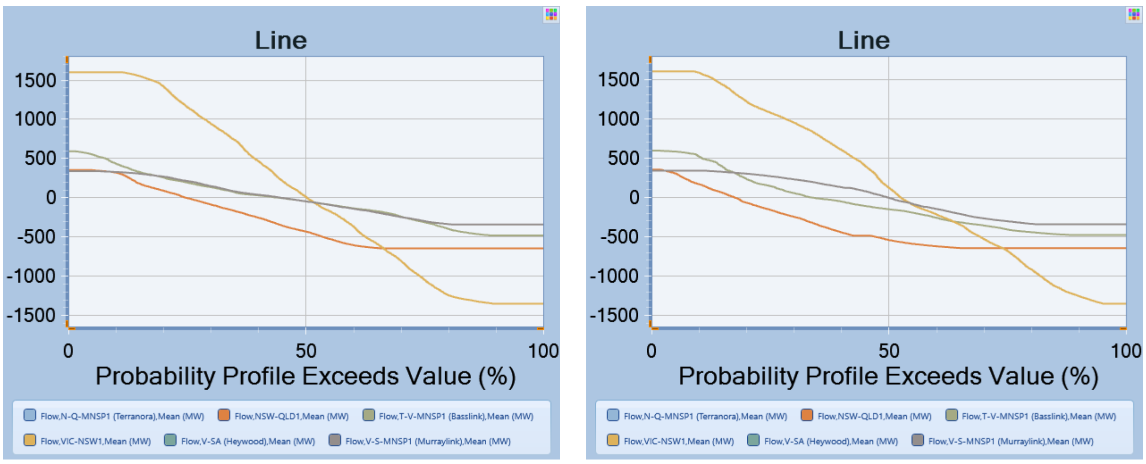


Figure 67: Cumulative Probability Distribution Profile Of Transmission Power Flows, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global battery Regulation Capacity

Chapter 3

4 Discussion

ALTHOUGH there were thirty-six different scenarios that were modelled for this project, the results for generator ramping and transmission line congestion only analyse twelve of them (i.e. the 10% variability scenarios). The reason for this is mostly due to time constraints and a consideration for the length of this report. Since the only differentiating factor between the scenarios that were and weren't analysed are the level of variability introduced to renewable energy generators, the scenarios with 10% variability were selected as a midway point and assumed to be the most representative of all thirty-six. The analysis of energy curtailment did look at all scenarios modelled, however suffered as a result of simplifying assumptions in the model which did not yield any correlations between variability and energy curtailment.

4.1 Energy Curtailment

In every scenario investigated, it was found that the inclusion of battery regulation capacity to the NEM had the effect of decreasing the amount of curtailed energy that resulted as a result of renewable energy intermittency. The extent to which energy curtailment was reduced varied between scenarios and, unfortunately, was skewed in the Proposed and High RE scenarios due to high levels of over-production and an assumption that excluded energy storage in the modelling.

The results from the summer Base scenario produced high reductions in energy curtailment, ranging between 88.21% and 94.34%. This is a surprisingly optimistic result, given that battery systems were modelled to exclusively provide regulation services, and not storage of excess energy generation. This would suggest that the main reason for curtailment of renewable energy generation is not due to over-production but because of large fluctuations in power to which generators are unable to respond. If this is the case though, it should be expected that energy curtailment increases as variability increases. However, looking at the results, there does not appear to be any correlation between the two. The reason for this is not immediately obvious however it is possible that the lack of economic constraints in this model had an impact on this result, affecting the co-optimisation algorithms that dictate the dispatch of generators and reserves.

Nevertheless, this result indicates that the inclusion of battery regulation capacity allows for a greater penetration level of renewable energy generation In the NEM, suggesting an improved economic performance of renewable energy generators.

4.2 Generator Ramp Rates

In every scenario analysed, generator ramp rates saw a significant decrease to their ramping requirements after the inclusion of battery regulation technology, ranging between 48.03% and 49.56% for the summer load and between 52.36% and 57.49% for the winter load. This is in contrast to the Victorian hydroelectricity generators, which showed *increases* in ramping times across all scenarios, ranging between 38.97% and 106.17% for the summer load and 33.7% and 144.54% for the winter load. There are two possible explanations for this sharp increase in ramping: firstly, although hydroelectric generators are not as fast to respond as battery systems, they were modelled to be much faster than other conventional generators. This is because the ramp rate of hydroelectric generators is typically much higher than thermal generators, being mostly limited only by the need to control water hammer events in the penstock. Thermal generators, on the other hand, need to be carefully managed so as to avoid damage from wet steam (in the case of supercritical steam generators) or excessive thermal expansion/contraction of their structures. Secondly, Victoria is the most well-connected state in the NEM, sharing major transmission lines with South Australia, Tasmania, and New South Wales. Since South Australia and Tasmania both have high penetration levels of renewable energy, it is very possible that FCAS services may need to be imported from Victoria during times of high renewable energy intermittency. So, although the total generator ramping requirements decreased in each scenario, the Victorian hydroelectricity generators increased their ramping in such a way as to supplement the service provided by battery regulation systems. Overall, this is a good result which also indicates improved generator lifetime, lower emissions, higher efficiencies, and therefore lower SRMCs.

4.3 Transmission Power Flows

In every scenario analysed, the total time at which transmission lines spent at their maximum flow limits was reduced after the addition of battery regulation capacity. It was also observed that the distribution of power flows on transmission lines generally became more uniform, as indicated by the shape of the probability distribution curves.

The relative decrease in transmission congestion was most apparent in the Base scenarios, which saw reductions of 17.77% and 13.50% for the summer and winter loads, respectively. Although there were some cases of individual transmission lines showing an increase in power flow congestion, it should be emphasised that this is not necessarily an undesirable tendency, if, for example, one region can export energy to another as a consequence of battery systems reducing the amount of curtailed renewable energy generation.

The findings from these results do suggest that, overall, battery systems enable individual regions to better manage power requirements without as much reliance upon electricity imports from neighbouring regions. This indicates an improvement to the robustness of the system by strengthening regional networks and lowering the potential impact of the failure of a transmission line.

4.4 Assumptions

One of the key limitations of this study is that if suffers from a lack of quality data and information. Therefore, careful discretion should be exercised when reflecting on the results, due to the simplifying assumptions that were made throughout the modelling process. Especially when considering the physical and operational complexities of such a system.

Another concern is with much of the datum and modelling information being sourced from differing sources, which could have resulted in inconsistencies or overlap; for example, with load demand and PV generation, where load demand already incorporates some ‘behind-the-metre’ contributions from PV. Another example is with the growth of wind generation to 2020 and 2050. These figures were taken from two different sources and therefore may have been based on entirely different assumptions. These inconsistencies were minimised as much as possible, however, given the breadth of this study, there does not exist any one source from which all relevant data is available.

Although modelling was done as accurately as possible, there were also a number of assumptions made throughout the model that may not necessarily reflect real-world conditions and could have introduced some level of uncertainty into the results. Many of these assumptions were simply due to time constraints while others are a result of a lack of quality data. These are described below:

4.4.1 Demand Side Energy Management

Due of a lack of data, and in order to avoid speculation about its role, demand side energy management was not taken into account in the modelling of this thesis. This was, in hindsight, perhaps the most profound assumption made in this project. Demand side management refers to ‘behind-the-metre’ methods of increasing energy efficiency or decreasing economic cost of consumer energy, such as energy arbitrage or peak load shaving. Although still a relatively small industry, the future growth of residential energy storage and arbitrage is expected to have a profound impact on the behaviour of the electricity grid, impacting load demand as ‘seen’ by the network.

The load profiles for 2015 are as accurate as possible, since they are direct measurements which include the impacts of demand side management. However, energy storage systems for residential, commercial, and industrial use are widely regarded to be at the cusp of a dramatic growth over the next decade and beyond. Although projected growth rates in energy demand to 2035 and 2050 were taken into account for the Proposed and High RE scenarios, it can be expected that the shapes of these corresponding profiles will be very different to today.

Another key assumption was that all PV generators were assumed to feed power back into the grid, rather than acting as a reduction in electricity load. Since load demand is measured at the system level, load data already includes existing PV generators that act to reduce demand behind the metre. Therefore, in each of the scenarios modelled, it is likely that the contributions of PV generation were overestimated, resulting in a high energy curtailment for the Proposed and High RE scenarios. This assumption was also compounded by the exclusion of energy storage, which is often used in conjunction with PV generators in order to utilise as much PV energy as possible.

4.4.2 PV Assumptions

It was assumed that PV generators behaved 'ideally', that is. without any losses due to soiling, degradation, shading or temperature effects. Wider system losses due to cabling and inverter inefficiencies were also omitted, as was inverter 'clipping' (i.e. maximum power output), inverter rate of change, degradation, and temperature effects.

It was also assumed that all PV generators in the NEM were horizontally oriented. In reality, PV modules (in the southern hemisphere) are typically north-facing in order to capture more solar irradiation. Furthermore, PV modules are often oriented towards either the east or west, in order to better correlate with morning and evening load demands and higher electricity tariff pricing. This should result in a 'stouter' PV profile, characterised by a broader, more square-shaped curve.

Perhaps the most profound PV generation assumption that was made had to do with the use of solar irradiation data. Due to a lack of accurate data that was consistent between dates, data from only 1 site from each state was used. And although these sites were selected as close as possible to areas of high concentration of PV generation, as well as being manipulated to eliminate any localised variabilities (such as cloud cover), the hourly to daily variation in these datum cannot be expected to be representative of their entire respective states. Therefore, this study could have been improved either with measured PV generation data, aggregated by state, or with more accurate short-term forecasting of solar irradiation on a state-wide level.

4.4.3 Wind Generation Assumptions

It was assumed in the modelling that wind capacity grows uniformly across all states, according to future projections for 2020 and 2050. A more accurate method to model wind capacity growth would have been to analyse the wind resources in each state and identify regions that are most suitable for wind capacity expansion.

A major flaw in modelling wind generation also had to do with forecasted growth rates that were used in the Proposed and High RE scenarios. Projections for 2020 wind capacity, which were used in the Proposed scenario, were taken from AEMO and were based on Australia's installed capacity in 2013. Here it was assumed that the installed wind capacity in 2013 was the same as that in 2015 – the year from which wind generation data was taken. Since wind generation capacity has grown between 2013 and 2015, the 2020 figure that was used in the Projected scenario was an overestimation. Another flaw was with the wind capacity figure used in the High RE scenario, which was based on BREE's projected growth rate from 2035 to 2050. Here it was assumed that the capacity used in the Projected scenario was representative of BREE's 2035 forecast, despite AEMO and BREE being two entirely separate entities with presumably different methods that led to each of their respective forecasts. This study could have been improved with more accurate and consistent wind generation capacity forecasting, taking into account regions in Australia that are best suited for these installations.

4.4.4 Variability Assumptions

Although there is no way to precisely recreate a highly-randomised dataset of 1-minute intervals from measurements taken at the 5-minute level, the method used in this project was not as accurate as it could have been. Rather than using a Microsoft Excel macro script to simply repeat each 5-minute value five times, a more accurate approach would have been to interpolate between measurements in order to produce a smoother trend line. Despite adding an element of random variability, the method used in this project produces a curve that is somewhat staggered in 5-minute intervals, therefore impacting the final result.

The introduced variability to wind, PV, and load were also difficult to verify and required simplifying assumptions. Because of this, three different levels of variability were modelled for wind and PV systems, ranging from 5% to 15% standard deviation of errors. In reality, this is a very high level of variability and would be unlikely to be witnessed over an entire week. Nevertheless, there are some reports which observe an even higher level of 1-minute variability in renewable energy generation. Load demand variability was set to a nominal value of 1% error standard deviation, since regulation capacity is often set to 1% of peak load, as used to be the case in the PJM Interconnection before the introduction of battery regulation systems (Boston & Baker, 2015). This study could have been improved with information on more accurate short-term forecasting of wind and solar resources when aggregated over a large area, taking into account Australia's unique climate and weather patterns.

4.4.5 Battery Assumptions

Battery characteristics were very roughly based on those of the advanced lead acid battery, however there were a significant number of assumptions that were made due to limitations with PLEXOS as well as a lack of information.

PLEXOS is unable to accurately model the nonlinear behaviours of battery systems and therefore the battery regulation systems were assumed to behave 'ideally'. For example, the discharge current was not modelled to have an effect on battery capacity, as is observed in real lead acid batteries as described by Peukert's Law. Battery voltages were assumed to be fixed, and not vary depending on SOC. Furthermore, temperature effects on voltage and cell degradation were also ignored. Finally, the maximum ramp rates of battery systems were assumed to be near instantaneous, and set to PLEXOS's default value of 1E+30 MW/min. This is an assumption that was not verified for this particular study.

Due to the peculiar characteristics and nuances that different battery technologies exhibit, this study could be improved by looking at measured data from a battery system that has been used over a long time for frequency regulation. However, since no such system currently exists in Australia, careful consideration should be taken for the differences between operating conditions.

4.4.6 Generator Assumptions

Like battery systems, generators do not behave linearly in the real world, and are subject to varying ROCs and efficiencies at different power outputs and temperatures. These were, however, ignored in this model.

The most profound generator assumption that was made was the omission of economic constraints that affect the dispatch of generators. The dispatch of generators are normally co-optimised based on their short-run marginal costs (SRMCs). PLEXOS calculates generator SRMCs based on fuel price, marginal heat rates, variable O&M costs, use of service charges, heat production value, and incremental emissions costs (if applicable). These were all ignored for the purpose of simplicity and a lack of relevant data, and instead generator dispatch was limited only by generator capacity, maximum power output, minimum stable output, and minimum/maximum ramp rates. The effects of generator inertia on the power system were also ignored in this model.

5 Conclusions

Despite facing a number of challenges and limitations, the results of this analysis serve as a good proof of concept as to the benefits that fast-responding battery regulation systems could provide to the NEM, in terms of reducing generation requirements, transmission power flow congestion, and curtailment of highly-variable renewable energy generation. PLEXOS was found to be a comprehensive software package that was able to meet the requirements of these simulations. This study is therefore considered to have been successful in meeting its own objectives of analysing the overall stability and robustness of the NEM as it transitions towards a low-emissions generation portfolio. In every scenario analysed, results invariably showed significant reductions to generator ramping requirements, transmission line congestion, and energy curtailment when battery regulation is integrated with the infrastructure of the NEM.

This line of work could be further investigated by taking into account economic constraints, particularly with FCAS market mechanisms that compensate fast-responding regulation technologies. Another point of enquiry could be to quantify the value of reduced generator ramping rates in terms of improved lifetime, reduced O&M costs, fuel and emissions costs, as well as the added value of using current generation capacity for other services such as energy generation and contingency events. Further areas that could be explored also include investigating the role that residential battery systems and electric vehicles could undertake in maintaining power quality in the electricity grid, and better methods for short-term forecasting of wind and solar resources.

6 References

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7 Appendices

7.1 Appendix A – Modelling Assumptions

Operating characteristics of each technology.

Characteristics	Coal	CCGT	OCGT
Unit size (MW)	600	500	150
Minimum generation (MW)	300	200	0
Ramp rate (MW/hour)	480	720	600
Fuel used during start-up (GJ)	2,500	1,500	200
Start-up fuel cost ($/start)	50,000	7,850	1,040
Full start-up costs ($/start)	250,000	23,550	2,080
CO_2 emissions during start-up (tCO_2)	187.5	90	12

Figure 68: Typical Ramp Rates for Coal, CCGT, and OCGT[41]

Queensland Scheduled Generation Portfolio					
Generator Type	**Rated Power (MW)**	**Maximum Power (MW)**	**Minimum Stable Level (% Rated Power)**	**Maximum Ramp-Up (MW/min)**	**Maximum Ramp-Down (MW/min)**
Coal	8,216	8,882	50	109.52	109.52
CCGT	1,124	1,307	40	26.98	26.98
OCGT	1,857	1,962	0	123.68	123.68
Hydro	664	664	-	284.72	284.72
Biomass	350	416.38	-	-	-
Gas Other	147	147	-	9.79	9.79
Other	1	1	-	-	-

Table 11: Queensland Generator Operating Characteristics

South Australia Scheduled Generation Portfolio					
Generator Type	**Rated Power (MW)**	**Maximum Power (MW)**	**Minimum Stable Level (% Rated Power)**	**Maximum Ramp-Up (MW/min)**	**Maximum Ramp-Down (MW/min)**
Coal	786	786	50	16.74	16.74
CCGT	419	594.75	40	51.32	51.32
OCGT	915	1088.60	0	60.94	60.94
Hydro	3	3	-	-	-
Gas Other	1,293	1,293	-	86.11	86.11
Other	109	109	-	-	-

Table 12: South Australian Generator Operating Characteristics

[41] (Vithayasrichareon & MacGill, 2014)

Victoria Scheduled Generation Portfolio					
Generator Type	**Rated Power (MW)**	**Maximum Power (MW)**	**Minimum Stable Level (% Rated Power)**	**Maximum Ramp-Up (MW/min)**	**Maximum Ramp-Down (MW/min)**
Coal	6,260	6,260	50	84.47	84.47
CCGT	21	21	40	0.50	0.50
OCGT	1,904	2,134.85	0	126.91	126.91
Hydro	2,296	2,296	-	1,971.80	1,971.80
Biomass	1	1	-	-	-
Gas Other	568	568	-	37.83	37.83
Other	1	1	-	-	-

Table 13: Victorian Generator Operating Characteristics

Tasmania Scheduled Generation Portfolio					
Generator Type	**Rated Power (MW)**	**Maximum Power (MW)**	**Minimum Stable Level (% Rated Power)**	**Maximum Ramp-Up (MW/min)**	**Maximum Ramp-Down (MW/min)**
OCGT	178	223.87	40	11.85	11.85
Hydro	2,281	2,281	-	1,504.64	1,504.64
Gas Other	5	5	-	0.33	0.33
Other	200	200	-	-	-

Table 14: Tasmanian Generator Operating Characteristics

NEM Regulation Raise Provision		
State	**Minimum Reserve (MW)**	**Maximum Reserve (MW)**
NSW	32.5	62.5
QLD	32.5	62.5
VIC	32.5	62.5
SA	32.5	62.5
TAS	50	50

Table 15: Regulation Raise Provision By Region

NEM Regulation Lower Provision		
State	**Minimum Reserve (MW)**	**Maximum Reserve (MW)**
NSW	30	62.5
QLD	30	62.5
VIC	30	62.5
SA	30	62.5
TAS	50	50

Table 16: Regulation Lower Provision by Region

Table 1-1 — Projected 2020 NEM wind generation

Region	Existing wind (MW)	Projected new wind by 2020 (MW)	Total 2020 wind (MW)	2012 minimum demand (MW)
QLD	0	266	266	4,098
NSW	265	2,117	2,382	5,124
VIC	884	4,090	4,974	3,780
SA	1,205	1,350	2,555	1,035
TAS	308	1,060	1,368	813
NEM	2,662	8,883	11,545	15,174

Table 17: Projected 2020 Wind Generation Capacity[42]

Table 9: Electricity generation, by state and territory (TWh)

State/territory	2014-15	2034-35	2049-50	% share 2014-15	% share 2049-50	% average annual growth 2014-15 to 2049-50
New South Wales a	69	91	94	27	28	0.9
Victoria	51	51	56	20	17	0.3
Queensland	64	82	85	25	26	0.8
South Australia	21	28	28	8	9	0.9
Western Australia	32	42	46	12	14	1.1
Tasmania	14	14	17	5	5	0.5
Northern Territory	4	6	7	2	2	1.4
Australia b	**255**	**315**	**332**	**100**	**100**	**0.8**

a includes Australian Capital Territory
b numbers in the table may not add up to their totals due to rounding

Table 18: Growth In Electricity Generation By Region[43]

[42] (AEMO, 2013)
[43] (BREE, 2014)

Table 10: Electricity generation, by energy type (TWh)

Energy type	2014-15	2034-35	2049-50	% share 2014-15	% share 2049-50	% average annual growth 2014-15 to 2049-50
Non-renewables	**216**	**252**	**265**	**85**	**80**	**0.6**
Coal	163	200	214	64	65	0.8
black coal	117	153	163	46	49	1.0
brown coal	47	47	51	18	15	0.3
Gas	50	49	48	19	14	-0.1
Oil	3	3	3	1	1	0.0
Renewables	**39**	**63**	**67**	**15**	**20**	**1.5**
Hydro	19	19	18	7	6	-0.1
Wind	16	32	33	6	10	2.0
Bioenergy	2	5	6	1	2	3.7
Solar	2	3	6	1	2	3.0
Geothermal	0	4	4	0	1	
Total a	**255**	**315**	**332**	**100**	**100**	**0.8**

Table 19: Growth In Electricity Production By Technology Type[44]

[44] (BREE, 2014)

7.2 Appendix B – Results

7.2.1 Proposed Summer Generation Profiles

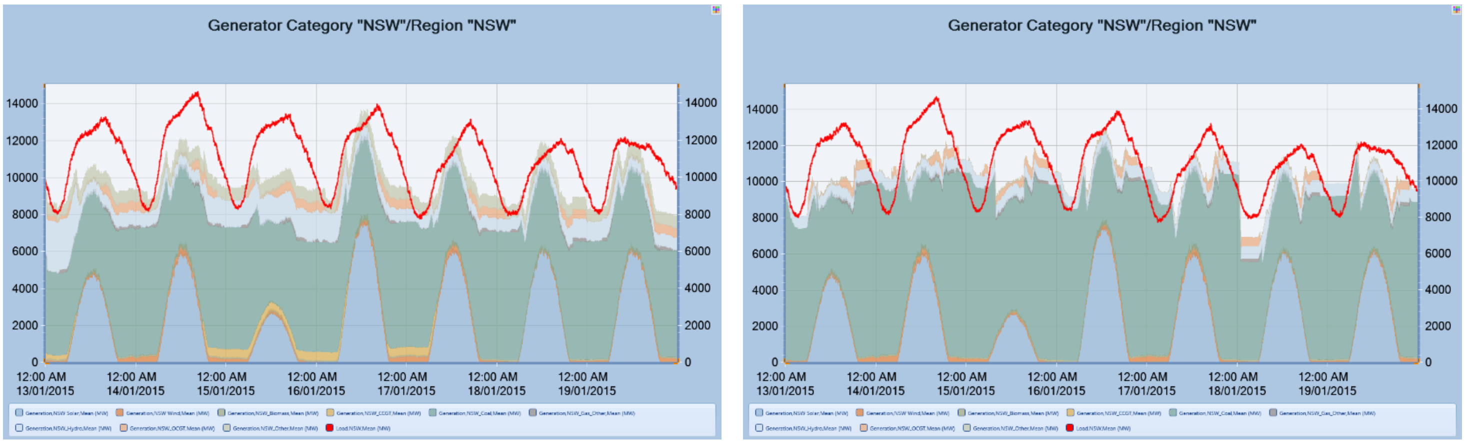


Figure 70: NSW Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

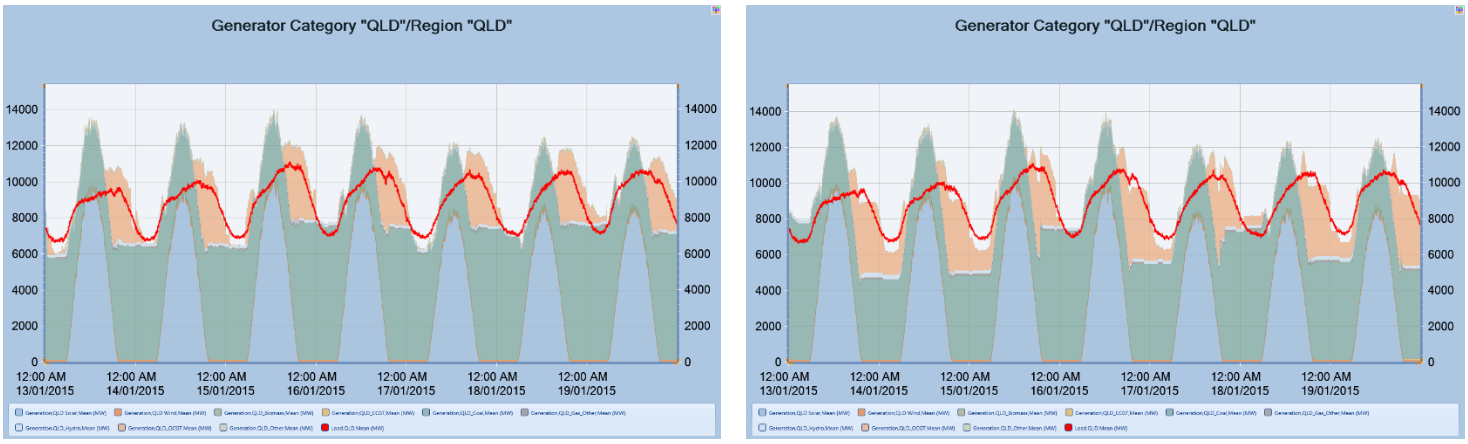


Figure 69: QLD Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

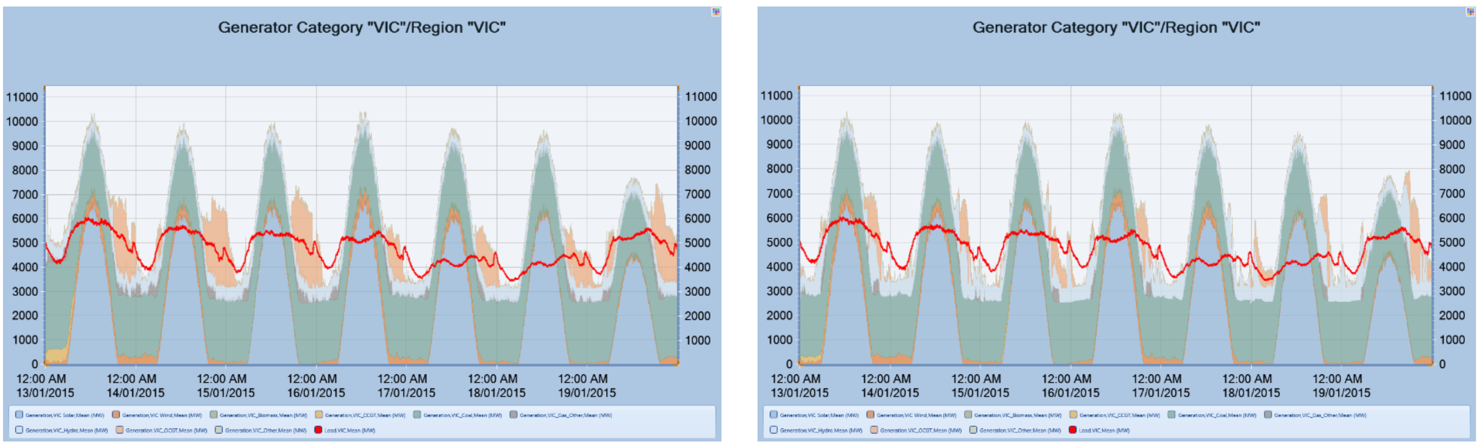


Figure 71: VIC Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

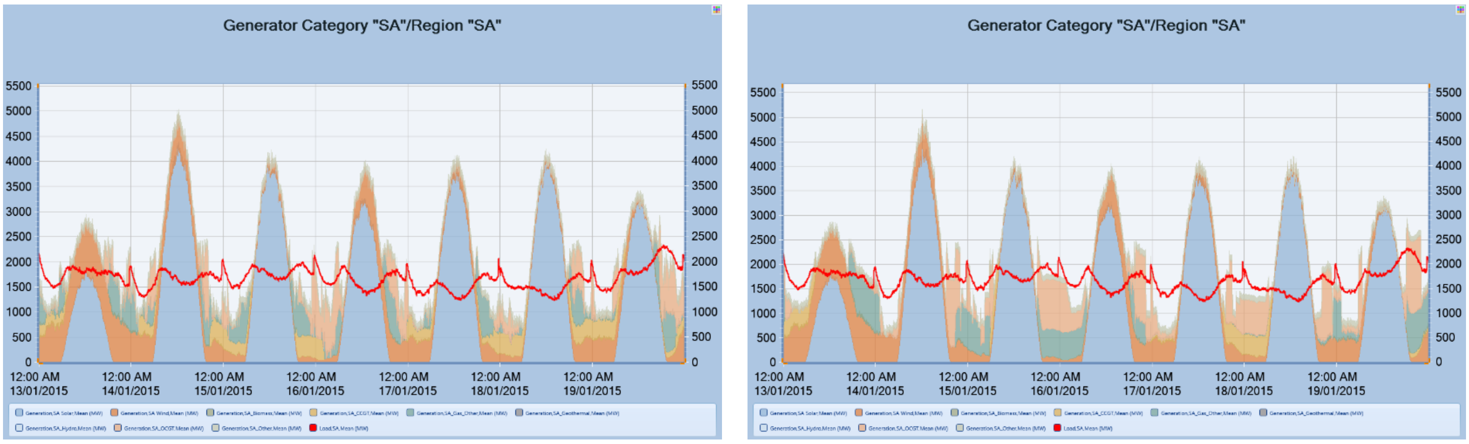


Figure 73: SA Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

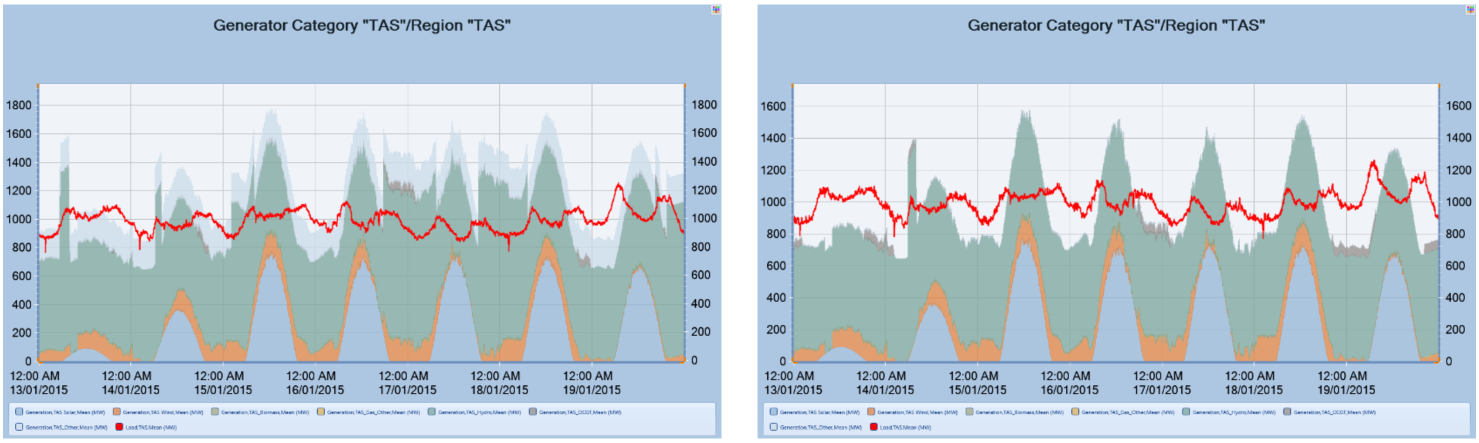


Figure 72: TAS Generation Profile, Base Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

7.2.2 Proposed Summer Transmission Profiles

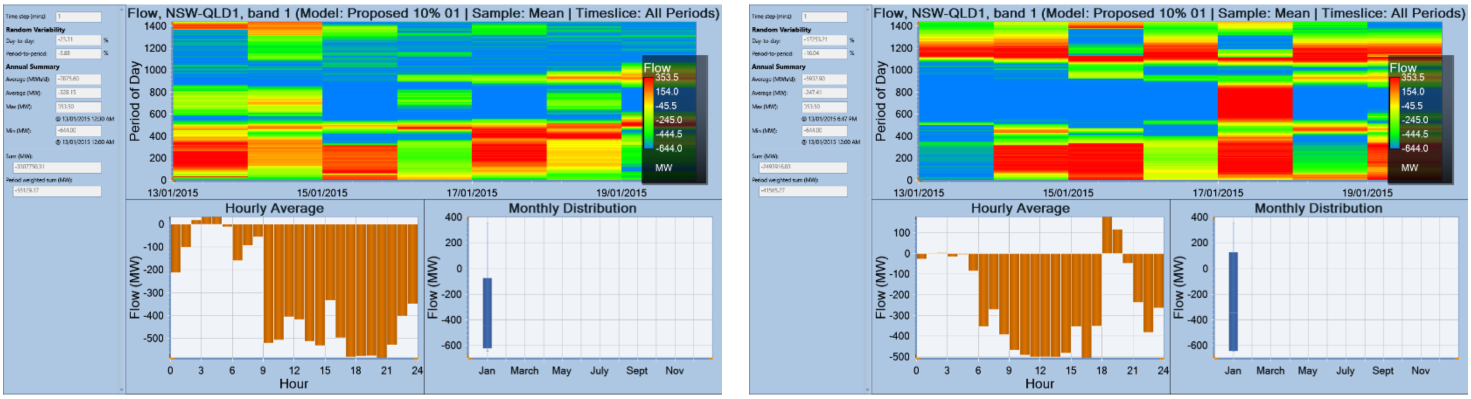


Figure 75: Heat Maps And Statistical Summary of Transmission Power Flow On Heywood Line, Proposed Scenario Summer Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

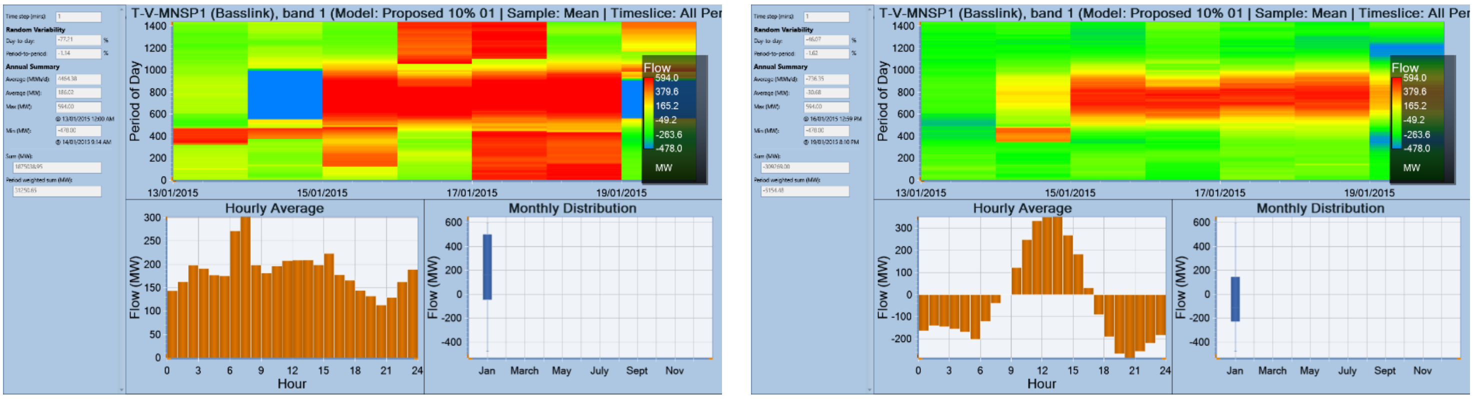


Figure 76: Heat Maps And Statistical Summary of Transmission Power Flow On NSW-QLD Line, Proposed Scenario Summer Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

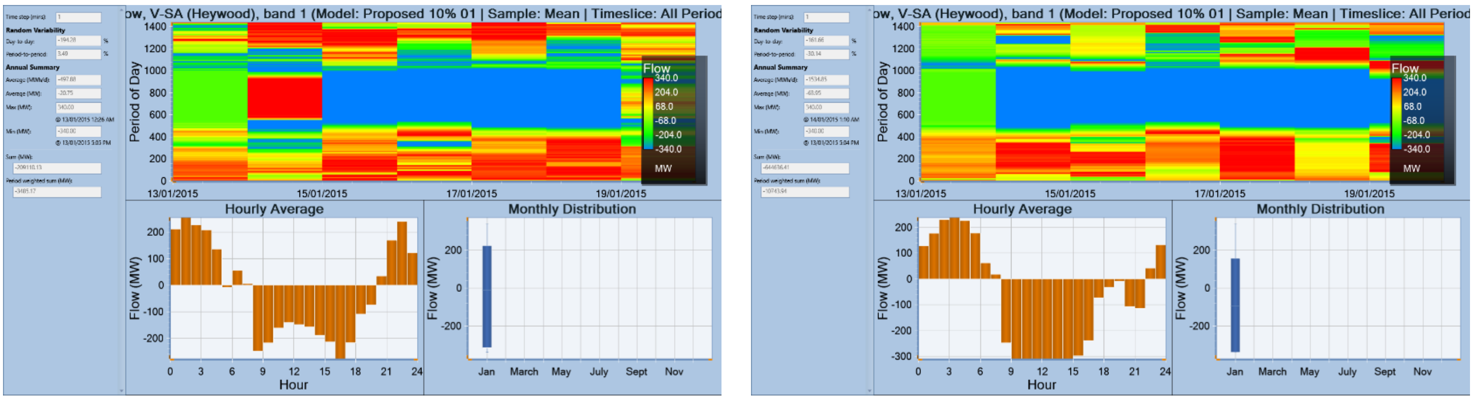
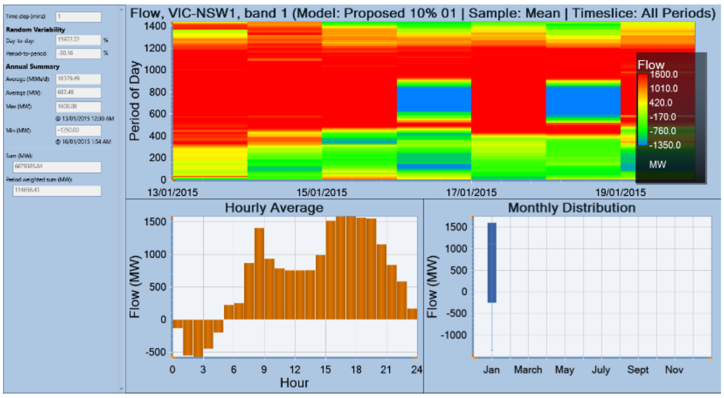


Figure 74: Heat Maps And Statistical Summary of Transmission Power Flow On Basslink Line, Proposed Scenario Summer Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity



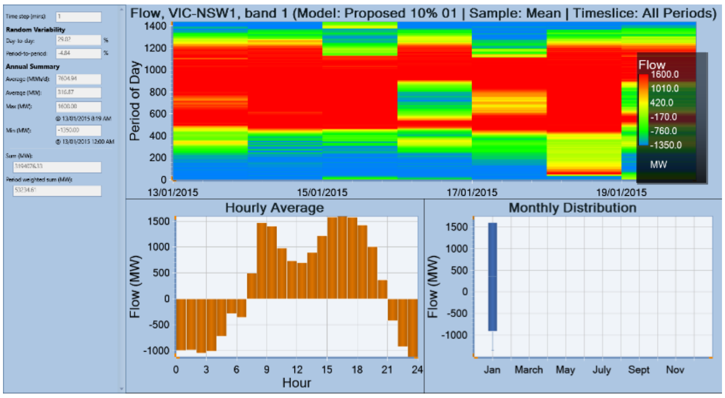


Figure 77: Heat Maps And Statistical Summary of Transmission Power Flow On VIC-NSW Line, Proposed Scenario Summer Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

7.2.3 High RE Summer Generation Profiles

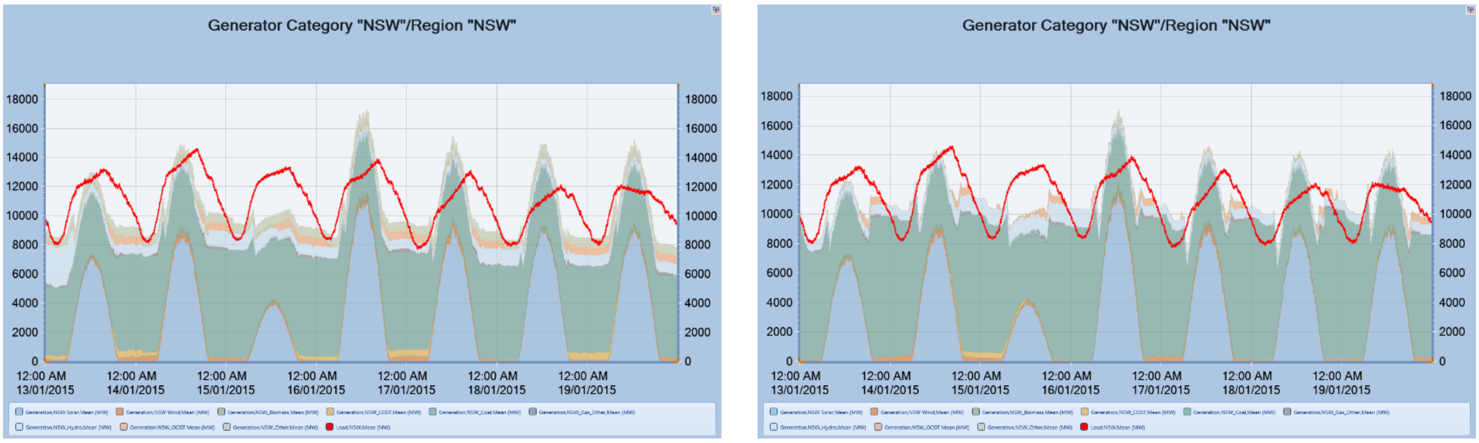


Figure 80: NSW Generation Profile, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

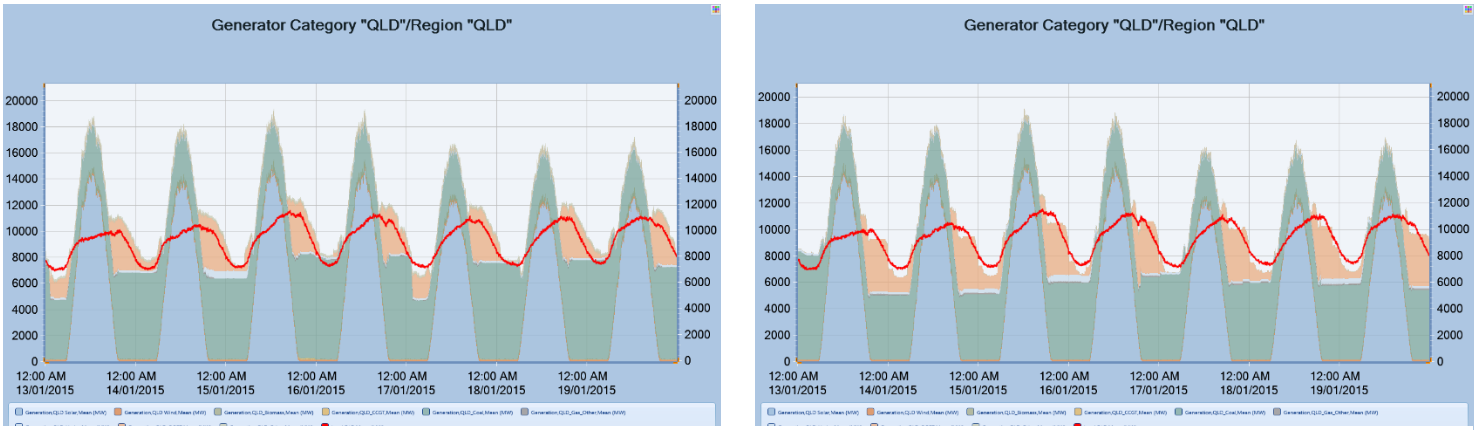


Figure 79: QLD Generation Profile, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

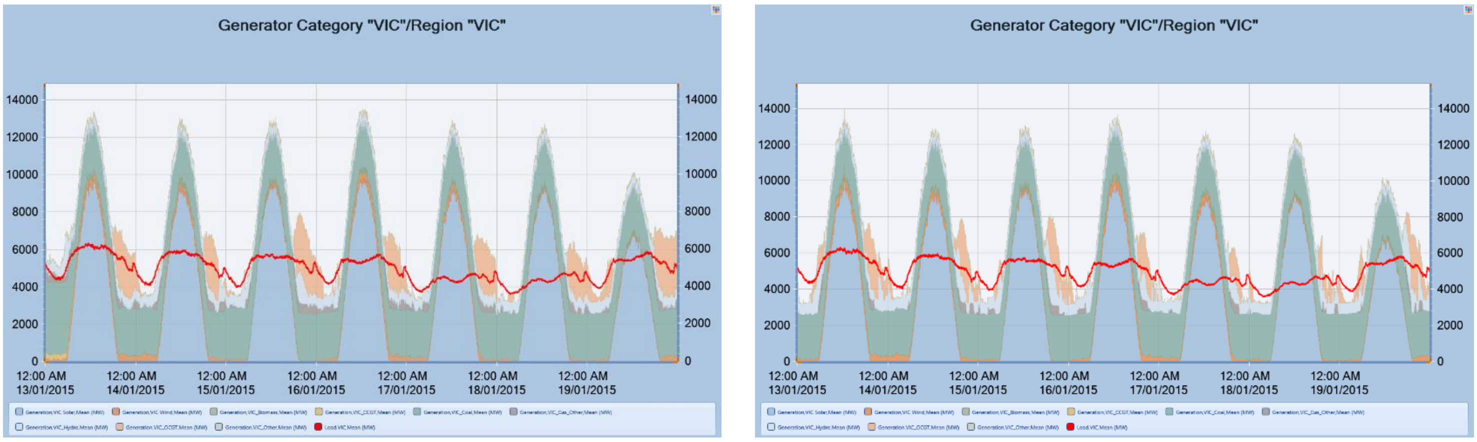


Figure 78: VIC Generation Profile, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

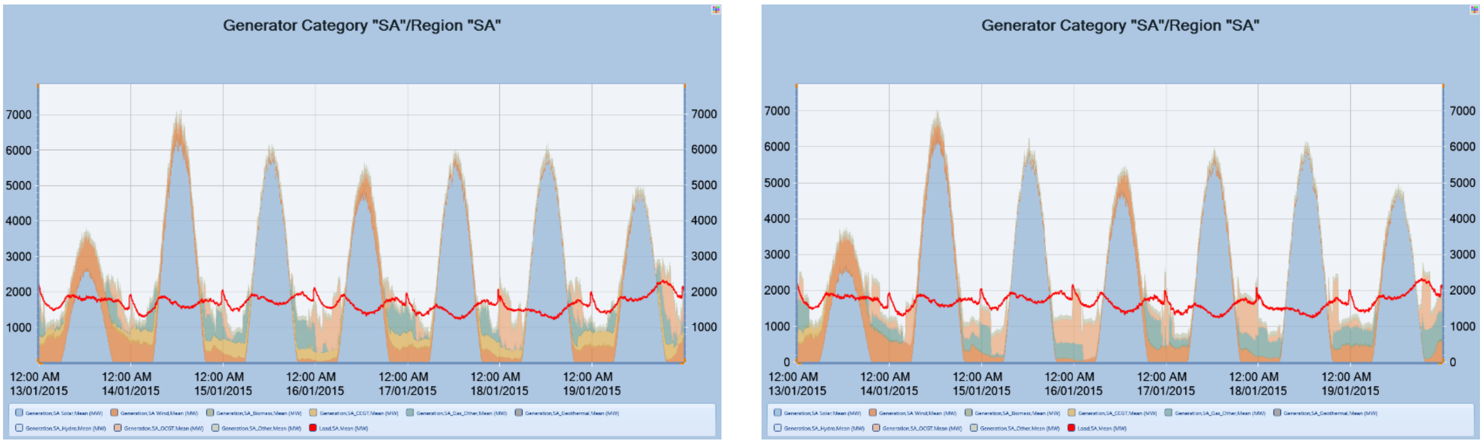


Figure 82: SA Generation Profile, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

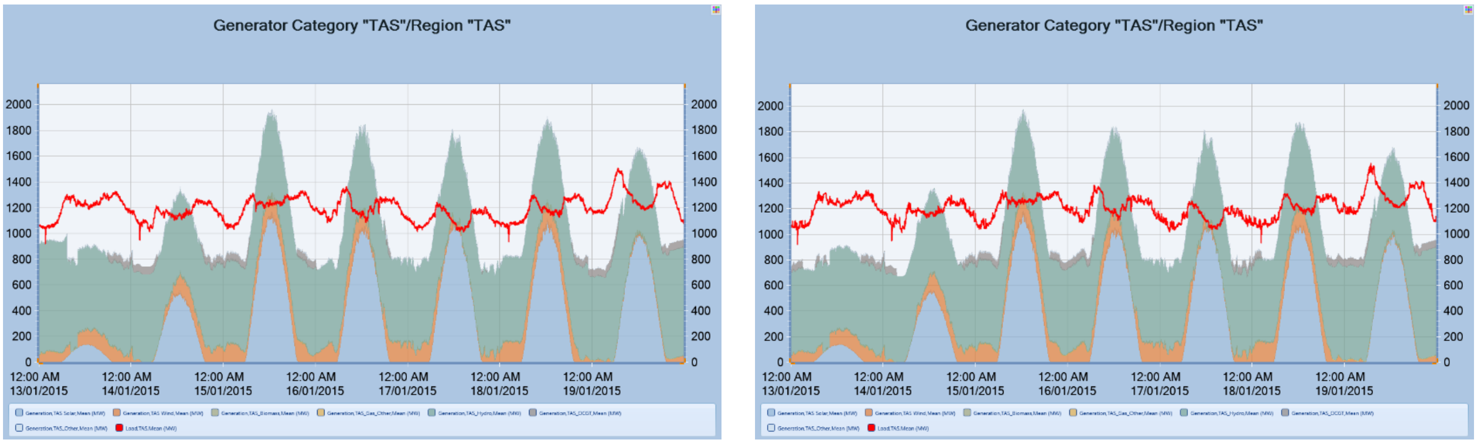


Figure 81: TAS Generation Profile, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

7.2.4 High RE Summer Transmission Profiles

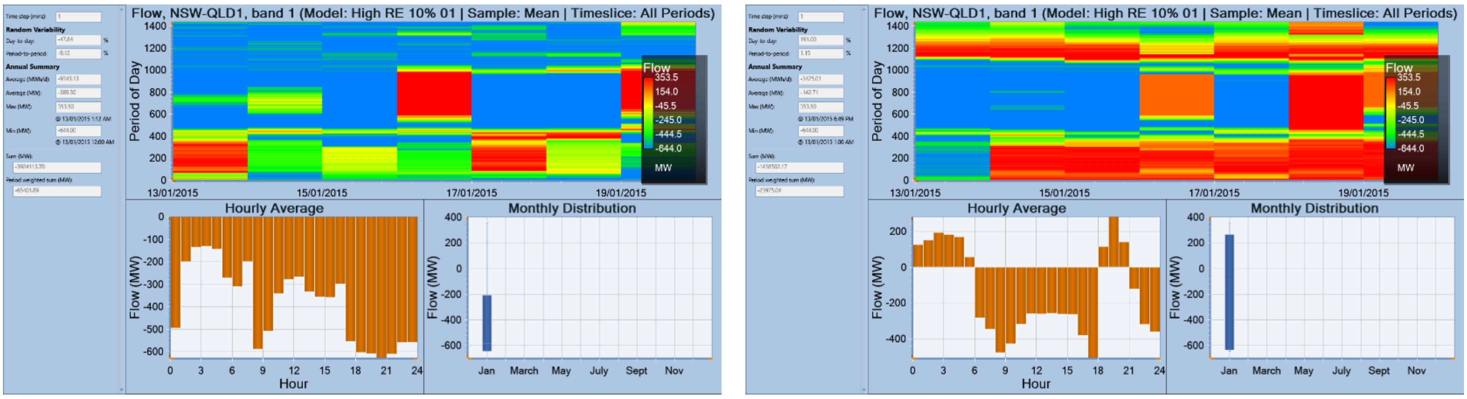


Figure 83: Heat Maps And Statistical Summary of Transmission Power Flow On NSW-QLD Line, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

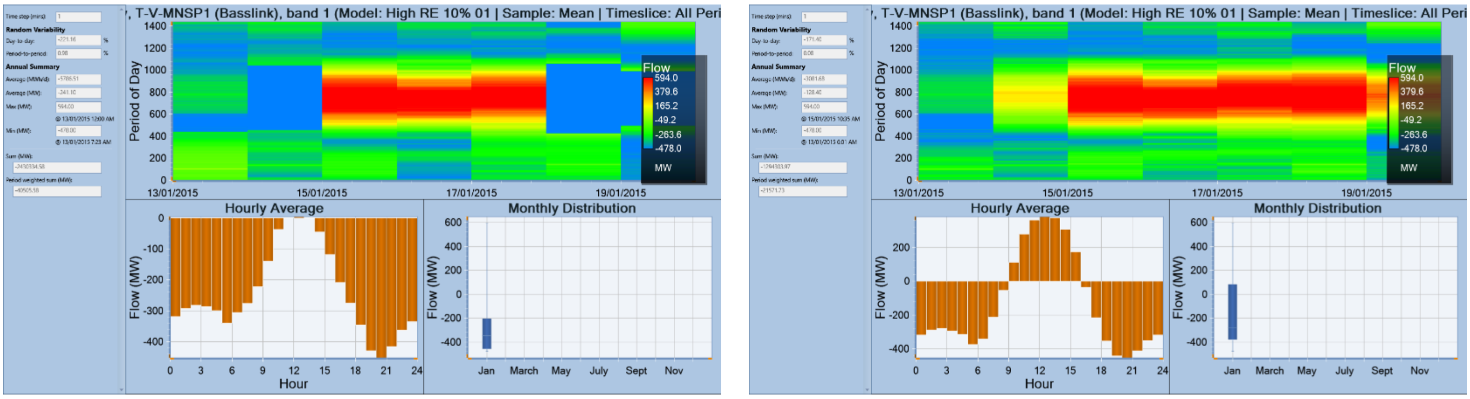


Figure 84: Heat Maps And Statistical Summary of Transmission Power Flow On Basslink Line, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

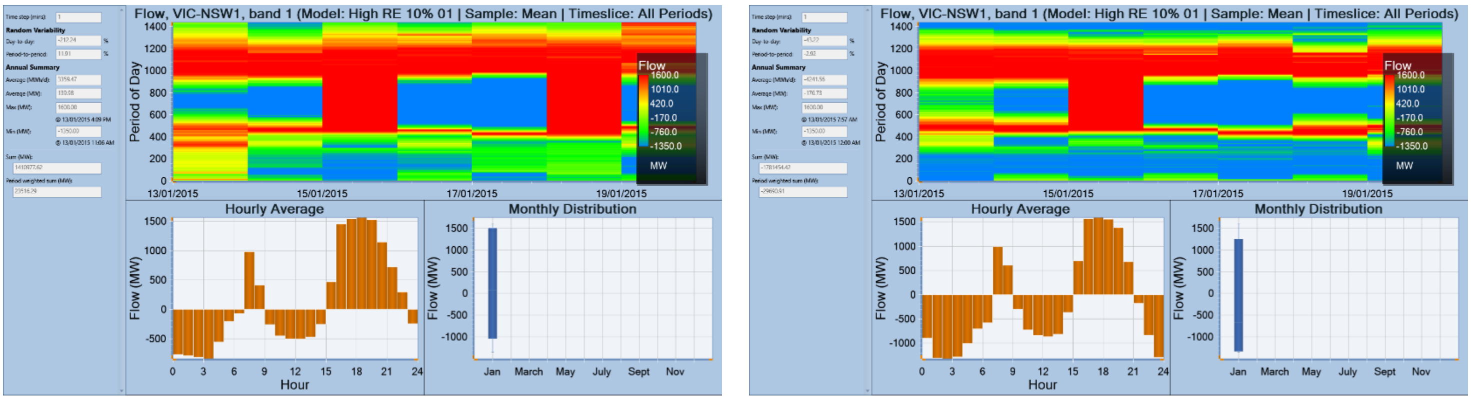


Figure 85: Heat Maps And Statistical Summary of Transmission Power Flow On VIC-NSW Line, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

Figure 86: Heat Maps And Statistical Summary of Transmission Power Flow On Heywood Line, High RE Scenario Summer Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

7.2.5 Base Winter Generation Profiles

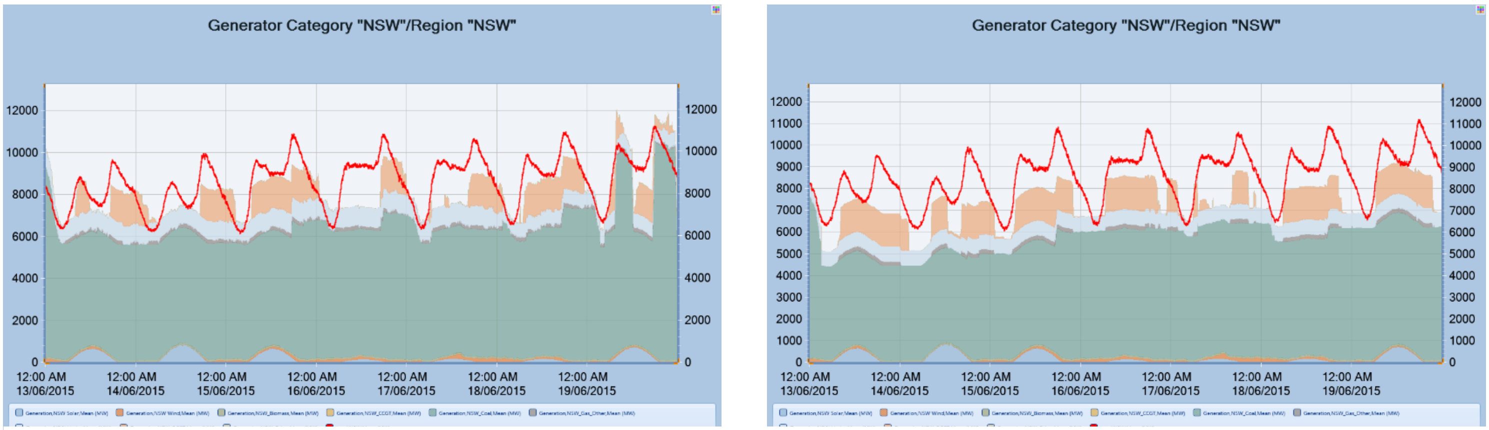


Figure 87: NSW Generation Profile, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

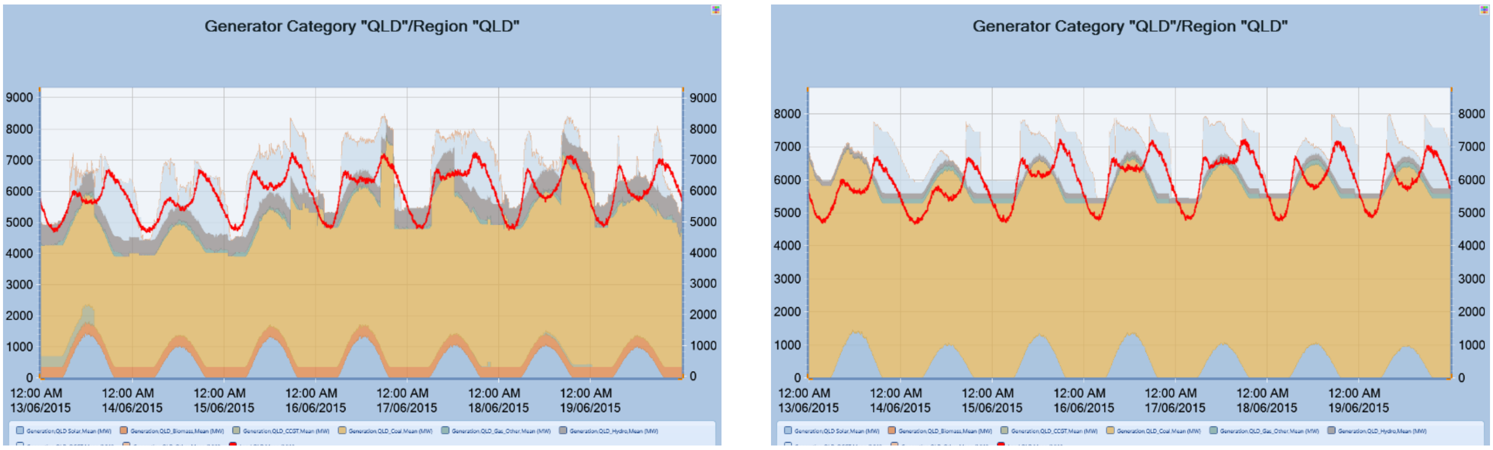


Figure 88: QLD Generation Profile, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

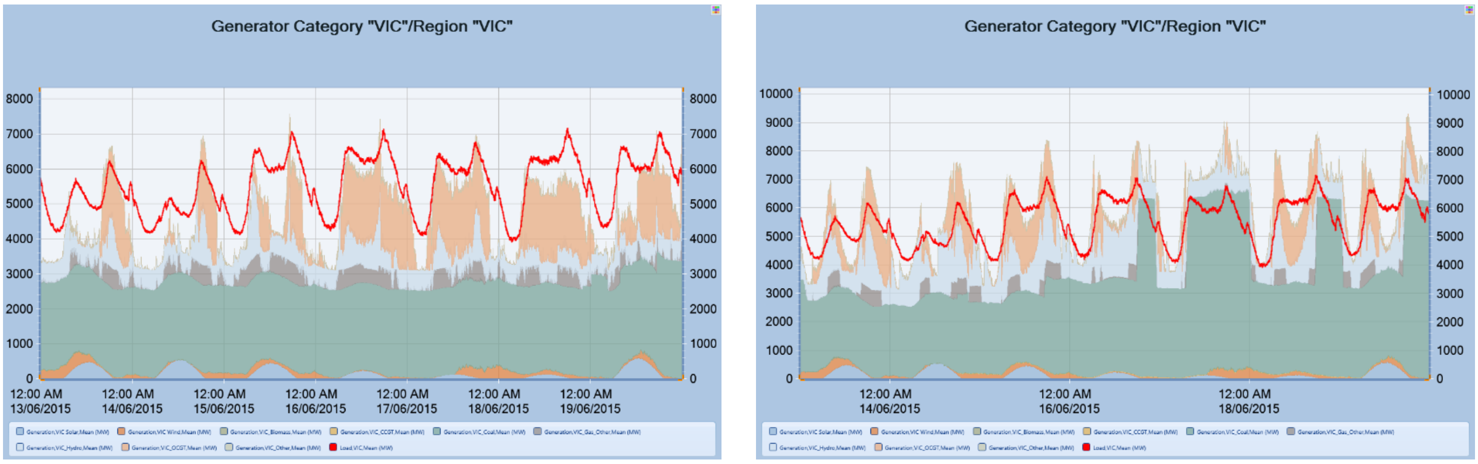


Figure 89: VIC Generation Profile, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

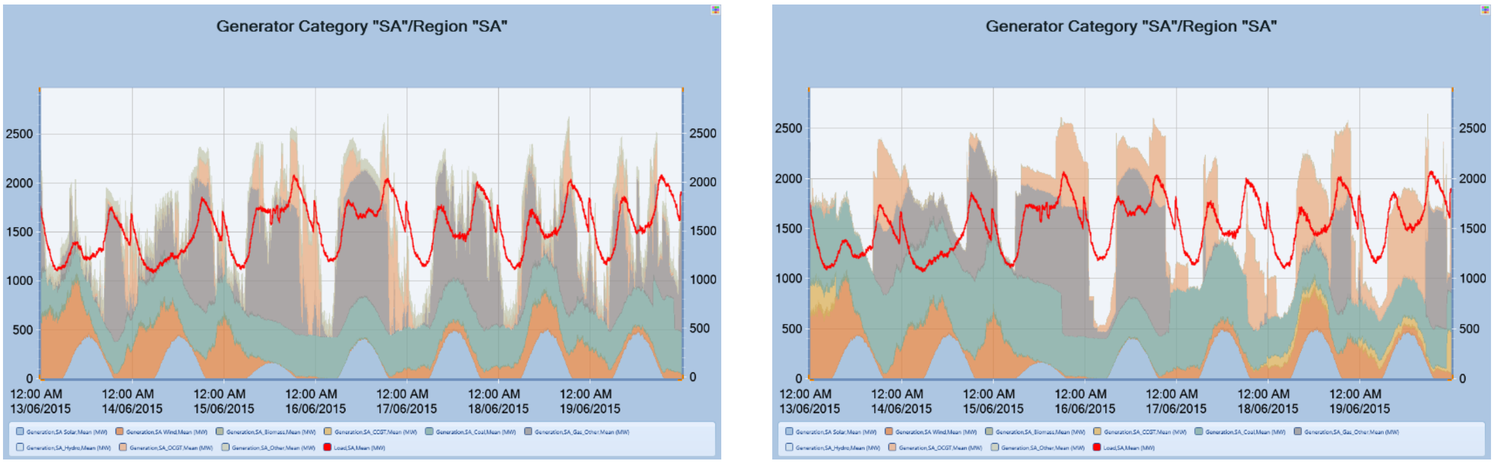


Figure 90: SA Generation Profile, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

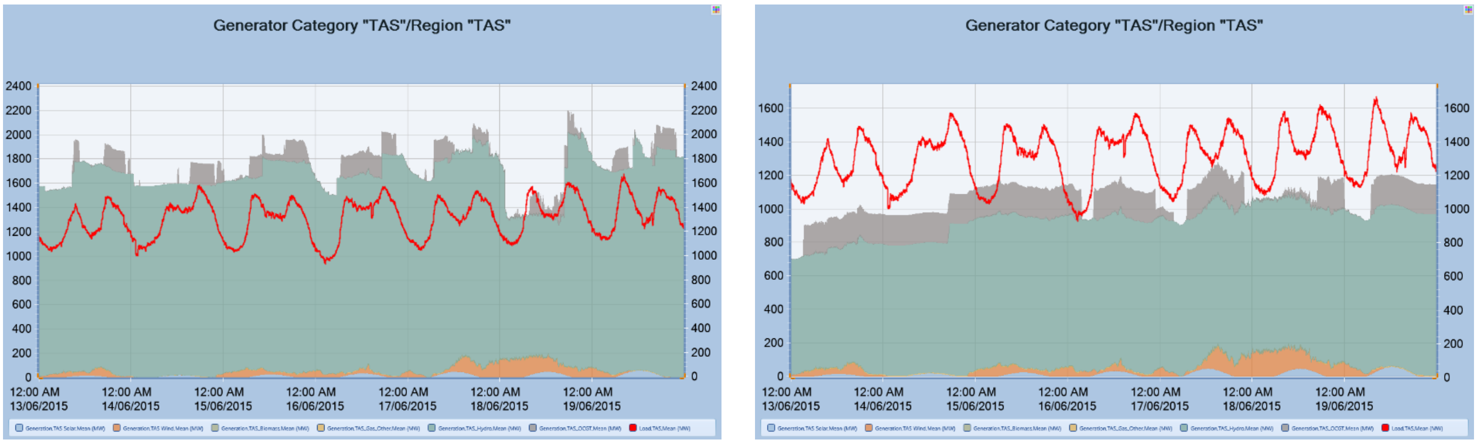


Figure 91: TAS Generation Profile, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

7.2.6 Base Winter Transmission Profiles

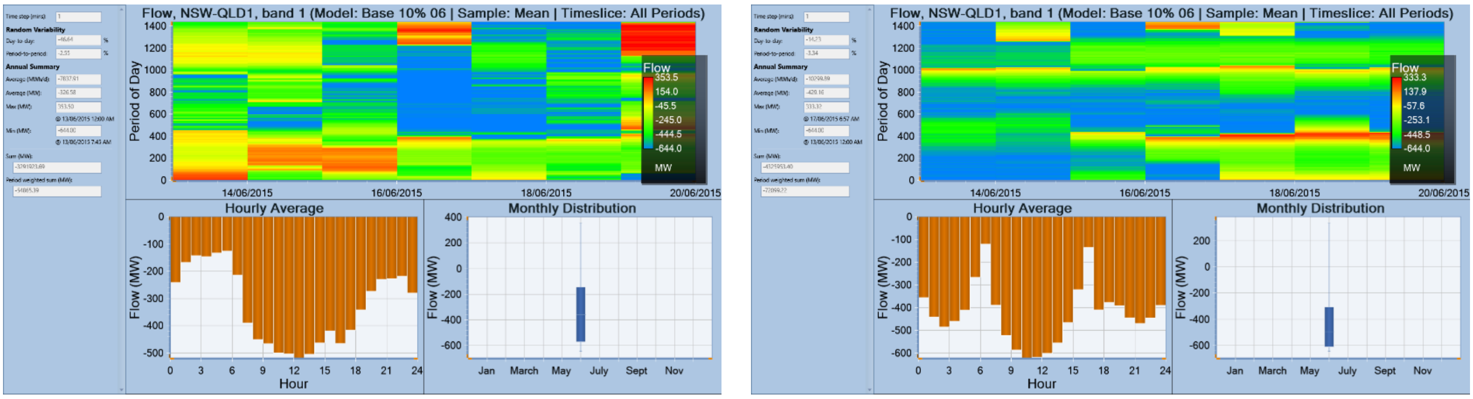


Figure 92: Heat Maps And Statistical Summary of Transmission Power Flow On NSW-QLD Line, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

Figure 93: Heat Maps And Statistical Summary of Transmission Power Flow On Basslink Line, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

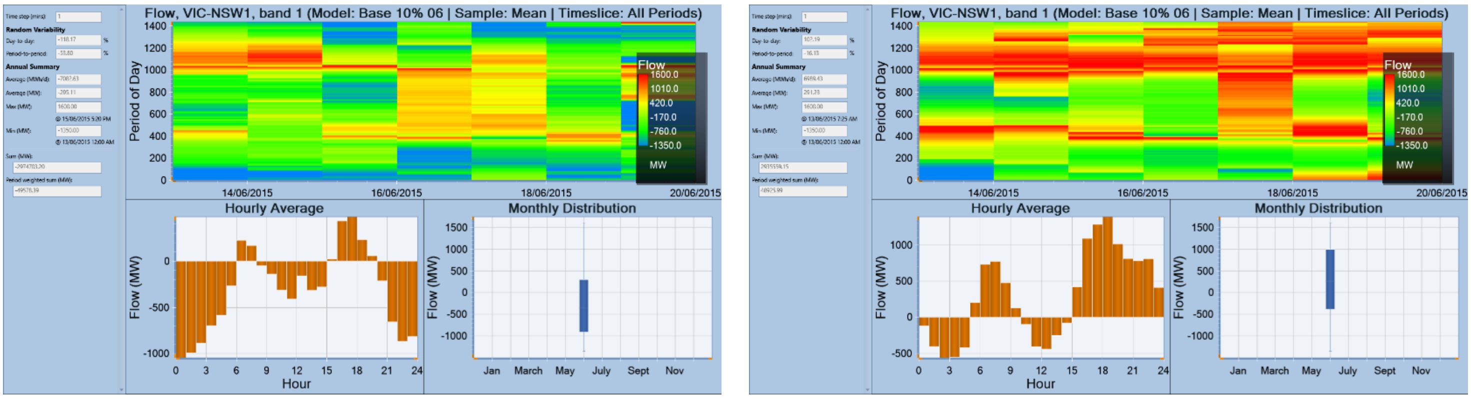


Figure 94: Heat Maps And Statistical Summary of Transmission Power Flow On VIC-NSW Line, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

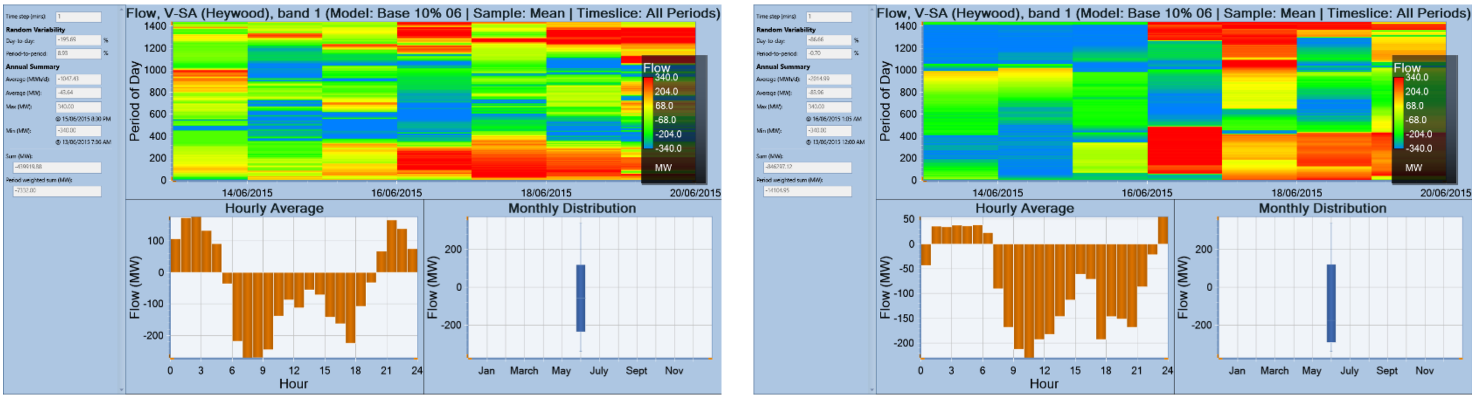


Figure 95: Heat Maps And Statistical Summary of Transmission Power Flow On Heywood Line, Base Scenario Winter Load. Left: Sans Battery Regulation, Right: 7.5 MWh Global Battery Regulation Capacity

7.2.7 Proposed Winter Generation Profiles

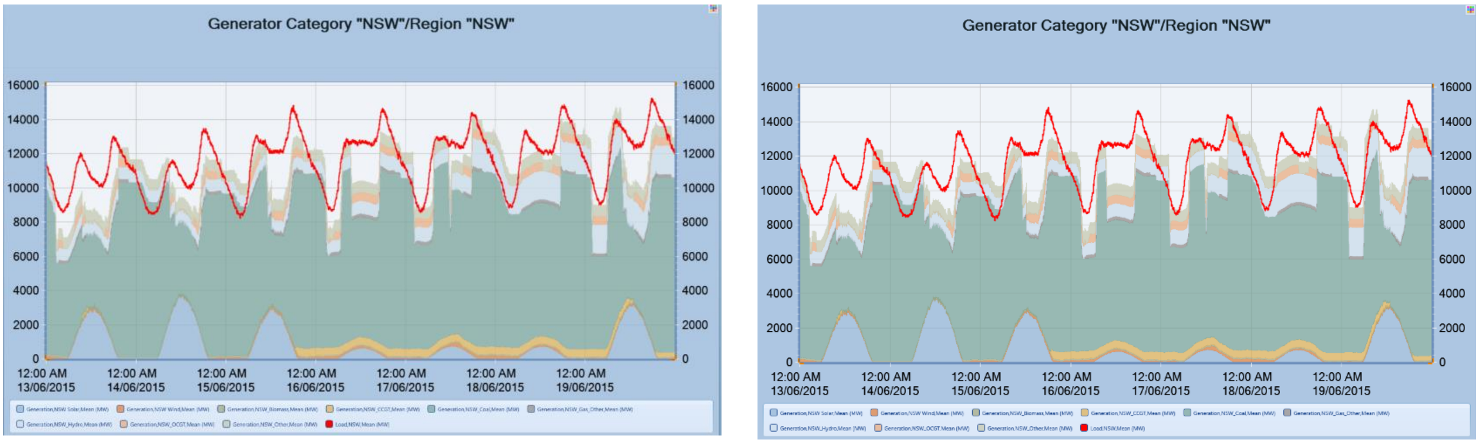


Figure 96: NSW Generation Profile, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

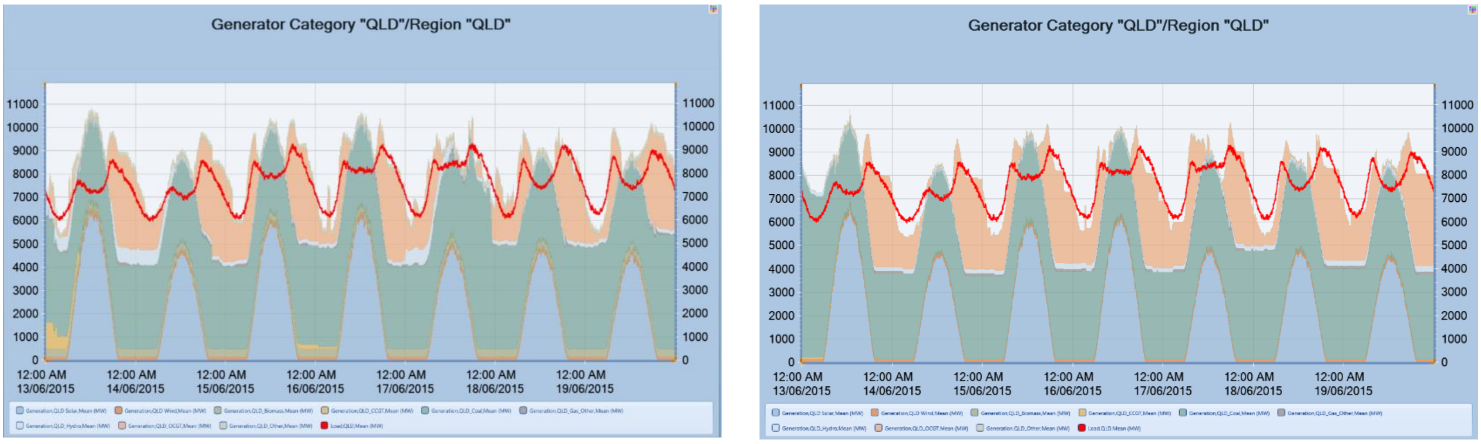


Figure 97: QLD Generation Profile, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

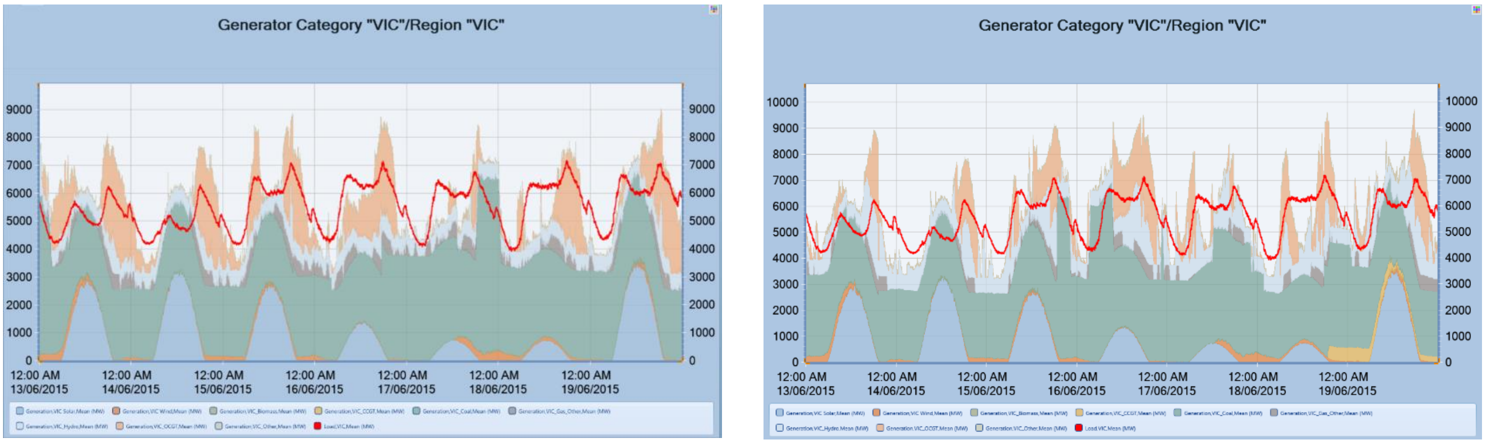


Figure 98: VIC Generation Profile, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

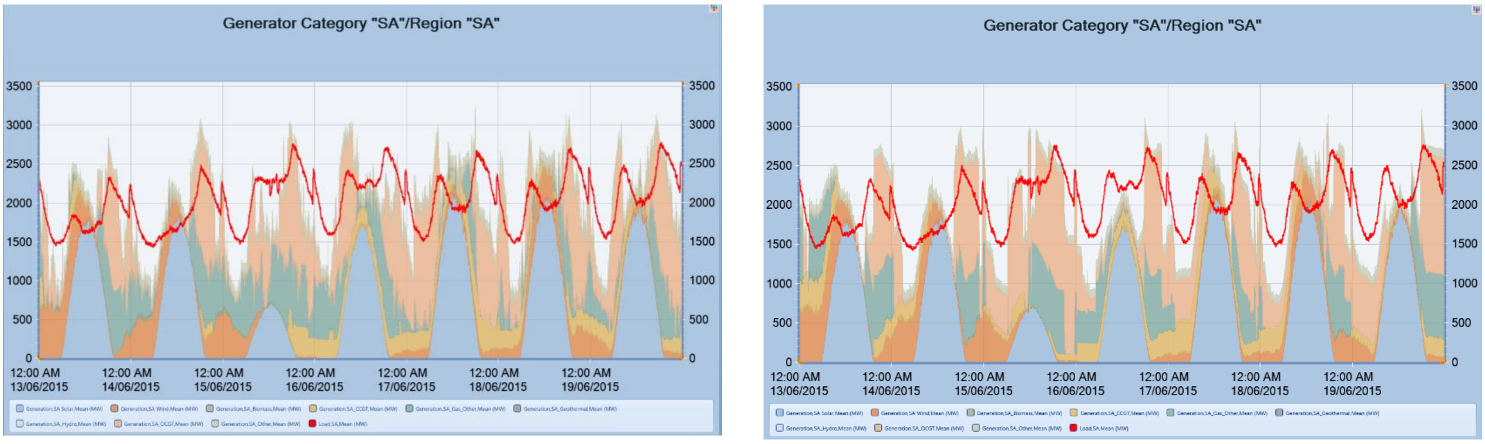


Figure 99: SA Generation Profile, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

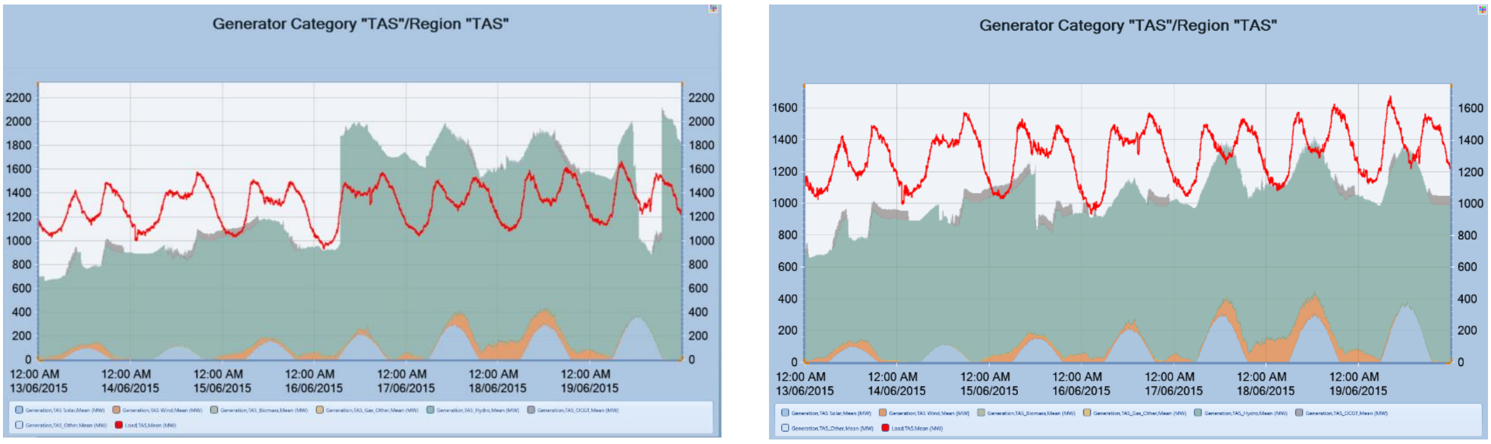


Figure 100: TAS Generation Profile, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

7.2.8 Proposed Winter Transmission Profiles

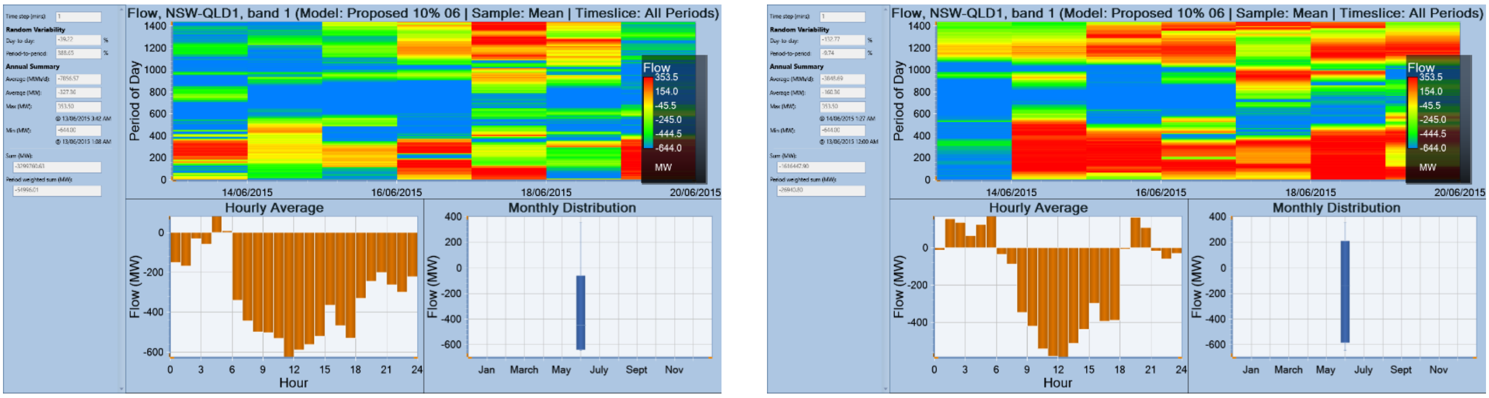


Figure 101: Heat Maps And Statistical Summary of Transmission Power Flow On NSW-QLD Line, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

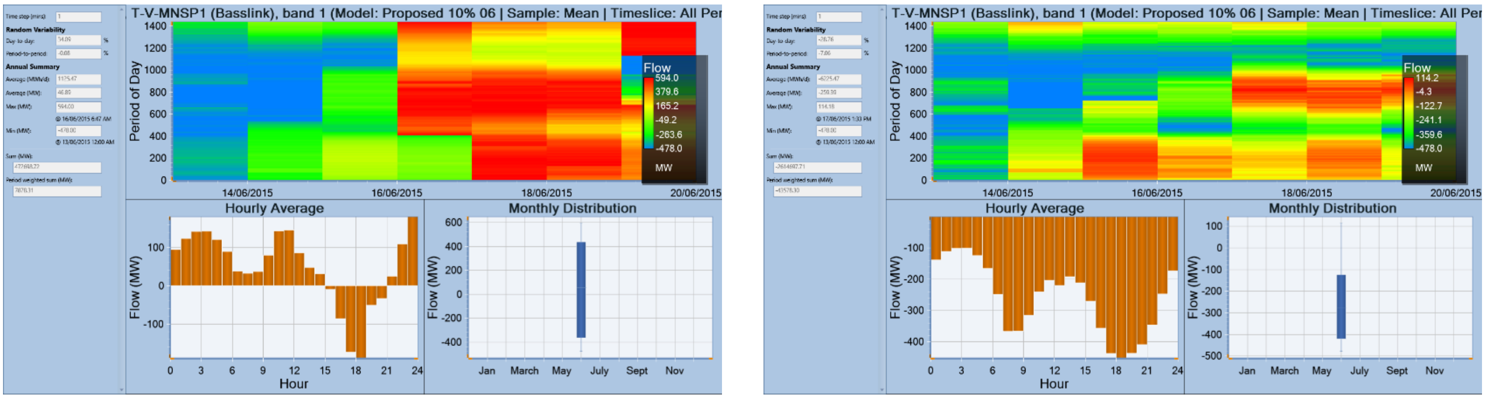


Figure 103: Heat Maps And Statistical Summary of Transmission Power Flow On Basslink Line, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

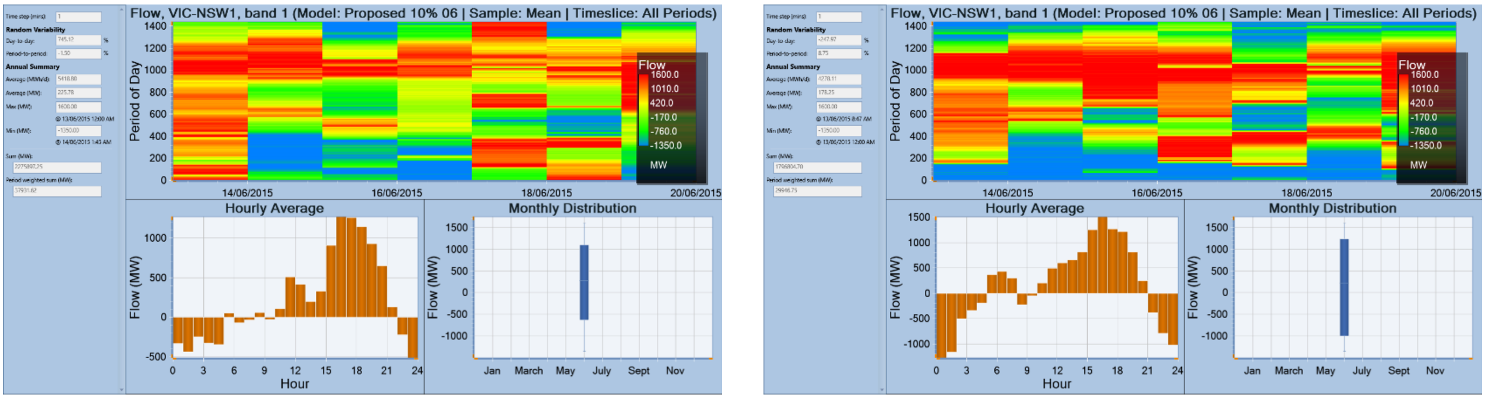


Figure 102: Heat Maps And Statistical Summary of Transmission Power Flow On VIC-NSW Line, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

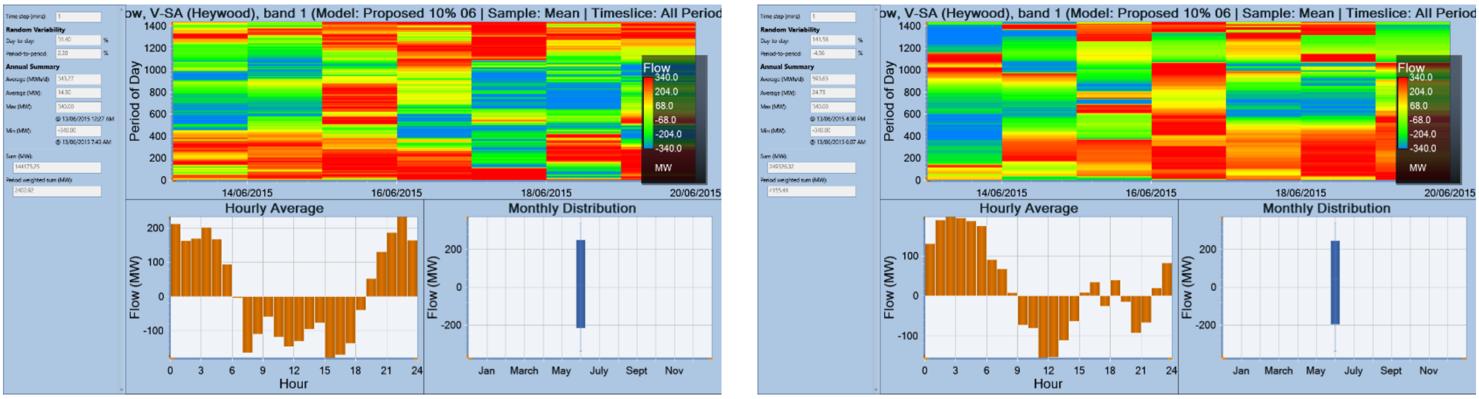


Figure 104: Heat Maps And Statistical Summary of Transmission Power Flow On Heywood Line, Proposed Scenario Winter Load. Left: Sans Battery Regulation, Right: 30 MWh Global Battery Regulation Capacity

7.2.9 High RE Winter Generation Profiles

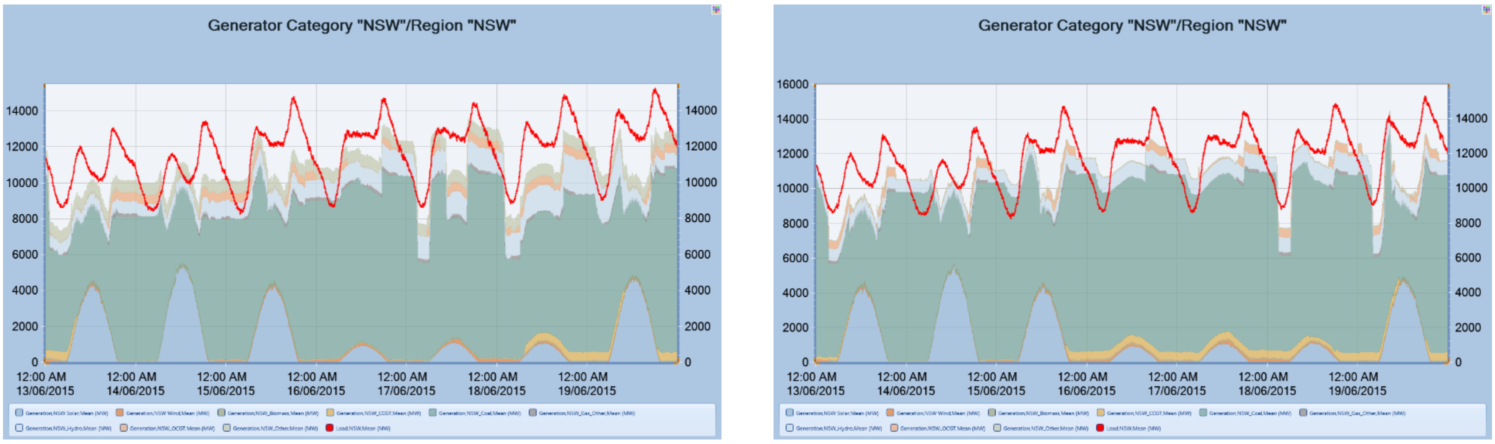


Figure 105: NSW Generation Profile, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

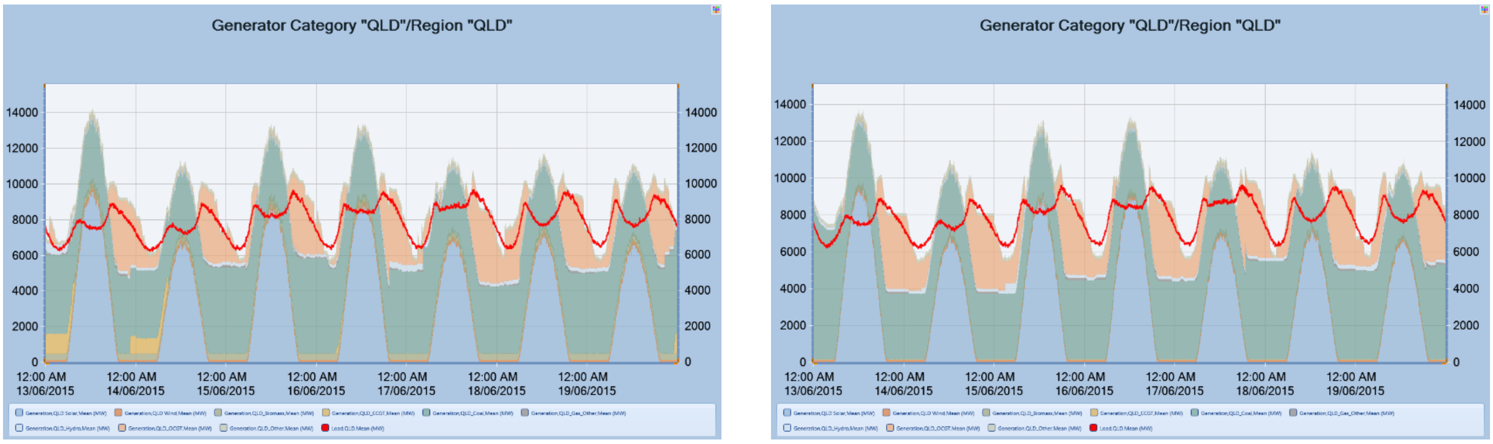


Figure 106: QLD Generation Profile, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

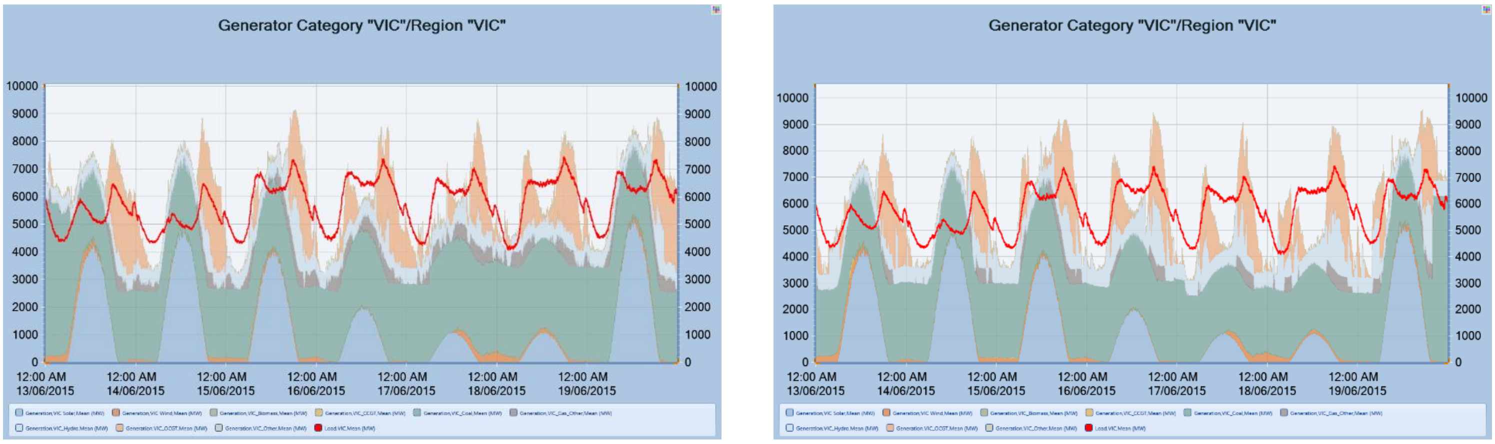


Figure 107: VIC Generation Profile, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

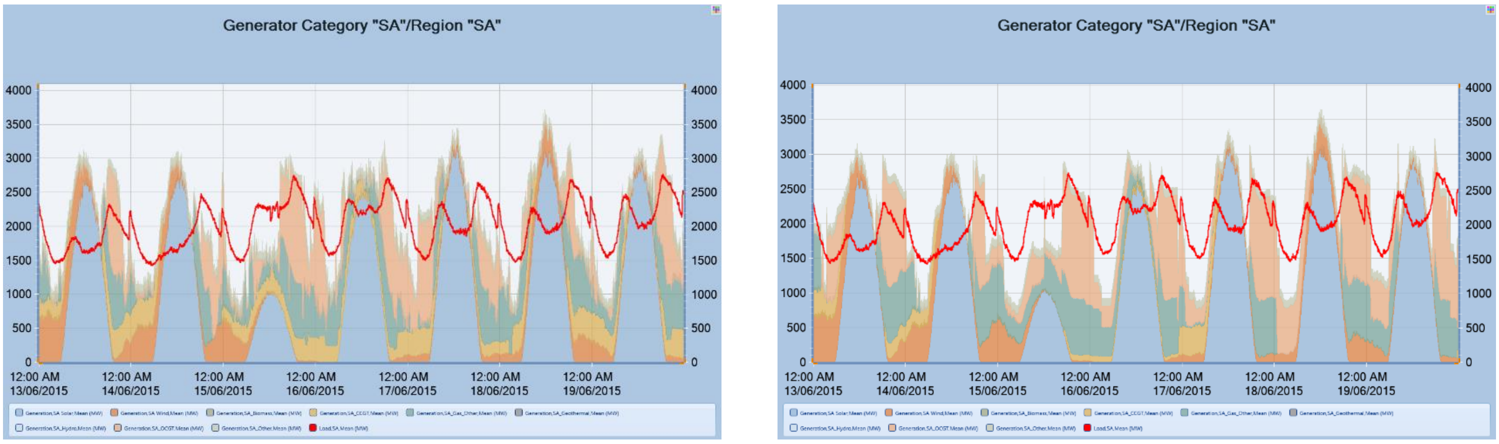


Figure 109: SA Generation Profile, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

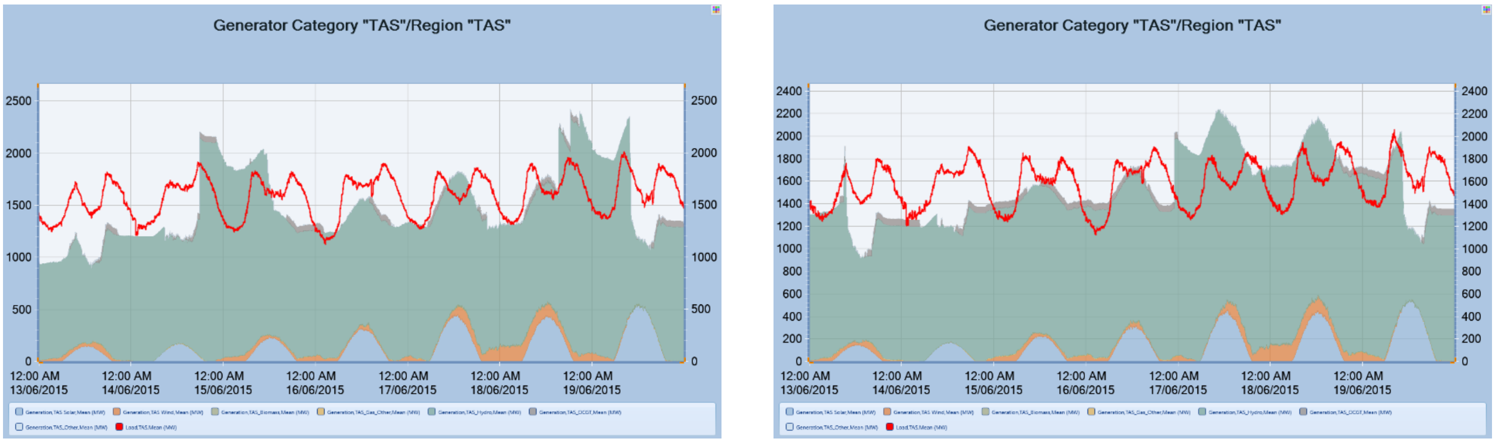


Figure 108: TAS Generation Profile, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

7.2.10 High RE Winter Transmission Profiles

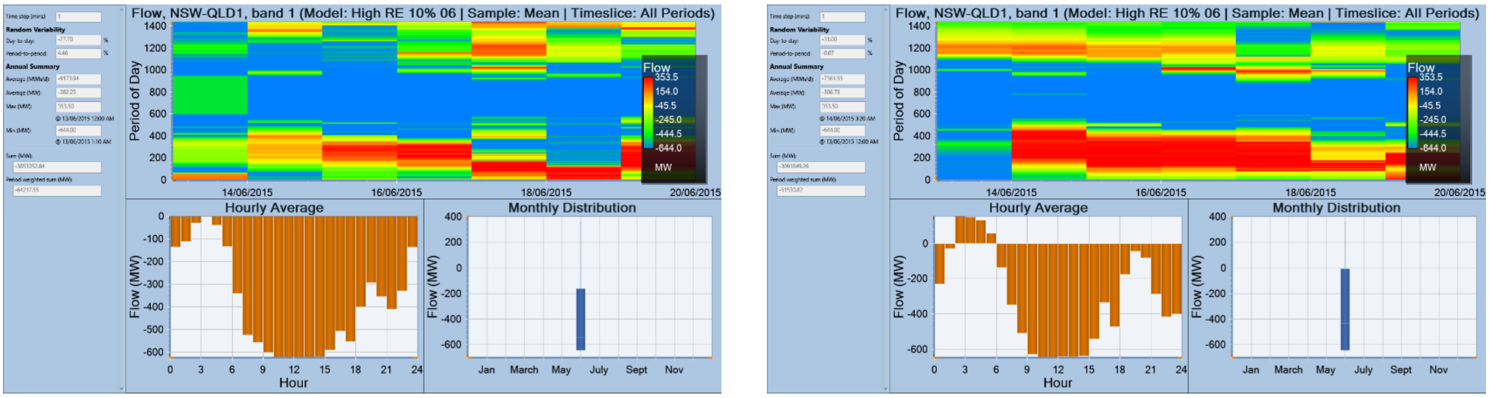


Figure 110: Heat Maps And Statistical Summary of Transmission Power Flow On NSW-QLD Line, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

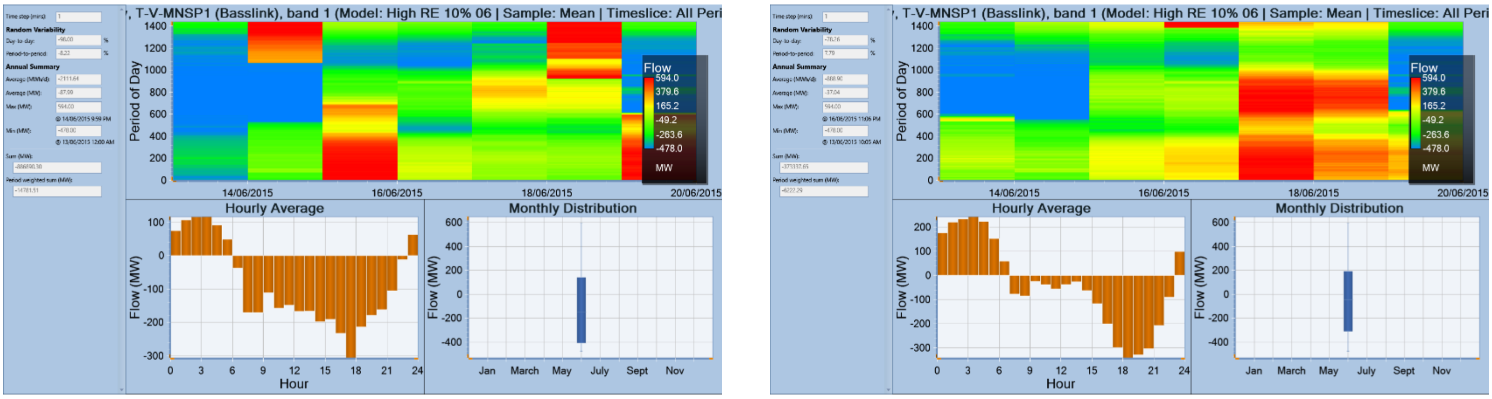


Figure 111: Heat Maps And Statistical Summary of Transmission Power Flow On Heywood Line, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

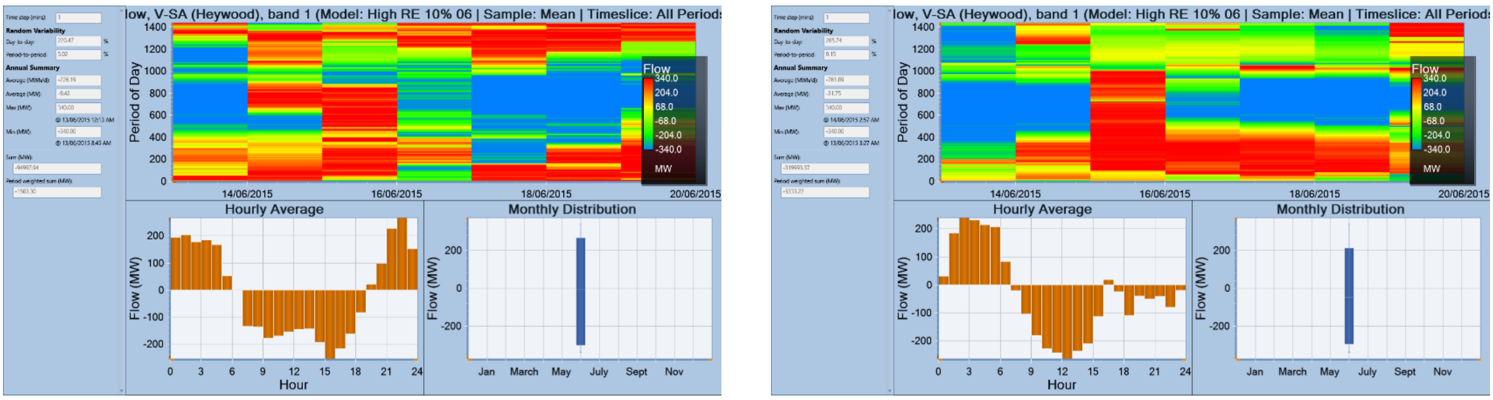


Figure 112: Heat Maps And Statistical Summary of Transmission Power Flow On Basslink Line, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity

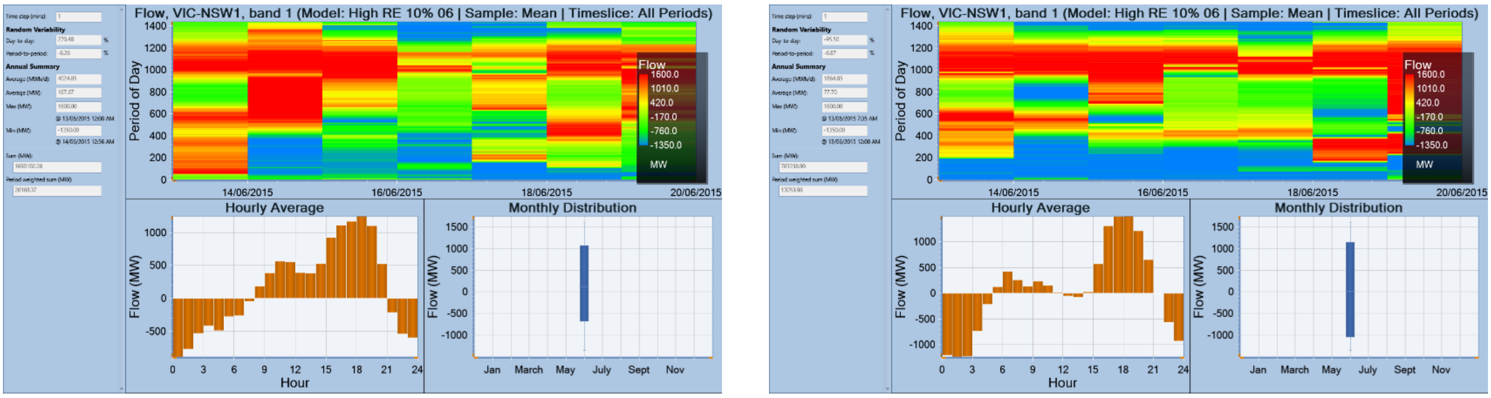


Figure 113: Heat Maps And Statistical Summary of Transmission Power Flow On VIC-NSW Line, High RE Scenario Winter Load. Left: Sans Battery Regulation, Right: 45 MWh Global Battery Regulation Capacity