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Electricity Industry
Operation and Control

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Electricity Industry Operation And Renewables Curtailment

Group 6

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Project Report Submission Cover sheet

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Group members	*Karan Joseph*	*Rahul Ashwin Mahendhran*	*Langchen Zhu*	*Moonpanha Seng*
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Key contribution of each group member to project	*- Literature Review* *- Executive Summary* *- Introduction*	*- Literature Review* *- Quantitative Analysis* *- Motivation*	*- Literature Review* *- Economic Analysis* *- Gap & Fix Gap*	*- Literature Review* *- Key Issues of Curtailments* *- Key insights for EI plaining*
I agree with the above list of contributions for each group member.	Karan Joseph	M. Rahul Ashwin	Langchen Zhu	[illegible]
My contribution does not include any plagiarised materials.	Karan Joseph	M. Rahul Ashwin	Langchen Zhu	[illegible]
For my contribution, I provide appropriate referencing within text	Karan Joseph	M. Rahul Ashwin	Langchen Zhu	[illegible]
My contribution has been proof read for obvious spelling and grammatical errors.	Karan Joseph	M. Rahul Ashwin	Langchen Zhu	[illegible]

1. Executive Summary

The report discusses the causes, effects, and impacts of renewable curtailment on the electricity industry operation. The introduction of the report gives a brief understanding of the role of electricity industry and defines what curtailment is. The following terms, network curtailment, economic, curtailment etc., are the basis for the report, and thus it is important to clearly define the terms in order to avoid any confusion. Frequency curtailment is also discussed briefly however, upon research it was found that the majority of curtailment cases in the year of 2022 were network and economic curtailment (ARENA, NOVEMBER 2022, AEMO, January 2023).The introduction also discusses the key parameters that have been used to conduct the qualitative analysis. Since the qualitative analysis's principle is to understand the cause of the curtailment, its impact on the market spot price, the pattern of how curtailment is initiated, when it is initiated and what kind of curtailment it is based on several parameters listed in the introduction section along with the justification for selecting the 2 states South Australia and Queensland for this analysis.

This introduction is followed by the motivation behind this project and report. Methods to mitigate the risk of investments in the renewable generation sector are mentioned, and the idea of due diligence and research being done not only with respect to current grid infrastructure, policies etc but also keeping in mind the trend of the past data and the future projections is proposed. Apart from this, ideas such as using financial derivatives such as a PPA contract to safeguard the operating profits and installing battery storage systems in order to charge during curtailment and sell during a relative hike in price have also been discussed.

The next section discusses the key issues of curtailment, mainly the rise in renewable energy sources and its impact on the electricity industry. The 3 main areas of focus are grid infrastructure, finance and instability of the grid due to curtailment. In order to conduct a quantitative analysis, a method to calculate curtailment has been described in the next section. This solving procedure is listed in AEMO's report regarding the semi-scheduled generation dispatch self-forecast procedure. However, 5-minute curtailment data was available on NEMLOG, and therefore the curtailment calculation for every 5 minutes was acquired via NEMLOG.

During the literature review, it was observed that the explanation regarding patterns of curtailment and its correlation with various parameters such as the installed capacity, interconnector metered flow of energy, electricity mix and spot price were scarce in the existing literature. It was concluded that this was perhaps due to each power system being unique, and thus it was decided that exploring this correlation would benefit in obtaining a nuanced and deeper understanding of the effects causes and impacts of curtailment in the electricity industry. The report presents the results of a quantitative macro analysis conducted over a period of a year for the states of Queensland and South Australia to gauge the economic severity of curtailment and a qualitative microanalysis to understand the specific intricacies of how the power system in these 2 states works to manage curtailment and to assess the potential improvements achievable through the implementation of feasible solutions.

The qualitative analysis was conducted using the data from 16th of March 2022 and was this date was chosen as it would be the best case to analyse keeping in mind the key factors of exports, imports, spot price, supply mix etc. The section 4 gives a clear description of the rise and fall in various supplies (different generation types) and tries to establish a pattern between the rising and falling of various generation types before during and after curtailment. In order to check for network type curtailment interconnector data was looked at, to establish connections and understand the limitation of the interconnector and the metered flow passing through the interconnector. Spot price changes during spikes in curtailment, charging and discharging of BESS and storing of water in hydro generators is also noted. The model with respect to the process followed to do the analysis is also mentioned in the report. Based on the analysis it was observed that a major part of curtailment in Queensland is due to network constraints whereas the central part of curtailment in the case of South Australia is economic curtailment. The report also shows the detail with regards to how each solar farm or wind farm responds to curtailment. Based on the annual curtailment data procured from NEMSight, the total curtailment of wind and solar has been aggregated for the term March 2022-2023.

Economic analysis was conducted based on the data collected to evaluate curtailment (28/03/2022 to 27/03/2023). The methodology was inspired by the studies conducted by ARENA and a recent paper published in 2022 addressing various financial aspects of Australian RE written by Srianandarajah, Wilson, and Chapman[1]. The analysis is based on the premise that revenue is viewed as bundled PPA comprising of electricity PPA and large generator certificates. Since these values vary and are different for different farms a particular range of PPA was observed in a paper published by PWC for wind farms (50-70$/MWh) and for solar (160-220$/MWh). Based on this information, the values of PPA were set as 70$ for wind and 180$ for solar farms. The analysis also indicates the recovery of losses if BESS technology is implemented, and its potential revenue is also calculated in this section of the report. The greatest potential revenue of 125.3 $million appears in wind generation in SA due to the magnitude of wind curtailment, followed by a potential revenue of 91.1 $million due to the curtailment of solar in Queensland and the higher spot price at peak demand. Please refer to section 4.3 for further information regarding economic loss due to curtailment and potential revenue due to the implementation of BESS.

The final part of the report compiles the possible solutions that can be Incorporating Distributed Battery Energy Storage Systems, Construction of transmission links to compensate for transmission constraints, introduction of Synchronous Condensers (SynCons) and Vehicle to Grid (V2G) and incorporating managed EV charging. These possible solutions were validated by the extensive literature review conducted in section 3. The Electricity industry must concentrate on strategic planning and investment in these key areas if it is to overcome this problem and fully harness the potential of renewable energy, integrate renewable energy and work towards Australia's commitment of NET-Zero emissions by 2050.

2. Introduction

Electricity industry is responsible for the total generation, distribution and transmission of electrical energy in the most economical way such that the demand is met with the supply with minimal cost of electricity per MWh. Due to the increase of utility renewable energy resources and distributed renewable energy resources like rooftop PV, it has been observed that during peak supply periods, usually ranging from 12 pm to 6 pm, there is a relative decrease in demand. During this situation, when the supply of energy surpasses the demand, renewable energy generation plants are sent a signal to cease or reduce energy production. This reduction of energy production is called curtailment. There are majorly 2 types of curtailment:

1. Network Curtailment – Usually non utilised energy is exported via transmission cables to another state with a deficit of supply (renewables not sufficient), or the cost of importing the energy via transmission cables is cheaper than dispatching a conventional source of generation.
2. Economic Curtailment – When the difference between the supply and demand keeps increasing negative price is achieved to ensure that the prices are positive/reasonable, and supply curtailment occurs.

These 2 types of curtailment are the most frequently observed forms of curtailment; however, there is a third cause of curtailment as well called frequency curtailment. Due to renewable generators being asynchronous in nature and having an intermittent nature of production, the dispatch of these renewable generators may lead to an imbalance in frequency. Curtailment is done in order to keep the frequency of the grid constant. Another solution unique to this form of curtailment is utilizing synchronous condensers that provide inertia in the form of reactive power. It is synchronized to the optimum grid frequency and stores and discharges reactive energy to stabilize any imbalance in the frequency; it essentially provides inertia. https://doi.org/10.2172/1126842

This report discusses these topics with a quantitative and qualitative analysis of 2 contrasting states and attempts to give potential solutions to ensure that the power system can be resilient in the future, considering the increasing penetration of renewable resources. The 2 states selected for the comparison and analysis are South Australia and Queensland. The reasons for this are provided below in Table 1. The main parameters used for qualitative analysis over a period of 3 days 14th March to 16th March, are:

- Capacity
- Supply mix
- Scheduled demand
- Generation
- Availability
- Curtailment
- Spot Price
- Import limit, Export limit, and metered flow of interconnector

South Australia	Queensland
Large penetration of renewables in the supply mix	Large penetration of conventional resources in the supply mix
Uncontrolled renewable energy resources (Solar and Wind)	In addition to uncontrolled resources possesses controlled renewable energy resources (Hydro)
Maximum curtailment in Australia	Lowest curtailment in Australia

Table 1 South Australia vs Queensland

2.1 Motivation

As Australia moves towards its commitment to be a net zero country, it is essential that it ensure the incentivization of electrical generators to generate electricity using a renewable medium. By 2025, Australia's largest power system is expected to safely run on up to 75% variable renewable generation, making it one of the world's leaders in the energy transition (Arrano-Vargas et al., 2022). However, renewables are dependent on external factors; most of renewable generators provide energy intermittently and have various limitations the most important one of them being the lack of controllability.

This lack of controllability leads to the forceful curtailment of renewable sources during periods where supply exceeds demand, largely due to renewables. Generation of renewables is not only location-dependent but also time-dependent, e.g., solar not being able to supply demand after sunset when the overall demand of the state is greater than the supply.

Therefore, without establishing solutions to these problems of supply matching the changing demand, curtailment cannot be solved. The motivation behind this paper was to analyze the curtailment situation qualitatively and quantitatively in 2 states of Australia in order to find ways in which curtailment can be reduced.

2.2 Methods

In order to avoid risks on investment the following steps could be taken

1. Due diligence and Research – The investor must ensure that he has conducted due diligence of not only the site and the potential supply that he can generate but also the network constraints in his state, potential increase in demand(projection), expected rise in increment, grid infrastructure and renewable energy policies that can mitigate the impact of curtailment

2. Storage Options - Investors can consider storage options that ensure that during curtailment periods when demand profile is lower than supply the surplus energy produced by the farm can be stored in a utility storage system connected to the generating farm. This stored energy can be used to sell energy at higher prices, covering for most if not all the loss faced during curtailment and in some cases actually make a profit for the plant.

3. Financial instruments – Financial instruments can be used by the plant in order to dampen the detrimental effect of curtailment on the operating profits of the plant. A PPA essentially ensures that the electricity generated by the renewable plant is sold to a consumer at a pre-determined price decided based on various factors, and this particular contract ensures that in the case of curtailment, even though the prices drop to negative. The producer gets the pre-determined prices. However, it must be noted that this security comes at a price, the price being that operational profits are reduced as the generator cannot sell at spot price unless a provision is made in terms of the PPA to sell at spot price for a limited time during the term of the contract. PPA's are generally sold for a term of 10-15 years.

3. Literature review/context

3.1 Key issues of curtailment

The rising integration of Renewable Energy Sources (RES) into the Electricity Industry has brought both opportunities and challenges, particularly in terms of renewables curtailment. Addressing these curtailment issues is increasingly important to ensure a resilient, efficient, and sustainable power system due to the growing penetration of RES, such as solar and wind generation. This section highlights some of the key issues related to renewables curtailments.

Underusing renewable energy resources refers to the curtailment causing some portion of renewable energy to go unused despite being accessible. Those wasted energy can lead to lower production. When renewable generation is curtailed, the total amount of clean energy produced is reduced. Due to this, RES are less successful overall in replacing fossil fuels, and it is more difficult to reach the greenhouse gas (GHG) emission targets (https://www.nrel.gov/docs/fy14osti/61721.pdf).

Planning for extending high-voltage networks is impacted by curtailment, particularly regarding the overall cost of network construction and operation. Because renewable energy sources are intermittent, networks must be continually extended to accommodate them without going against operating restrictions. However, this expansion could result in underused resources and greater expenses. The balance between network growth and operational flexibility may be optimised by including curtailment techniques at the planning stage, which lowers the overall costs of network development and operation. However, putting in place curtailment mechanisms necessitates accounting for extra expenses, such as replacing energy that has been restricted and coordinating renewable energy sources via ICT systems (https://ieeexplore-ieee-org.wwwproxy1.library.unsw.edu.au/document/7540971). Addressing this issue is essential for ensuring affordable and effective network operations as renewable energy sources expand.

The decrease in return on investment refers to decreasing revenues, increasing costs per unit of energy, and lowering capacity factors of the renewable energy project. Maximising energy output is essential for wind and solar producers to recover their capital costs since they have high initial costs, no fuel costs, and low operating costs (or low marginal costs) (https://www.nrel.gov/docs/fy14osti/60983.pdf). When resources are limited, renewable energy developers may experience a loss of income due to both lower generating sales and a decline in the value of production tax credits (https://www-sciencedirect-com.wwwproxy1.library.unsw.edu.au/science/article/pii/S1040619015001372?casa_token=_74j46jiXjYAAAAA:oPijteqOZjhjMOnoIVk_lFIRysdC-8ocjqvexjkMZfetUfY010S62nxawG9R65Mzax2rBokjBMU). So, renewable energy projects will be less attractive for investors and developers.

The electricity grid experiences instability and uncertainty due to integrating intermittent renewable resources like wind and solar. The stability and dependability of the grid may be impacted by the variations in power generation that these resources can provide. For instance, incorporating renewable energy, particularly large-scale PV systems, into the power grid is leading to significant changes in load patterns and ramping requirements of conventional generation systems. This variability poses challenges in maintaining grid stability and frequency as system operators strive to balance generation and load (https://pdfs.semanticscholar.org/1b98/3e6c213e42098eec65a4e34596e09dd62a38.pdf?_gl=1*uhdqx5*_ga*OTk1Mjg1OTQ0LjE2ODA1Mjc2OTI.*_ga_H7P4ZT52H5*MTY4MjM0NDgzNi41LjAuMTY4MjM0NDg2OC4wLjAuMA..).

One of the series reports conducted by Australian Renewable Energy Agency (ARENA) clearly defines curtailment of renewable generators as the difference of capable generation of the generator and generator dispatch at that time (ARENA, 2022) the-generator-operations-series-report-six.pdf.pdf (arena.gov.au). A paper presented by Srianandarajah, Wilson and Chapman states that the available capacity of generation technology is calculated by market operator, which is AEMO, based on the unconstrained intermittent generation forecast (UIGF). Dispatch target signal is sent to generator by AEMO (Srianandarajah, Wilson and Chapman, 2022). From green to amber: is Australia's National Electricity Market signalling a financial warning for wind and solar power? - ScienceDirect Concerns about the rising economic losses of renewable energy due to higher installed capacity are shown in these two articles. They also demonstrate the patterns and results of economic analysis in terms of curtailment, which will be further discussed in Section 4.3.

AEMO's report regarding semi-scheduled generation dispatch self-forecast procedure explains the definition and solving processes of UIGF, which is a parameter created by AEMO and renewable generators to forecast the available generation (AEMO, 2023).Semi-Scheduled-Generation-Dispatch-Self-Forecast---Assessment-Procedure.pdf (aemo.com.au). Participants provide self-forecast (SF) dispatch for the next interval and this SF must go through a series of assessments conducted by AEMO and other industries such as Australian Wind Energy Forecasting System (AWEFS) and Australian Solar Energy Forecasting System (ASEFS) to be credited as UIGF. Every 5-minute curtailment data is available and acquired on Nemlog therefore the calculation of curtailment value is not required.

Arraño-Vargas et al. and other researchers showcase that the lack of capability of renewable generators to maintain system strength, which could threaten system security, is one of the main contributors to curtailment (Arraño-Vargas et al., 2022) Energies | Free Full-Text | Challenges and Mitigation Measures in Power Systems with High Share of Renewables—The Australian Experience (mdpi.com) Nonetheless, AEMO's Quarterly Energy Dynamics (2022 Q4) report argues that RE generators are less prone to system constraints in 2022 compared with 2021 and 2020. qed-q4-2022.pdf (aemo.com.au)

Srianandarajah, N., Wilson, S.J. and Chapman, A.C., 2022. From green to amber: is Australia's National Electricity Market signalling a financial warning for wind and solar power?. *Energy Policy*, *167*, p.113052.

Solutions

Challenges and Mitigation Measures in Power Systems with High Share of Renewables—The Australian Experience
Authors: Felipe Arraño-Vargas, Zhiwei Shen , Shan Jiang , John Fletcher and Georgios Konstantinou
The following paper provides a comprehensive outlook of the problems faced by the power system of South Australia with regards to grid stability and curtailment. The paper discusses the iea of integration of renewables and the instability and challenges that are faced in markets where there is high penetration of renewables. The paper discusses the short circuit ratio system strength and the effect of inverter-based resources as compared to synchronous generators. It also discusses mitigation technologies such as synchronous condensers, their working and lists the operational synchronous condensers in Australia and the upcoming synchronous condensers. The paper focuses on BESS management system as well as a mitigation method followed by a discussion of the energy portfolio of South Australia and the effects of synchronous condensers, BESS and expanding transmission network.

The paper provides a conclusion that states that "traditional renewables do not provide essential services" and a portfolio should consist of diverse technologies with the presence of synchronous condensers, BESS and grid forming converters in order to increase the share of renewables and successfully integrate renewables in the system.
Arraño-Vargas, F., Shen, Z., Jiang, S., Fletcher, J. and Konstantinou, G., 2022. Challenges and mitigation measures in power systems with high share of renewables—the Australian experience. *Energies*, *15*(2), p.429. [https://scholar.google.com.au/scholar?hl=en&as_sdt=0%2C5&q=Challenges+and+Mitigation+Measures+in+Power+Systems+with+High+Share+of+Renewables%E2%80%94The+Australian+Experience&btnG=]

The Generator Operation Series : Report Six: Unlocking Curtailed Solar Energy on the NEM through Storage. Nov 2022
The following report estimates the available generation using satellite data and calculates curtailment using NEMWEB database for dispatch data and the actual available generation. The report discusses the types and causes of curtailment, namely economic and physical and distinguishes between types of physical curtailment, namely the local limit curtailment and the network curtailment. The report models the average annual value of curtailment (economic, network and local limit) in terms of $/year and were sold in the evenings at the average spot price for 4 states SA,VIC,QLD and NSW. The paper discusses the breakdown of energy dispatch and curtailment, mitigation measures and comes to the conclusion that BESS with solar farms have the potential to increase profit and improve the stability of the system. Apart from this the report also speaks about the risk of installing battery storage solutions near existing solar farms and regulatory barriers that come in the way of increasing revenue streams.

(Sharma et al., *Reduction of PV curtailment through optimally sized residential battery storage* 2020) This study explores the possibilities for installing household battery storage systems of the right size to reduce photovoltaic (PV) curtailment. The ideal battery size for home energy storage is determined by user demand, local solar irradiation, and grid constraints using the authors' unique optimization approach. The study considers the effects of various regulatory incentives and pricing schemes on the adoption of battery storage systems while examining the effects of battery storage on PV curtailment and overall system efficiency. An estimated 54.7% reduction in curtailment could be achieved compared to an installation with no battery leading to a significant amount of savings by consumption of "curtailed to be power" in high price conditions during the evenings.

Title: BESS Deployment Strategy in Jeju Carbon-Free Islands for Reducing Renewable Energy Curtailment
The aims to attain carbon neutrality by establishing a battery energy storage system (BESS) deployment strategy to reduce renewable energy curtailment on Jeju Island, South Korea. After reviewing several battery technologies, the author were keen to use Lithium batteries, that could be best used for frequency regulation, voltage and peak shaving, and can help integrate various renewable energy sources several battery technologies, the author was keen to use Lithium batteries. The and can help integrate various renewable energy sources several battery technologies, the author was keen to use Lithium batteries. The authors propose a 50 MW BESS with a power conditioning system and a battery capacity of 25MWh, from as reliable solution to avoid curtailment. Based on the simulation it was observed that an estimated 9804MWh of energy was added to the battery from a period of 2015 to 2019 (which was to be curtailed) , effectively increasing the efficiency 5.3times higher than compared to a system without BESS.

Lee, C., Im, S., Jung, J. and Lee, B., 2020. BESS deployment strategy in Jeju carbon-free islands for reducing renewable energy curtailment. *Energies*, *13*(22), p.6082.

Topic: Renewable energy curtailment practices in Jordan and proposed solutions
Authors: Ammar Alkhalidi a,b,* , Khalid Alqarra b , Mohammad Ali Abdelkareem a,c,d,* , A.G. Olabi a,c
Jordan, a leader in renewable energy in the Middle East, faces a challenge, with 17% of its overall wind energy capacity being curtailed due to low energy demand during peak generation. The paper explored energy storage systems to use curtailed energy better, reduce costs, and minimize emissions. The Al-Tafilah wind farm was used as the case study since it has Jordan's highest energy curtailment rate. The study focused

on storing the curtailed energy using Li-ion batteries. A 120 MWh battery capacity was used to store daily curtailed energy. 11.8% of Jordan's total number of electric vehicles may be charged daily at the planned battery energy storage system. The economically feasible option has a payback period of 6.15 years and an annual revenue of 5,863,725 JD, albeit these numbers might alter depending on regional regulations and market trends. Using curtailed energy from other wind farms in Jordan may possibly power 50% of the country's electric cars, producing revenue, opening up employment opportunities, and promoting public-private partnership (PPP) initiatives for recharging facilities. Jordan can benefit from its potential for renewable energy, grow its economy, and lower its carbon footprint with the use of energy storage technologies like Li-ion batteries.

https://www-sciencedirect-com.wwwproxy1.library.unsw.edu.au/science/article/pii/S266620272200060X
Alkhalidi, A., Alqarra, K., Abdelkareem, M.A. and Olabi, A.G., 2022. Renewable energy curtailment practices in Jordan and proposed solutions. *International Journal of Thermofluids*, *16*, p.100196.

Topic: Effects of Home Energy Management Systems for Reduction of Renewables Output Curtailment
Authors: Takashi Himeno, Takashi Ikegami
This research examined how Home Energy Management Systems (HEMSs) affected the reductions in renewable energy generation in Japan's Kansai area. Researchers examined how more home batteries and heat pump water heaters (HPWHs) will affect curtailments by enhancing their optimal operation-scheduling model for numerous homes. The findings showed that increasing battery and HPWH penetration rates in HEMSs helped to reduce renewable curtailments, allowing for more effective utilization of excess renewable energy. The study also clarified the importance of more research to provide appropriate and unbiased pricing signals for demand response that considers societal cost reduction. This is essential for encouraging the use of HEMSs and effective renewable energy consumption, which will assist in balancing supply and demand in the power networks. The study clarifies the potential advantages of using HEMSs over a whole area, focusing on managing renewable production curtailments and assisting the transition to a low-carbon energy future.
https://ieeexplore-ieee-org.wwwproxy1.library.unsw.edu.au/stamp/stamp.jsp?tp=&arnumber=7386989
Himeno, T. and Ikegami, T., 2015, November. Effects of home energy management systems for reduction of renewables output curtailment. In *2015 IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)* (pp. 1-6). IEEE.

3.2 Gap

Curtailment has emerged as a prevalent topic in the field of renewable energy, garnering significant attention from numerous researchers. However, explanations of curtailment patterns on an hourly basis remain scarce in existing literature. It is important to note that the primary factors contributing to curtailment may differ based on the specific characteristics of a given power system. These characteristics include, but are not limited to, the installed capacity of renewable energy sources and the capacity of transmission lines connecting to other power systems. Therefore, the detailed correlation between curtailment and system characteristics is worth investigating.

3.3 Fixing the gap: Micro modelling in SA and QLD

Power systems in South Australia and Queensland have been selected as the subjects of this study due to the significant differences in system parameters, especially the installed capacity of different types of generations. South Australia boasts a high proportion of renewable installations and gas plants, whereas Queensland relies heavily on black coal, with a comparatively lower share of renewables. The generation mix data for both South Australia and Queensland has been gathered through Nemsight and is illustrated in the figure 1. These contrasting characteristics make the two states excellent candidates for pattern identification and analysis.

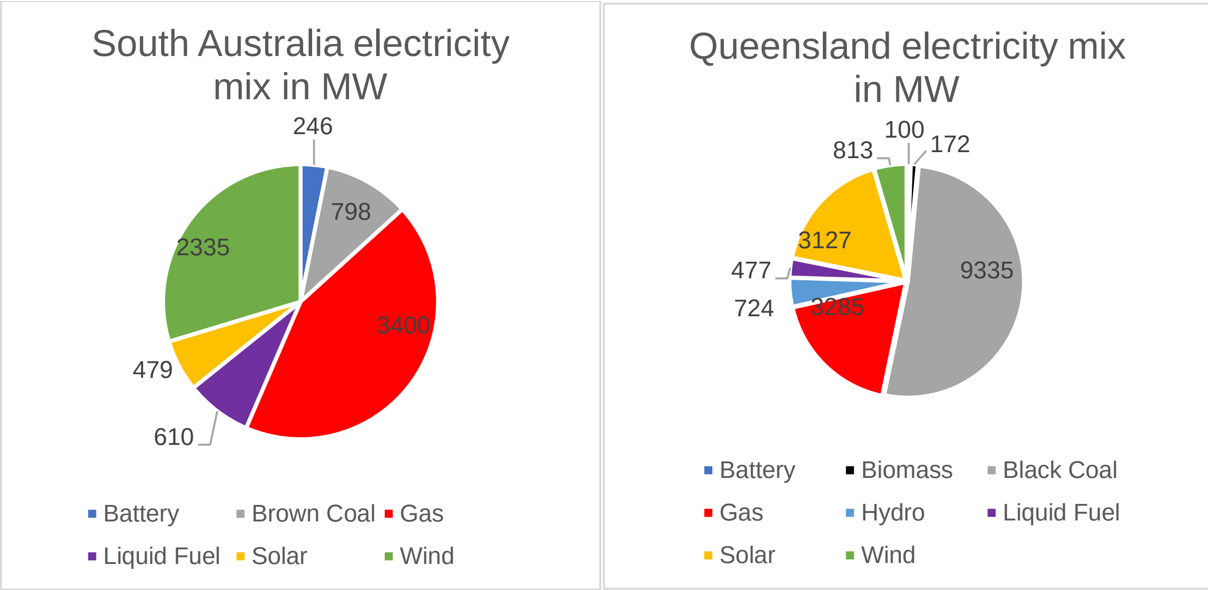


Figure 1 Installed Generation Capacity in SA and QLD

Micro modelling, which involves monitoring multiple parameters and identifying curtailment patterns on an hourly basis, has been conducted by analysing two specific days in South Australia and Queensland, respectively. Key parameters include spot prices, export limits, metered export flows, generation and curtailment of different types of generators, and their corresponding timelines. These patterns are thoroughly discussed in Section 4.1.

A quantitative analysis, along with an economic assessment, has been conducted from a macro perspective, spanning an entire year. The study period is defined as a full year leading up to the commencement of this research, which is set on 28/03/2023. The objective of the macro analysis is to gauge the economic severity of curtailment and assess the potential improvements achievable through the implementation of feasible solutions such as Battery Energy Storage Systems (BESS). Further details on this aspect can be found in Sections 4.2 and 4.3.

4. Data Analysis or modelling

4.1. Modelling

To study the quantitative analysis of curtailment of two states (South Australia and Queensland), the Demand, Supply data, supply mix, and transmission constrain data across the transmission links are obtained on a 5minute interval for the dates of March 1 to March 31, 2022, and is computed. The curtailment data is sourced from an open-source platform named NEMLog, which provides 5-minute annual, monthly, and daily data on Solar, wind, and daily curtailment across all the states. Based on the literature review from the previous sections and by observing the daily patterns of curtailment, the figure below shows the activities and signs of curtailment.

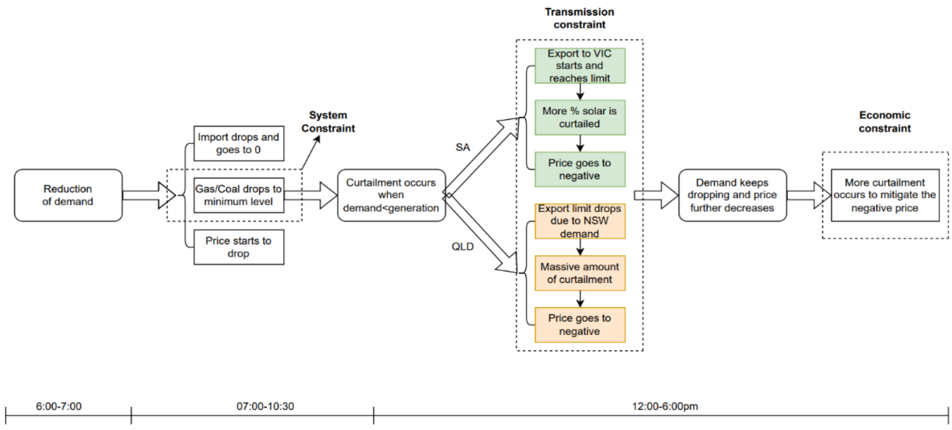


Figure 2 Curtailment Modelling and Pattern

The model shows the signs of curtailment. It starts with the demand reduction followed by the reduction of highly controllable dispatch units like gas power stations, hydro, and thermal steam stations that operate at a stable minimum operational level based on the penetration/share of power from renewable for the demand. Then the imports to the state gradually decreased. Curtailment occurs initially to prevent the fall of prices (economic curtailment), and in the case of QLD central portion of the curtailment is caused due to network constraints. As demand falls mid-day with increased solar, curtailment of wind or solar is performed to maintain economic power dispatch to the grid.

4.2 Quantitative Analysis

South Australia

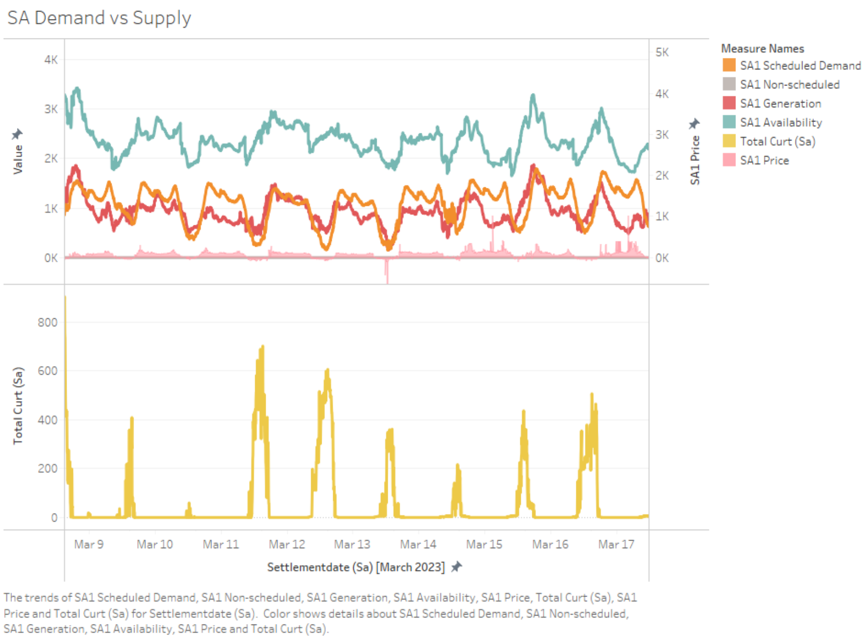


Figure 3 South Australia Demand vs Supply vs Curtailment

The figure above shows the demand and supply and the curtailment profile of South Australia from March 9, 2022, to March 17, 2022. For this qualitative analysis, the data from March 16, 2022, is used to explain best the supply, demand, export, import, and various other parameters based on the price and movement of the market to best understand the causes and effects of curtailment.

To better understand the supply mix of South Australia, the figure below shows the three-day supply mix and the net export of South Australia. It is observed that the night-time loads are majorly covered by wind energy, and the peak demand is assisted by gas plants and imports. Therefore, the share of supply for SA for three days is given below.

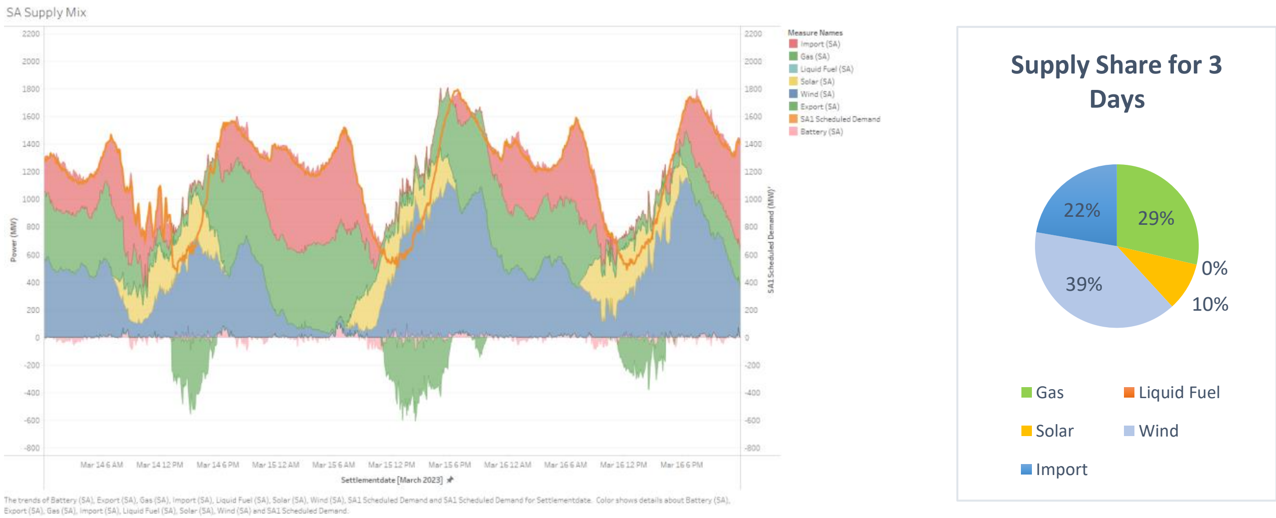


Figure 4 South Australia Supply Mix

As we can see from the supply mix figure, when the solar and wind supply pumps in during the daytime, a significant portion of the power is exported to Victoria through the Heywood connector, which has a rated capacity of 650MW. The above negative area in the above graphs shows the net export from SA to VIC and a small amount of charging through BESS batteries.

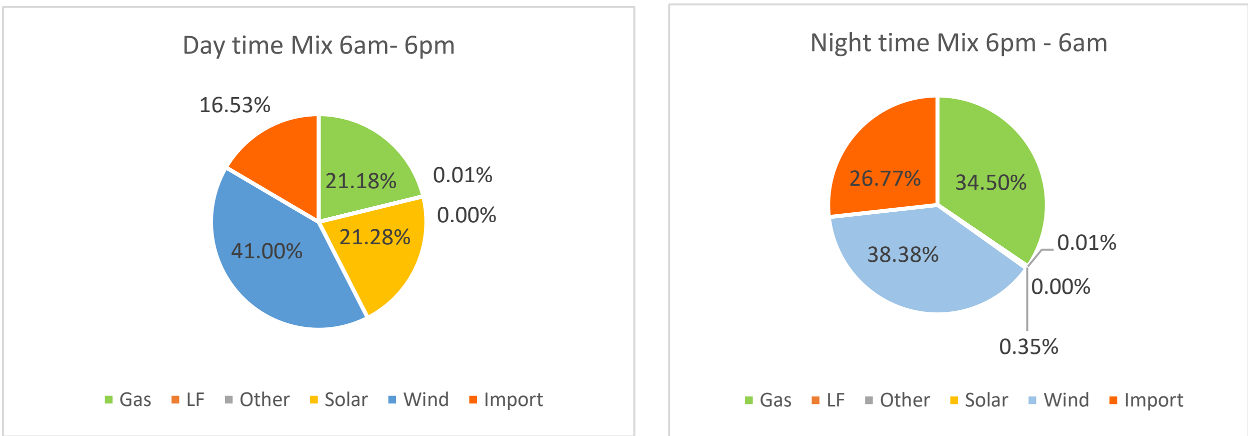


Figure 5 Day time and Night time Mix of Supply in South Australia

As seen in the above pie charts, the central portion of the demand is supplied by wind and Solar, which account for 21.28% and 41%, respectively, and the sudden spikes in demand are managed by gas. However, during night time demands, around 38.38% of the supply is through wind, and the supply from solar is replaced with gas and imports, which account for 34.5% and 26.77%, respectively. Power export is determined by the state demand and excess generation.

To better understand the sequence of conditions that lead to curtailment, a single-day study is performed to understand the pattern better.

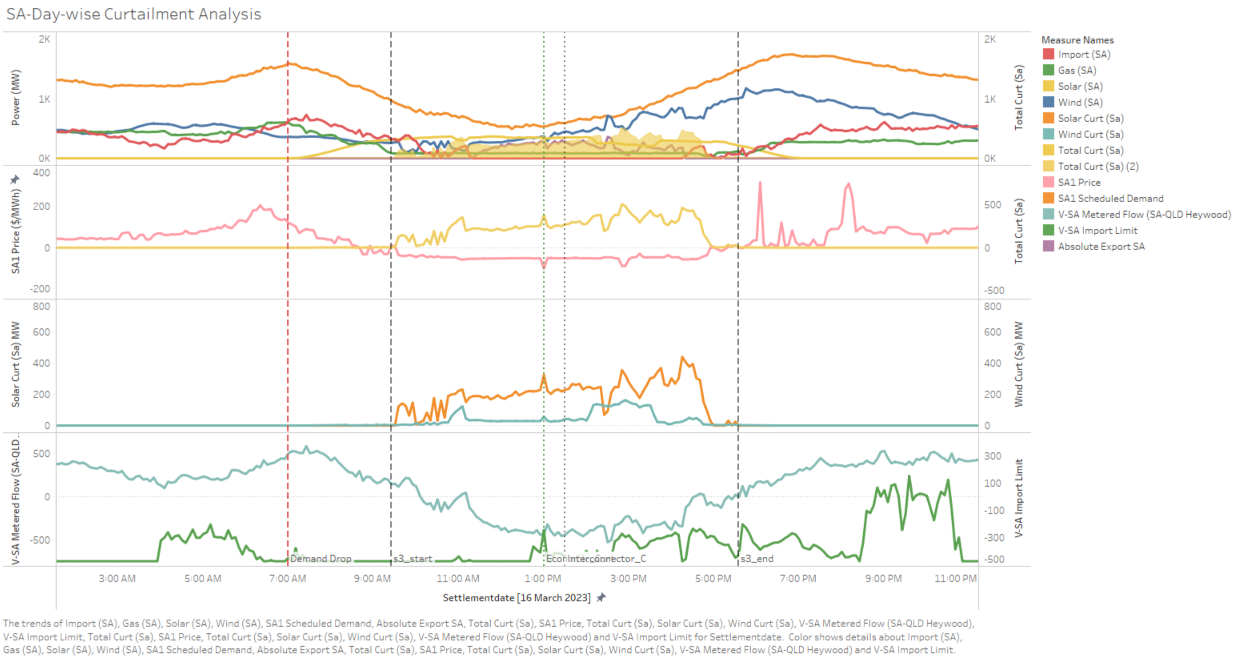


Figure 6 South Australia Day wise Curtailment Analysis

>7:00 AM

From the graph, we can see the demand trying to reduce after the morning peak; the decrease in orders from 1592MW to 967MW is sharply responded by the reduction of dispatch from CCGT and OCGT in the state, and the import net import starts decreasing from 07:25 AM, precisely when the solar PV output pumps in. The Heywood interconnector is reducing its imports from VIC, considering the reduced demand. From 7:00 AM to 09:25 AM, we could observe that the gas output is gradually reduced based on the gradual increase in solar. As the spot market price enters negative values by 08:45 AM, the dispatch from gas is sharply reduced to its minimum operation levels of 85MW, and the imports are brought down gradually to maintain a balance in price.

09:25 AM to 12:00 PM

The solar output in SA has gradually reached a collective generation of 305MW, with an ongoing reduction in demand; the prices hit a negative peak of -32$/MWh. Hence we could observe gradual solar curtailment signals to prevent further price drops. It is to be noted that the curtailment in this period is performed to stabilize the economics of production (Economic curtailment). By 10:00 AM, the demand falls to 814MW, and the excess generation is exported by the Heywood interconnector, as seen in the metered flow line in the graph. By 12:15 PM, with a sharp decrease in demand to 491MW, the price hits a new negative peak of -52$/MWh, with an increase in wind generation from 125MW to 294MW, the power from solar and solar is gradually curtailed to prevent further falling of prices.

12:00 PM to 06:00 PM

By 1:00 PM, we could observe that the metered flow from the Heywood connector had hit the export limit from SA (or the import limit to VIC). The graph shows few import constraints in the transmission line, which would be caused due to the economic or technical limitations in the Victoria grid. The possible reasons would be the excess generation in the Victoria grid due to renewables during-day the day, which might reduce the supply requirements to keep the market price in a stable region.

Hence the export from SA is sharply responding to stay within the transmission import limit to Victoria. Thus a sudden negative spike in price (-102$/MWh) is observed at 1:00 PM, which is immediately responded to by a sharp point in curtailment from solar and wind power production (network constraint curtailment). This action is followed by the retrieval prices back to -49$/MWh. Finally, a gradual rise in solar curtailment is observed to increase over the rise of wind power production from 449MW to 670MW. It is to be noted that the gas tends to operate at the minimum level rating of 85MW.

By 5 PM, with a gradual increase in the demand to the night peak, and with a decrease in solar output and increase in wind power output, the price increases from -52$/MWh to 3.9$/MWh; the graph shows that the net export to VIC becomes zero.

>06:00 PM

As the demand increases to the night peak, the prices rise with the increase in the production of power from gas and imports from VIC. Therefore, sometimes cases of wind curtailment do exist at midnight when the wind production is unexpectedly higher than forecasted.

Its observed that the major portion of curtailment is performed to maintain the economic stability of spot prices , and small portion of curtailment to maintain network stability.

Response to Curtailment Signals by Solar and Wind Plants:

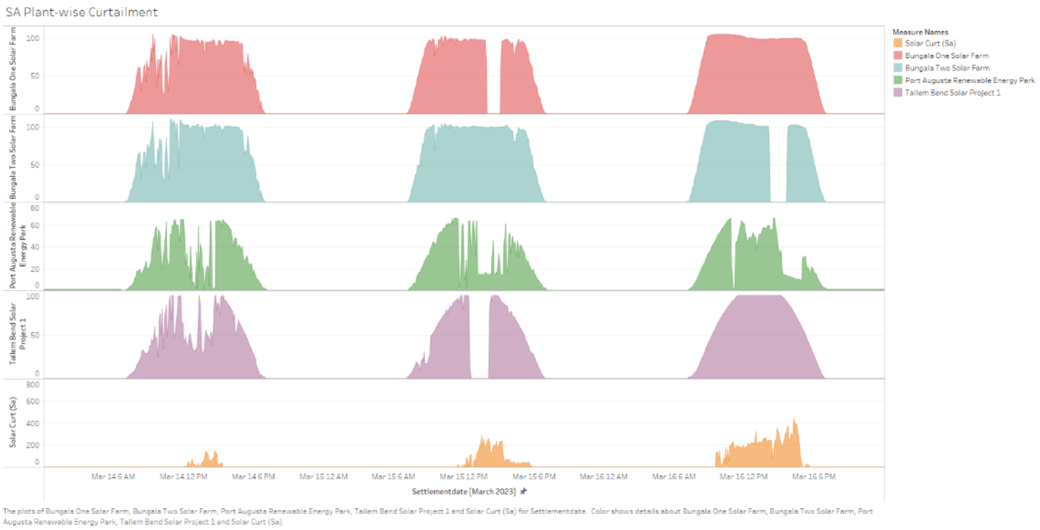


Figure 7 Performance of Solar Farms in South Australia

The above graph shows that the plants respond to the curtailment signal from AEMO in a varied pattern. It is to be noted that only a set of solar plants react to the curtailment on a given day. For instance, Bungala One Solar Farm, Port Augusta, and Tailem Bend Solar Farm responded for curtailment on March 15, and Bungala Two Solar Farm and Port Augusta responded to curtailment on March 16; this could be due to geolocation of the plant and concerning the degree of intrastate transmission congestions at a given point of time.

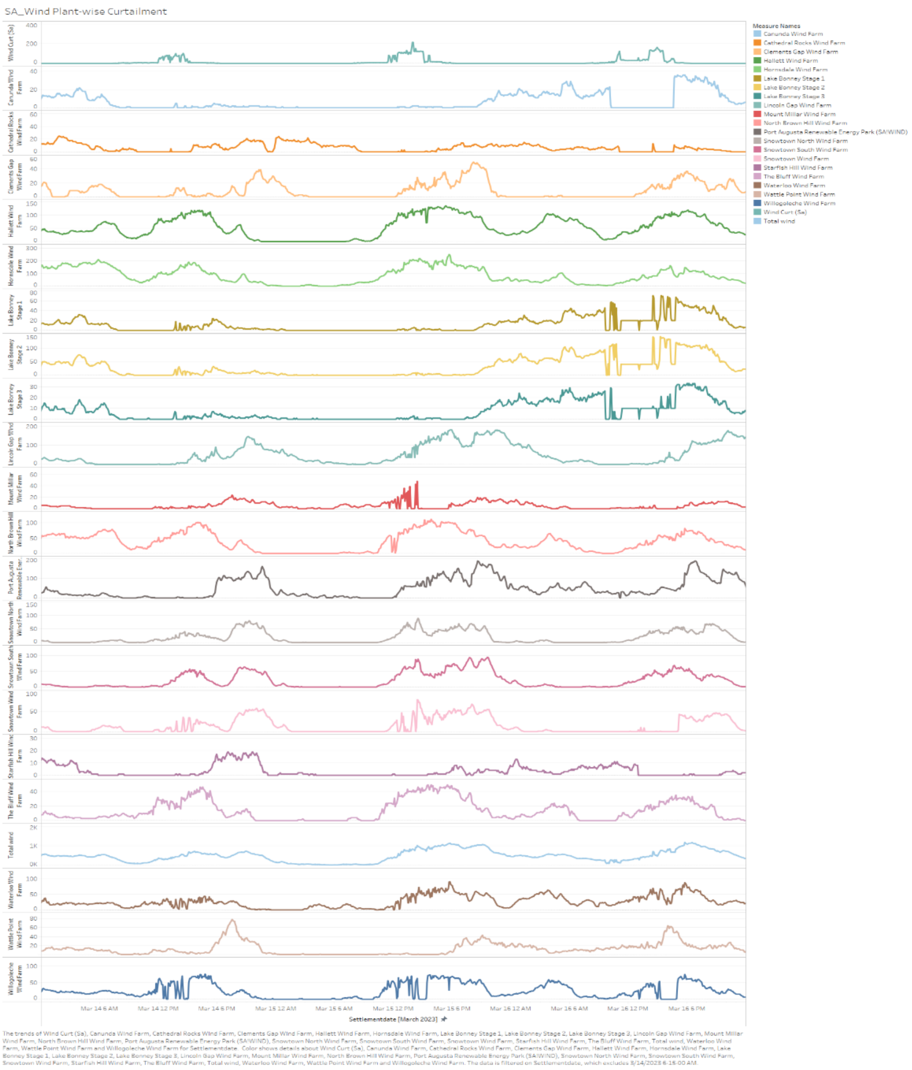


Figure 8 Performance of Wind Farms in South Australia

From the graph, it to be observed that only a set of wind farms responded to the curtailment signals to the AEMO, it was followed that the early entrants to the market had been non-scheduled generation farms, but as per the current regulations of AEMO, new entrants are to by default become generators planned.

Queensland

Compared with SA, QLD has a significantly higher demand of 2500-3500MW and accounted for similar rates in curtailment. As seen from the above sections, solar comprises the majority of installed renewable energy sources compared to wind.

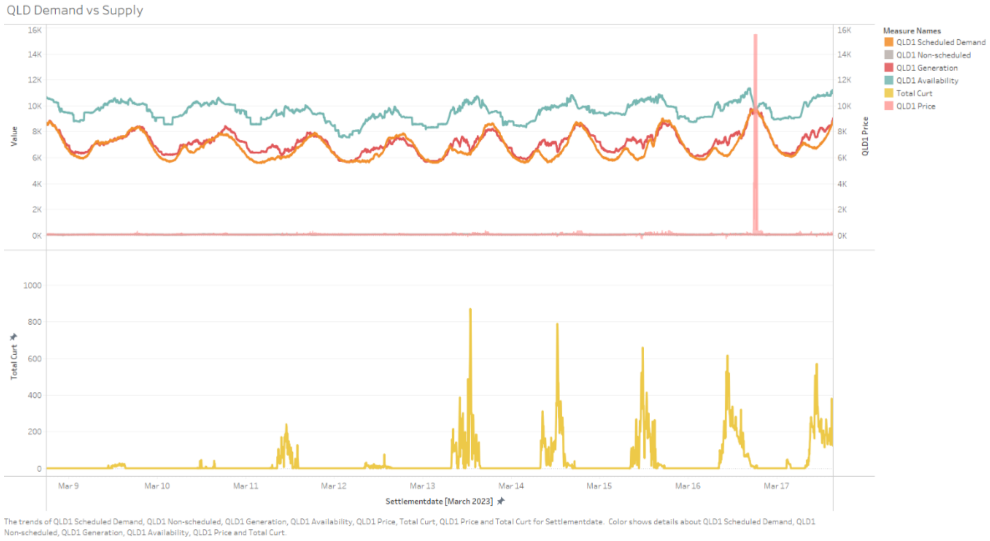


Figure 9 Supply vs Demand in Queensland

The figure shows the demand and supply and the curtailment profile of Queensland from March 9, 2022, to March 17, 2022. For this qualitative analysis, the data from March 16, 2022, is used to explain best the supply, demand, export, import, and various other parameters based on the price and movement of the market to best understand the causes and effects of curtailment.

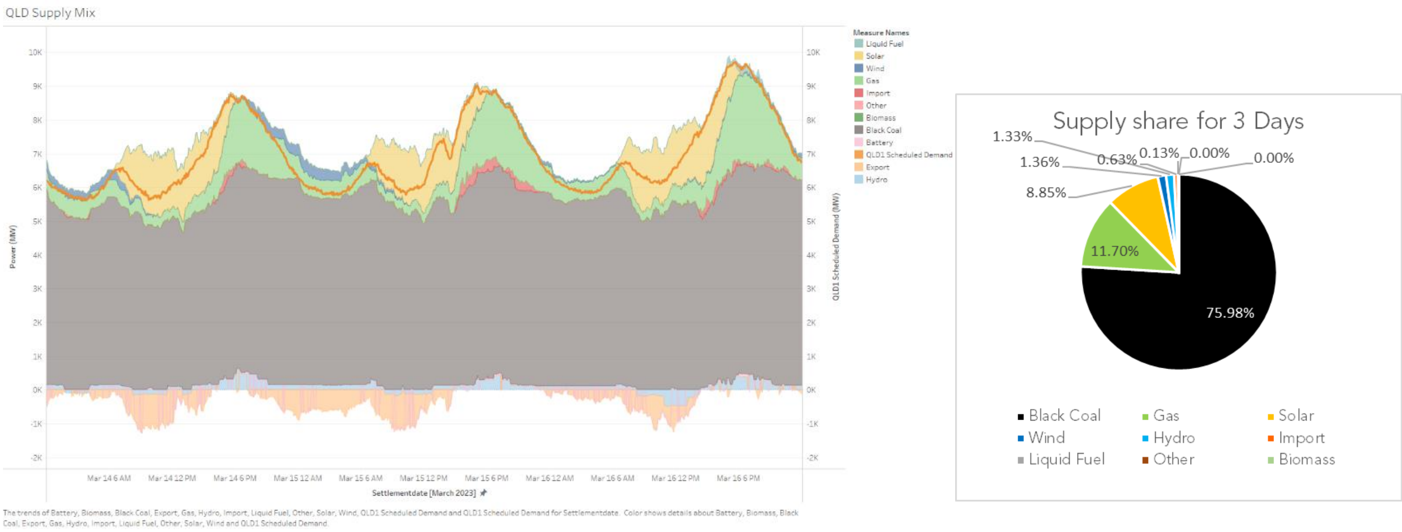


Figure 10 Queensland Supply Mix

From the pie chart seen above, we can observe that black coal has around 75.98% share, followed by 11.7% of gas and 8.85% of solar of the overall dispatch. It is also noted that import only comprises 0.63% of the overall demand, showing that Queensland is a primary power-exporting state. The supply share of Queensland over the time of 3 days is shown in the above graph. The negative portion of the supply mix graph offers the power export to NSW, BESS charging, and hydro pumping.

To understand the causes of curtailment in Queensland, the share of supply over day and night is studied. The pie charts below show the percentage of supply resources during the day and night. It is evident from the graph that around 72.22% of power is supplied from black coal, followed by 17.36% of the supply by utility solar and 8.8% of the share by gas plants. It is observed that only 0.59% of the collection is provided by wind. However, at night, the supply share is estimated at 79.89% from Black Coal, 14.72% from gas, and

2.17% from wind. This is because the imports in Queensland are minimal and are established to ensure grid synchronous and stability. The data shows that an estimated 5% of the supply is exported to NSW for these three days.

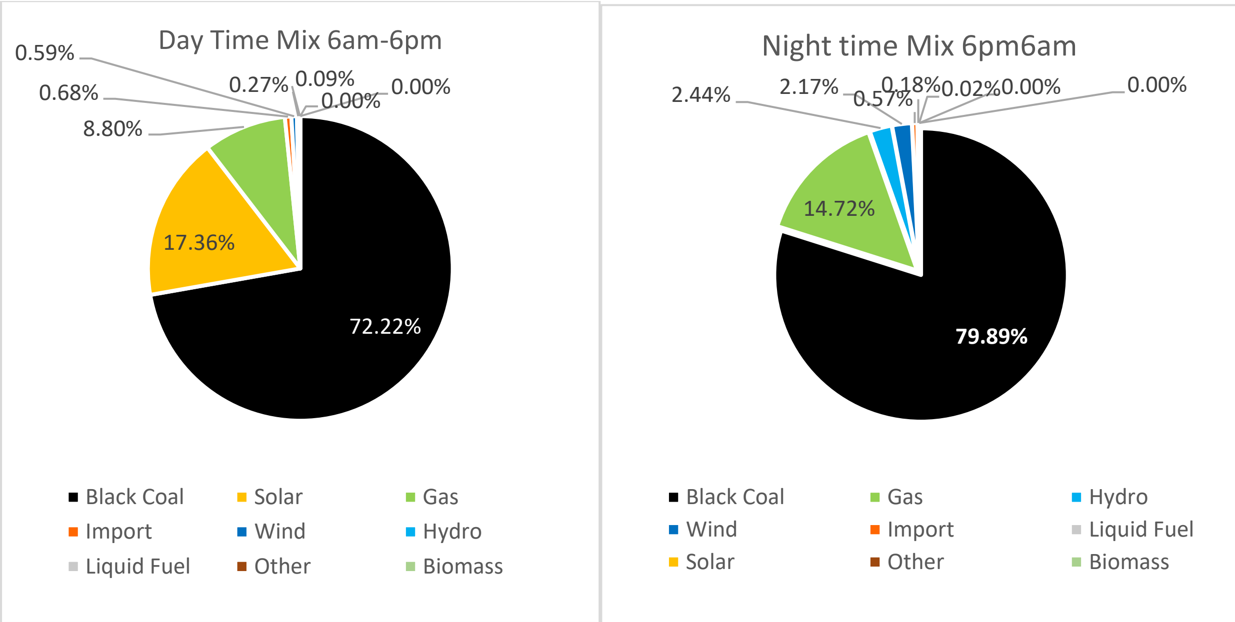


Figure 11 Day time and Night time Supply Mix in Queensland

Queensland exports power to NSW via the QNI interconnector, which has a rated capacity of 1078MW and is considered one of the significant assets for the NSW grid, as NSW highly relies on imports from VIC and QLD. It is important to note that sources such as Pumped Hydro and growth charge daily to avoid curtailment.

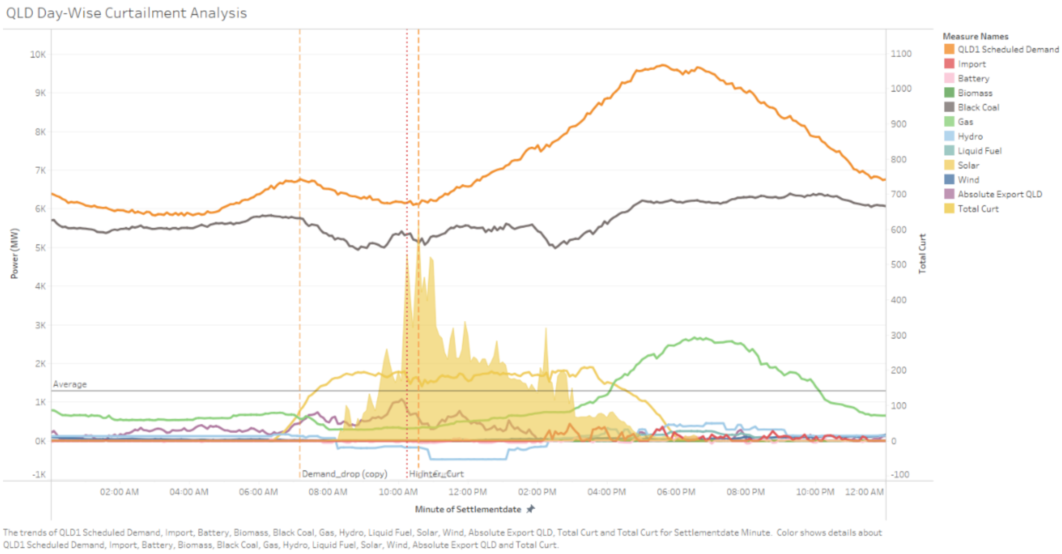


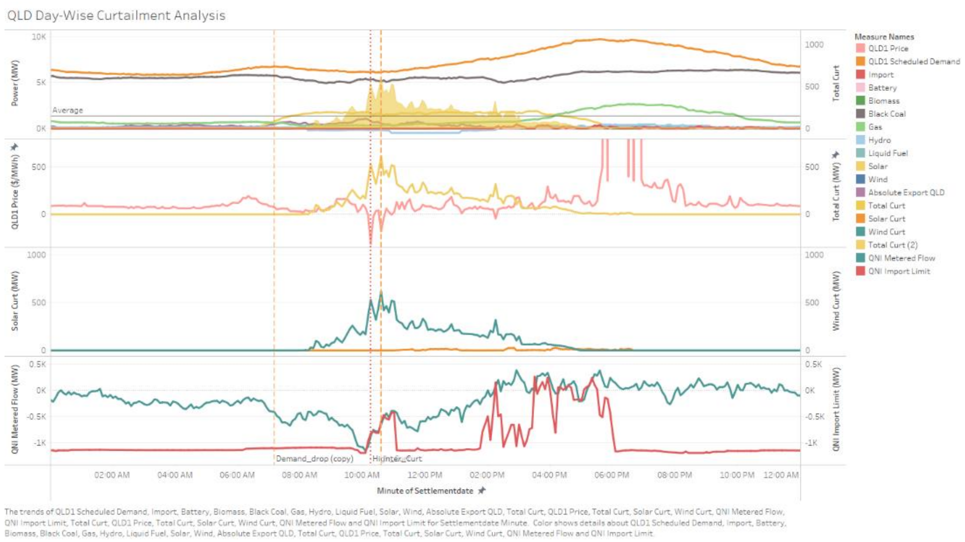
Figure 12 16th March, Demand and Supply vs Curtailment

>7:00 AM

The graph shows that the demand starts to fall at 7:00 AM from 6772MW to 6370 MW. It is to be noted that the coal and gas supply sharply reacts to that of the demand profile. And by 7:00 AM, the solar output has reached 797MW. As we have seen earlier, QLD increases export to NSW to meet local demand. Hence the price was high pre-7:00 AM. As the demand decreased, the prices fell. By 08:00 AM, as the market is still falling, the generation output from gas is made to operate at a minimal operation limit; the generated electricity is utilized in the pumping mode of hydro, which acts as a load of 172MW.

From 08:00 AM to 06:00 PM

With the increase in solar output to 197MW by 09:00 AM, the demand is steadily decreasing; since coal has comparatively low ramping rates, solar and wind are curtailed to respond to the excess generation for reducing need, and curtailment is made to ensure grid stability. By 10:00 AM, as the demand ramps down to 6147MW, the excess power is pushed for export, but due to a sudden reduction in the export limit to NSW,s seen in the graph below, sudden spikes of curtailment are reserved in the wind, the effect is seen as sudden harmful spikes in price as supply is > demand (that includes export)



To ensure the metered export is within the import limits to NSW, curtailment signals are given to wind farms to cut down production. The spikes in the import limit of QNI to NSW may be due to internal network congestion/ constraints and supply-demand economic and technical coregulations within the NSW grid.

The curtailment effect is shown in the movement of the price in the market. By the mid-day from 02:00 PM to 06:00 PM, due to less import demand from NSW, the export from QLD to NSW is gradually decreased to ensure energy system security. As seen in the graph above, the wind curtailment rate is slowly reduced as the load increase post-02:00 PM. By 2:00 PM, the QLD increases input from NSW to meet the demand increase. As the demand rises to 9723MW by 05:35 PM, we can observe the price hitting the market ceiling price 15500$/MWh, as import stabilizes, and the production of power from gas is ramped up to 2672MW and coal 6230MW to meet the demand.

As seen above, it is essential to note that only wind farms are curtailed at a higher % than compared to that of solar, is because of the geographical location of the wind plants in areas away from the population and where the transmission infrastructure is comparatively highly congested.

Response to Curtailment Signals by Solar and Wind Plants:

The graph shows that the wind farms respond to curtailment signals by a complete shutdown of output from almost all the wind farms. These patterns of curtailment might lead to a risk in investment in wind projects in Queensland.

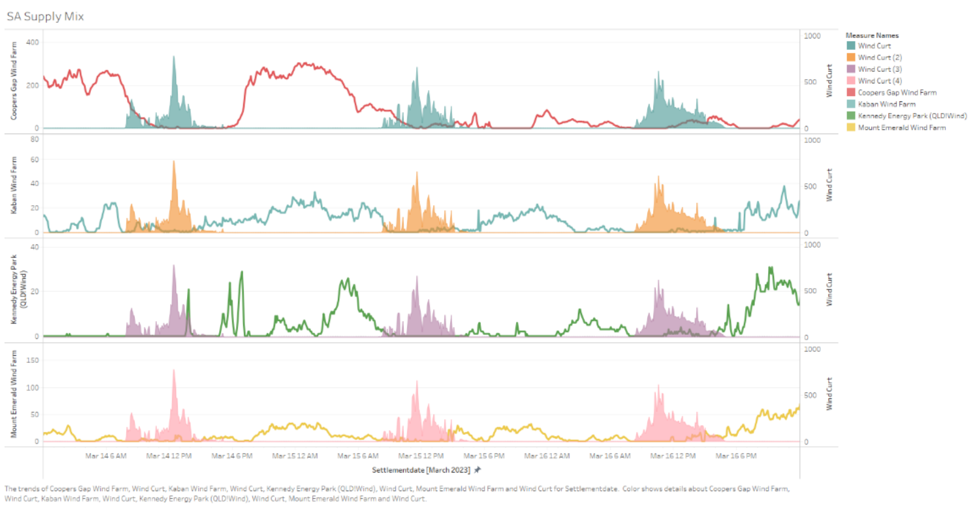


Figure 13 Performance of Wind Farms vs Curtailment in Queensland

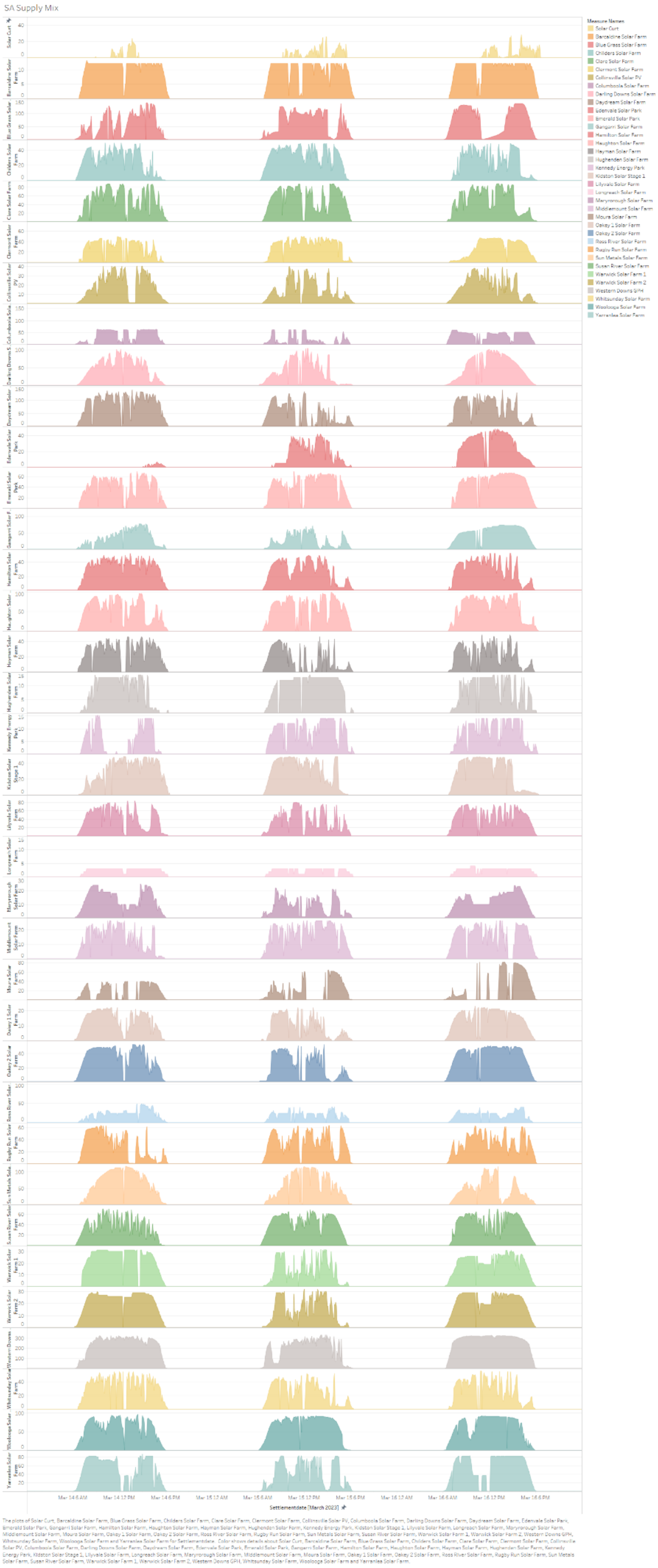


Figure 14 Performance of Solar Farms vs Solar Curtailment

The graph on the left shows the individual output from solar farms across QLD; since the curtailment in QLD is relatively small compared to wind, the change in power output to the curtailment signals are not seen.

Based on the annual curtailment data procured from NEMSight, the total curtailment of wind and solar has been aggregated for the term March 2022-2023.

		Generation GWh	An. Curtailment GWh
SA	Solar	691	118
	Wind	6578	514
QL	Solar	4548	281
	Wind	1973	37

The table shows the annual generation and curtailment of solar and wind farms from South Australia and Queensland. It is evident that there is a significant loss of energy due to curtailment.

The next section elaborates on the economic analysis linked to the curtailment.

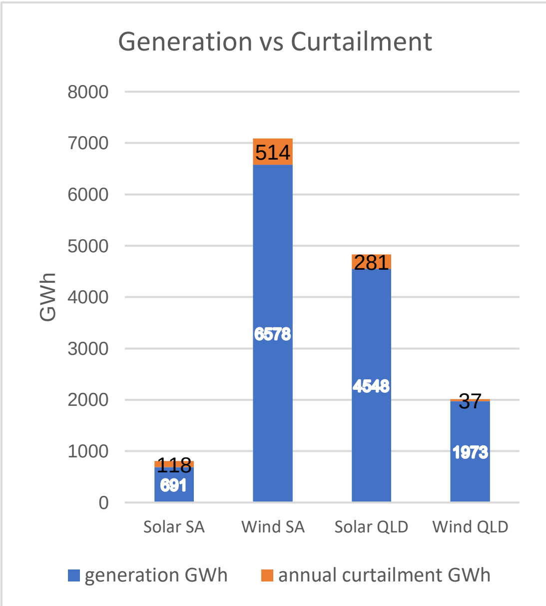


Figure 15 Annual Curtailment and Generation Data of Renewable Generators in SA and QLD

4.3 Economic Analysis

The methodology used to evaluate curtailment in this report is based on a series of studies conducted by the Australian Renewable Energy Agency (ARENA, 2022)the-generator-operations-series-report-six.pdf.pdf (arena.gov.au) and a paper addressing the financial aspects of Australian renewable energy (Srianandarajah, Wilson, and Chapman, 2022)From green to amber: is Australia's National Electricity Market signalling a financial warning for wind and solar power? - ScienceDirect. The revenue generated by a renewable energy project can be viewed as a bundled Power Purchase Agreement (PPA), comprising of electricity PPA and Large Generator Certificates (LGC). While the values of PPAs vary among generators and are typically confidential in Australia, a report published by PwC (PwC, 2017) optimising-energy-corporate-ppas-nov17.pdf (pwc.com.au) provides insights into some PPAs for Australian wind and solar farms. These values are illustrated in the accompanying figure 16.

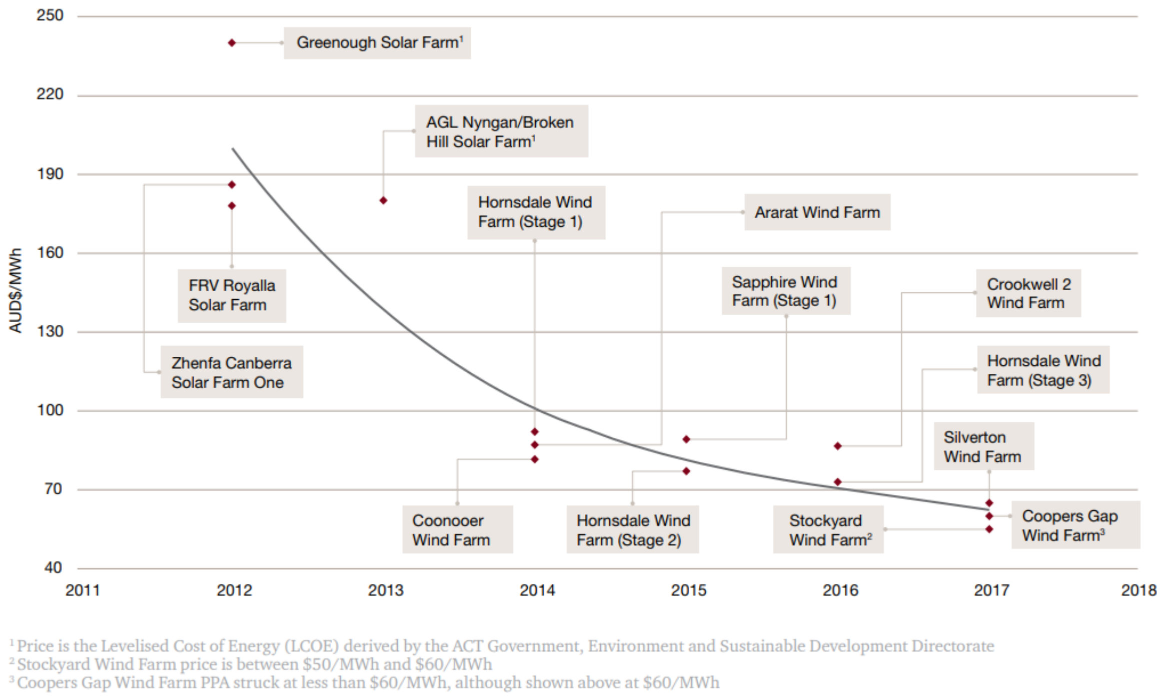


Figure 16 Australian Renewable PPA Prices

As depicted the figure, PPAs of wind farms range from 50-70$/MWh while PPAs of solar farm lie in a much higher range from 160 to over 220$/MWh. Thus, the PPA of wind farm and solar farm is set to be 70$/MWh and 180$/MWh respectively in economic loss calculation. Annual economic loss of the renewable generators is derived via the following equation:

$$E_L = C * PPA$$

where C is annual curtailment in MWh calculated in Section 4.2. On the other hand, these losses can be recovered by implementing Battery Energy Storage Systems (BESS) so that generators are able to store the curtailment energy in the battery and sell it during peak demand periods with high spot market prices. As a result, the potential revenue of curtailment by introducing BESSs is defined as this equation:

$$R_P = C * P_{peak}$$

where P_{peak} stands for peak demand spot prices and is derived by averaging the spot market prices from 5-9pm in the evening using the data collected in Nemsight. All prices employed in this report including PPAs are listed in table. Following figure demonstrates the economic losses and potential revenue of wind and solar generation in SA and QLD.

Table 2 Prices Employed in the Report

	Solar of SA	Wind of SA	Solar of QLD	Wind of QLD
PPA($/MWh)	180	70	180	70
P_{peak}**($/MWh)**	243.675611		322.9004202	

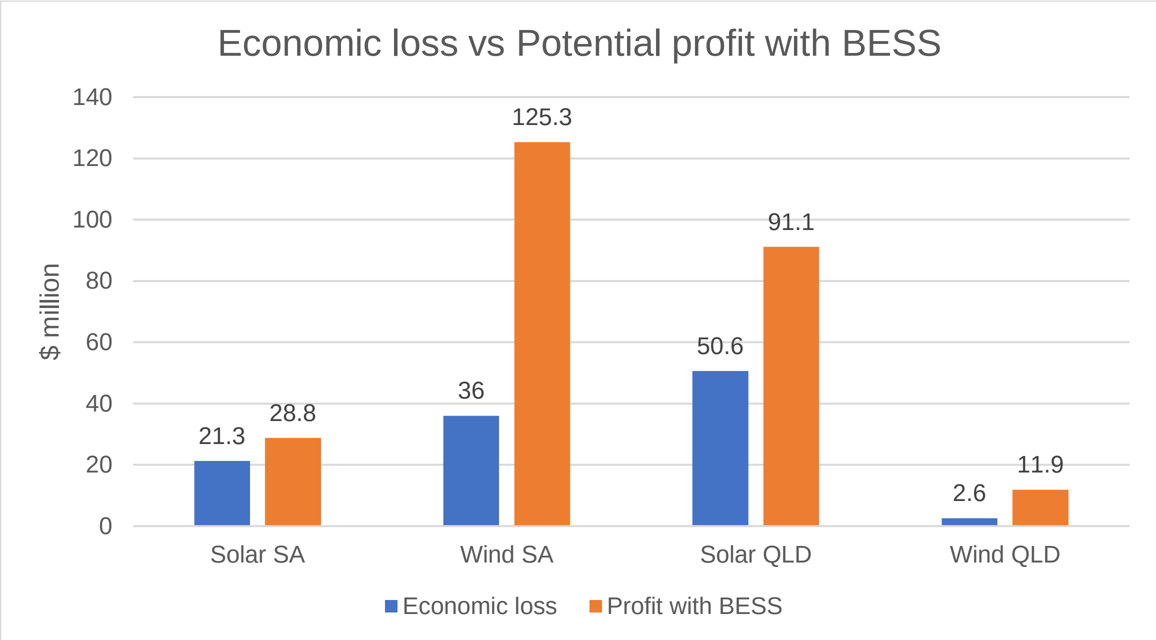


Figure 17 Economic Losses and Potential Revenues of Renewable Generation

Values and results employed and calculated in this report have been carefully examined and compared with other reports to ensure great data quality.

As shown in the graph, the greatest potential benefit appears in wind generation in SA due to the enormous magnitude of wind curtailment happened in SA during the analysed period, with the R_P showing 125.3 million dollars. Solar generation in QLD accounts for the second highest potential revenue of 91.1 $million, motivated by the high peak demand spot price in QLD. In summary, the total curtailment losses of 57.3 $million (SA) and 53.2 $million (QLD) could potentially be reversed into revenues of 154.1 $million (SA) and 103 $million (QLD) if all curtailment is stored and sold properly.

5. Key insights for EI planning and investment

Numerous advantages result from the increasing use of renewable energy sources in the power mix, including decreased glasshouse gas emissions and enhanced energy diversity. However, intermittent renewable energy sources like wind and solar power can present problems like curtailment. When renewable energy generation is restricted or squandered due to limitations in the grid infrastructure or other causes, curtailment occurs. The EI must concentrate on strategic planning and investment in key areas if it is to overcome this problem and fully harness the potential of renewable energy. These key areas include:

5.1. Incorporating Distributed Battery Energy Storage Systems (BESSs)

Distributed battery energy storage systems (BESSs) offer a potential solution to address renewable energy curtailment in the electricity industry. BESS can store surplus wind and solar energy produced during times of high production for later use, minimising curtailment and assisting in maintaining stability and reliability. By balancing supply and demand, energy storage systems can assist in the continuous operation of the grid and potentially defer investments in transmission and distribution infrastructure upgrades.

BESSs for grid-scale battery energy storage are viewed as more modular and adaptable technologies. BESSs are able to control the inherent unpredictability of renewable energy systems, which helps with energy balance, in addition to providing ancillary and crucial grid services (such as frequency and voltage management and system restoration) (https://www.mdpi.com/1996-1073/15/2/429).

However, Distributed BESS deployment needs to be carefully evaluated, considering their kind, size, location, and cost-effectiveness. Although BESS can increase renewable energy generation, the lengthy payback period may make it less appealing commercially (https://ieeexplore-ieee-org.wwwproxy1.library.unsw.edu.au/stamp/stamp.jsp?tp=&arnumber=8085955). It is vital to re-evaluate the potential advantages and cost-effectiveness of implementing BESS and analyse supplemental cost benefits and the impact on regional renewable energy targets as renewable energy integration rises and energy storage technologies advance.

5.2. Construction of transmission links to compensate for transmission constraints.

By building transmission lines, regions with plentiful renewable energy sources can export excess energy to other states or regions with higher demand. By ensuring that the electricity generated is used effectively, this assists in reducing the need to reduce the use of renewable energy. This in turn encourages improved grid stability, resource utilisation that is more effective, and overall power system resilience. In order to manage energy resources on a greater scale, cooperation and coordination are also encouraged through expanding transmission networks and interconnectedness across areas.

Without the need for any further basic alterations to the structure of the energy system, exporting electricity to neighbouring grids can aid in minimising curtailment peaks and aid in grid stabilisation (https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9392581).

A research by the National Renewable Energy Laboratory (NREL) titled "Reducing Wind Curtailment through Transmission Expansion in a Wind Vision Future" provides an excellent illustration of the usefulness of transmission in reducing the curtailment of renewable energy. The analysis emphasises how crucial transmission expansion is to enable the grid integration of wind energy and minimise curtailment. By examining various scenarios, the authors show how wise investments in transmission infrastructure can significantly lower the costs of wind generation and curtailment. This emphasises the crucial role that transmission links play in overcoming the difficulties associated with integrating renewable energy into the power grid (https://www.nrel.gov/docs/fy17osti/67240.pdf).

5.3. Introduction of Synchronous Condensers (SynCons)

Synchronous Condensers (SynCons) provide a practical response to issues with grid stability and dependability brought on by a greater integration of renewable energy sources. SynCons provide a more seamless integration of sporadic renewable energy sources like wind and solar by supporting reactive power and improving voltage management. This lessens the need for curtailment and guarantees that the electricity system functions within the necessary constraints. SynCons can be extremely important in ensuring grid reliability while maximising the use of clean, sustainable energy sources as the electrical industry embraces renewable energy more and more.

SynCons, which may offer fault current, mechanical inertia, and voltage regulation and aid with the stability of the system as well as power system protection and coordination, are enhancements that can act as inverter-based resources (IBRs) enablers (https://ieeexplore-ieee-org.wwwproxy1.library.unsw.edu.au/document/7866938) (https://www.sciencedirect.com/science/article/pii/S0038092X20305442) (https://www.mdpi.com/1996-1073/15/2/429).

5.4. Vehicle to Grid (V2G) and Incorporating managed EV charging

Grid stability and reliability challenges have arisen with the integration of renewable energy sources. Vehicle to Grid (V2G) technology offers an innovative solution. Electric vehicles (EVs) can contribute to a more flexible and effective grid system by supplying power back to the grid during times of high demand or when renewable output is low. By doing this, the rising fleet of EVs is utilised as an additional source of grid flexibility, which not only aids in reducing the need for curtailment. V2G technology may be extremely useful in maximising grid performance, guaranteeing dependability, and utilising clean and sustainable energy resources to the fullest extent as the adoption of electric cars and renewable energy generation continue to grow.

Because they interfere with the routines used for planning and managing the daily operations of the electric grid, intermittent renewable energy generation sources present specific challenges. Additionally, the grid operator must modify its operational processes due to the power's fluctuating output over a variety of time frames. This would be a highly effective method of storing renewable energy while simultaneously addressing the issue of energy intermittency if this intermittent energy source was used to charge the electric vehicles (EVs), which are interconnected with the power grids (https://www.mdpi.com/1996-1073/15/2/589#B29-energies-15-00589).

Energy storage technologies, like EVs, feature a range of intelligent power consumption patterns, including elastic power consumption time, bootable power consumption behaviour, and predictable power consumption. The control of grid optimisation can be aided by a big space for load-side resources as reasonable dispatching of EVs (https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9215166). In electricity industries with high renewable energy penetration, properly regulated charging or smart charging might actually help to reduce renewable energy curtailment. For instance, in California, compared to unmanaged plug-in electric vehicles (PEVs), 0.95 to 5 million "smart" charging PEVs cut RE curtailment by up to 40% and save $120 to $690 million in yearly grid operating expenses (up to 10% of overall expenditures) (https://www.sciencedirect.com/science/article/pii/S030142151930638X).

The electricity industry can create a thorough strategy for handling the complexity brought on by the growing use of renewable energy sources in the power system by prioritising and investing in these areas. A more effective, dependable, and sustainable power system is eventually made possible by these insights and solutions, which work together to direct industry actors in their planning, decision-making, and investment processes.

6. References

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