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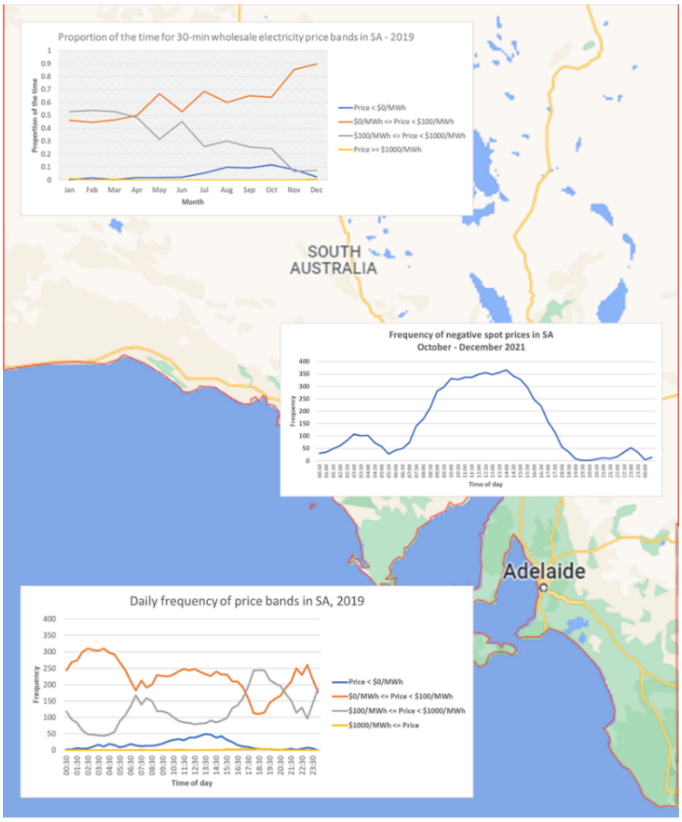

Analysis of historical wholesale electricity spot price volatility in South Australia and their projections in 2030 and 2040

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A REPORT FOR THE SOUTH AUSTRALIAN PRODUCTIVITY COMMISSION

April 2022

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Purpose

The South Australian Productivity Commission (the Commission) has engaged the University of Wollongong (UOW) to assist with addressing certain technical questions to help inform the Commission's Inquiry into Renewable Energy Competitiveness. This report contains the findings from research conducted by UOW into research Question C. Research Question C seeks to forecast the frequency of low or negative and high (above $1,000/MWh) wholesale electricity spot price events in 2030 and 2040 under certain energy market development scenarios published by the Australian Energy Market Operator (AEMO).

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Abbreviations

$/MWh	Australian dollars per Megawatt-hour
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
APC	Administrative Price Cap
AFP	Administrative Floor Price
DER	Distributed Energy Resources
DRSP	Demand Response Service Providers
EV	Electric Vehicle
FCAS	Frequency Control Ancillary Services
GPG	Gas-powered generation/generator
IASR	Inputs, Assumptions and Scenarios Report
ISP	Integrated System Plan
MW	Megawatt
MWh	Megawatt hours
NEM	National Electricity Market
PV	Photovoltaic
RRP	Regional Reference Price
SA	South Australia
SAPC	South Australian Productivity Commission
VRE	Variable Renewable Energy
WDRM	Wholesale Demand Response Mechanism

Executive Summary

The South Australian Government asked the South Australian Productivity Commission (SAPC) to undertake an inquiry to assess South Australia's actual or potential renewable energy competitive advantage and identify any further actions the SA Government may take to enhance it and any consequential economic development opportunities.

The SAPC invited researchers from University of Wollongong to provide analysis of the following research question as specified by SAPC:

C. *Assuming transition pathways that align with the AEMO 2022 ISP scenarios 'Step Change' and/or 'Hydrogen Superpower', what proportion of the time would South Australia be expected to have negative or zero wholesale electricity spot prices in 2030 and 2040? And what proportion of the time would spot prices be expected to be very high (say in excess of $1,000/MWh)?*

This report contains the findings from research conducted by UOW into research Question C. The specific objectives of the document are:

- To analyse historic volatility of wholesale spot prices in South Australia.
- To enumerate major development trends and outcomes in 2030 and 2040 in South Australia according to two AEMO's scenarios – Step Change and Hydrogen Superpower.
- To assess potential impact of these two scenarios on future electricity prices in 2030 and 2040 in South Australia

Transition of the electricity market

Australia's National Electricity Market (NEM) is experiencing one of the fastest-growing variable renewable generation (VRE) in the world, raising new challenges to system security and reliability. South Australia is at the forefront of this transformation with significant amount of wind and solar PV generation capacity. Not only in South Australia, but in other regions of the NEM, this transformation has produced many extended periods of negative spot prices and increased uncertainty and variability of electricity prices. The assessment and management of electricity price volatility becomes a major challenge for the NEM. It is related to the intermittent character of VRE, which makes it harder to balance the variable by nature demand with frequently changing supply. Renewable generation has a zero-fuel cost and helps to reduce the electricity spot prices; however, higher spot price volatility can result in higher wholesale contract prices and therefore higher prices for end consumers, offsetting some or all of the initial price reductions.

Recent electricity market dynamics in South Australia

Over the last two years, South Australia has experienced several records related to its electricity. For the first time, aggregated solar generation - from distributed PV and utility solar - was equivalent to 100% of SA's underlying demand. During the last quarter of 2020, South Australia became the lowest price region in the NEM since 2012. On several occasions, the VRE curtailment in SA reached more than 1,000 MW, which was a substantial proportion of the renewable generation. During the last quarter of 2021, South Australia recorded negative spot prices 28% of the time due reduced demand and high distributed solar production. On 21st November 2021, the half-hour minimum operational demand of 104 MW was reached due to mild sunny conditions, low weekend demand, reduced industrial load and increased distributed solar PV output.

Historical trends of electricity spot prices in South Australia

This study provides an analysis of monthly spot electricity data in South Australia for the last seven calendar years – 2015-2021, which are illustrated by chart trends. The study considers four price bands that are specified according to the following spot price intervals:

- P1: Regional reference price (RRP) < $0/MWh
- P2: $0/MWh <= RRP < $100/MWh
- P3: $100/MWh <= RRP < $1000/MWh
- P4: $1000/MWh <= RRP

The frequency of negative prices (P1) in SA for the years 2015-2018 was very low (one or two percent) and approached 5% only in 3-4 months for the whole four-year period. The frequency of negative prices started to grow from the middle of 2019 and exceeded 37% for September and October in 2021.

The frequency of very high prices (P4) was in the range of 0.1% - 0.5% on average. This frequency was a bit higher in 2015 and 2016 (in comparison with the following years), exceeding 3.5% for July 2016.

Negative prices

The frequency of negative spot prices has increased substantially in the last several years in all regions of the NEM with biggest increases in the southern regions of South Australia, Victoria, and Tasmania. Key drivers for negative prices included low operational demand, high renewable generation and interconnector constraints preventing export of excess generation with wind generation being the dominant factor. The most likely periods with negative spot prices in SA are during peak solar production time (10:00 – 15:30), when distributed solar PV and utility-scale solar generate significant power, reducing operational demand. The next likely period with negative prices is during the off-peak, early in the morning (3:00 am - 4:00 am), when the operational demand is very low and when there are good conditions for wind generation.

Very high electricity spot price

Very high spot prices (>= $1000/MWh) usually occur when there is scarce generation and growing electricity demand. More and more expensive generation offers must be accepted and dispatched by the market operator during these conditions. Key drivers for very high spot prices include high temperature when extra demand is created by air-conditioning use, generator outages reducing available generation, low wind output, and network outages reducing import of cheaper electricity from other regions. Extreme temperatures, heat waves and coincidence of conditions for high prices in other regions of the NEM – all increase the likelihood of very high prices.

A list of events with spot prices exceeding $5000/MWh for the last three years (2019-21) is included as an appendix to this report.

The Step Change and Hydrogen Superpower scenarios

Recently AEMO published its document "Draft 2022 Integrated System Plan for the NEM". AEMO uses a scenario modelling approach to outline a range of plausible development paths into the future, considering four scenarios. This report analyses the potential impact of the two most ambitious and transformational scenarios - Step Change and Hydrogen Superpower - on very high and negative spot prices in South Australia.

Research findings

- Negative spot prices - due to excessive supply from renewable generation with zero fuel cost, associated to low demand - will continue to be persistent in the market in South Australia. In the Step Change and Hydrogen Superpower scenarios the frequency of negative spot prices is expected to increase slightly in comparison with recent market trends. The Hydrogen Superpower scenario will provide a more significant change compared with the Step Change one.

- With significant new generation capacity planned over the next two decades in South Australia, it is expected that market conditions for very high spot prices (more than $1,000/MWh) will occur less frequently in comparison with events recorded over the last two years. Therefore, under the Step Change and Hydrogen Superpower scenarios, the frequency of very high prices will decrease only marginally, with the latter scenario providing a more significant change.

Recommendations

While more studies are necessary for greater understanding of price volatility across the NEM, some initial recommendations are provided.

Significant work has been done by market participants and other stakeholders for better integration of renewables into the market; however, there are still many issues which require further attention and new solutions, including very high and very low spot prices. One significant issue is better integration or coupling of renewable generators and battery storage. There are options both for utility-based and distributed generation and storage.

A significant opportunity perhaps exists for coupling of renewable generators and hydrogen production plants. Electrolysis plants for green hydrogen which are able to follow closely the output from renewable generators may mitigate the stability issues resulting from the intermittence of renewable output and when connected to the grid, mitigate the price volatility.

In general, improving the climate resilience and climate adaptation of the electricity grid in relation to failures, heatwaves, flooding, bushfires, and other disasters impacted by climate change is a significant issue that must be further addressed by stakeholders.

More research on some of these topics is recommended which includes advanced modelling and simulation.

Introduction

BRIEF DESCRIPTION OF THE PROJECT

The South Australian Government asked the South Australian Productivity Commission (SAPC) to undertake an inquiry to assess South Australia's actual or potential renewable energy competitive advantage and identify any further actions the SA Government may take to enhance it and any consequential economic development opportunities.

In order to inform this inquiry, the SAPC is examining a range of issues related to the current and future energy sector in SA, and its impact on the broader economy and the scale of any potential economic opportunities that may emerge as a result of renewable energy. The SAPC has specified six research questions that require specialised knowledge and so the SAPC was exploring the capacity of the energy policy research community to support its work.

The expected output for each research question is to be a short report (between 10 and 15 pages of text, excluding technical appendices if required), written in a manner that is accessible to a non-technical audience.

The SAPC invited researchers from University of Wollongong to provide analysis of the following research question as specified by SAPC:

C. *Assuming transition pathways that align with the AEMO 2022 ISP scenarios 'Step Change' and/or 'Hydrogen Superpower', what proportion of the time would South Australia be expected to have negative or zero wholesale electricity spot prices in 2030 and 2040? And what proportion of the time would spot prices be expected to be very high (say in excess of $1,000/MWh)?*

Australia's National Electricity Market (NEM) is experiencing of one the fastest-growing variable renewable generation (VRE) in the world raising new challenges to system security and reliability (Mwampashi, 2021). South Australia is at the forefront of this transformation with significant amount of wind and solar PV generation capacity. Not only in SA, but in other regions of the NEM, this transformation has produced many extended periods of negative prices and increased uncertainty and variability of electricity prices. The assessment and management of electricity price volatility becomes a major challenge for the NEM (Mwampashi, 2021). It is related to the intermittent character of VRE, which makes it harder to balance the variable by nature demand with frequently changing supply. Renewable generation has a zero-fuel cost and helps to reduce the electricity spot prices; however, higher spot price volatility can result in higher wholesale contract prices and therefore – higher prices for end consumers, offsetting some or all the initial price reductions.

Recently AEMO published its document "Draft 2022 Integrated System Plan for the NEM" [AEMO, 2021a]. AEMO uses a scenario modelling approach to outline a range of plausible development paths into the future, considering four scenarios. This report analyses the potential impact of the two most ambitions and transformational scenarios - Step Change and Hydrogen Superpower - on very high and negative spot prices in SA.

This report has three main sections and additional information, and charts are included in several appendixes. The first section provides an analysis of historical electricity price volatility in SA. The second section describes some supply and demand assumptions of the selected two scenarios that may have relevance to the question under investigation. The third section aims to assess the protentional impacts of the scenarios on negative and very high spot prices in South Australia.

Analysis of historical electricity price volatility in South Australia

RECENT ELECTRICITY MARKET DYNAMICS AND EVENTS IN SOUTH AUSTRALIA

The recent changes in the electricity market dynamics in South Australia have been overwhelming. The State is not only a leader in the NEM, demonstrating how to sustainably transform its electricity generation and electricity use but also becoming a world leader in utilizing renewable generation. This rapid transition is characterised with many developments such as high renewable generation, low underlying demand, price volatility and recent falling and even negative electricity prices.

The period of analysis in this report also includes the NEM's commencing operation in accordance with the AEMC's five-minute settlement (5-min) rule requiring AEMO to align operational dispatch and financial settlement at every five-minutes since 1 October 2021. It is important to acknowledge the underlying network constraints embedded in the Murraylink and Heywood interconnectors also influencing the regional wholesale price development which past studies in the NEM have documented (Nepal and Foster, 2016; Do, Nepal and Smyth, 2020).

Based on AEMO's reports, and especially quarterly energy dynamics reports published every three months, we summarise some recent events and developments in South Australia to illustrate this deep energy transition.

2016

28/09/2016: SA Black System cascading event: Tornados with wind speed up to 260 km/h damaged three transmission lines; nine wind farms reduced their output or disconnected from the grid due to grid instability – a generation reduction of 456 MW in less than seven seconds; the Victoria - SA Heywood interconnector tripped due to sudden increase in the imported power; the SA power system separated from the rest of the NEM; all supply to SA was lost at 4:18 pm; 850,000 customer lost power for several hours, some of them – for several days. AEMO suspended the market in SA until 11/10/2016 (AEMO, 2017).

2020

Q1: The total system cost in the NEM increased to $310 million (8% of the energy cost for the quarter). This was much higher than the usual value of 1% - 2% of a typical quarterly value. The system cost is associated with Frequency Control Ancillary Services (FCAS), directions compensation, the Reliability and emergency reserve trader function, and variable renewable energy curtailment. The system cost is recovered from generators and retailers and generators are also recipients of revenue for providing these system services. The main reason for the record system cost was 18-day separation of the South Australian and Victorian power systems after a storm damaged key transmission lines in Victoria on 31/01/2020 (AEMO, 2020_q1). SA experienced very high FCAS cost. Grid-connected batteries in SA received approximately $50 million for the provided high level of FCAS during the separation events,

Q1, 1/01/2020: New Q1 minimum demand record of 520 MW occurred in SA due to a combination of mild weather (27 °C in Adelaide), sunny conditions (high solar PV output), and low demand associated with the public holiday.

Q1: Large reduction (-266 MW) of gas-powered generation (GPG) in South Australia, its lowest Q1 average since Q1 2016.

Q2: The percentage of negative or zero spot prices in SA was 5.2% of the time in Q2. In Victoria the percentage of negative spot prices was 3.9% of the time. There was a high degree of price alignment between South Australia and Victoria with 92% of negative prices in Victoria occurring at the same time as negative prices in SA. The Heywood interconnector was non-binding 89% of the time in the quarter, contributing to this alignment. SA recorded its lowest quarterly average spot wholesale electricity price since Q1, 2015 (AEMO, 2020_q2).

Q3: Sunday, 13/09/2020, 13:00 h: New minimum operational demand record of 379 MW was set in SA. The minimum demand in SA has declined steadily since 2012 (AEMO, 2020_q3).

Q3: South Australia recorded its lowest Q3 average wholesale electricity price of $40/MWh since 2011. The September average of $15/MWh was its record monthly low. Negative spot prices in SA 10.2% of the time. In September negative spot prices in SA occurred in 22% of the trading intervals.

Q4, Sunday, 11/10/2020, 12:30 pm: New minimum demand record of 300 MW occurred at 12:30 in SA. Key drivers were low underlying demand during the weekend, sunny conditions and estimated 992 MW provided by distributed solar PV output. During this time interval aggregated solar generation (from distributed PV and utility solar) was equivalent to 100% of SA's underlying demand for the first time on record. This was also world-first record for a jurisdiction of its size (AEMO, 2020_q4).

Q4, 2020: South Australia becoming the lowest price region in the NEM for the first time since 2012. The quarterly average price was $29/MWh. The quarterly average operational demand in SA of 1,213 MW was the lowest quarterly average since the start of the NEM. In SA wind generation set the spot price for 8% of the time in the quarter at an average of minus $75/MWh, predominantly during the day (9:00 – 15:00). Spot prices in SA were negative 17% of the time during that quarter, representing a new record. Key drivers for negative prices included low operational demand, high renewable generation and interconnector constraints. Volume weighted prices (VWAP) in SA had a large decrease of 65% (in comparison to Q4 2019) falling to $21/MWh and the VWAP for solar farms was $17/MWh (AEMO, 2021). The cost of directing gas-fuelled generating units in SA to maintain system security increased to a near record high of $16 million and the time on direction reach a record quarterly high of 64% (AEMO, 2020_q4).

Q4, 2020: Operated by AGL SA Generation Pty Ltd, the gas-based Torrens Island Power Station decommissioned two Torrens Island A units (120 MW each) in September 2020.

2021

Q1, 2021: The average spot price during peak solar production time (10:00 – 15:30) was negative $12/MWh in SA. This is the first quarter for any region in the NEM, when daytime average has fallen consistently below $0/MWh. AEMO directed Gas Powered Generators (GPG) for system security for a record 70% of the quarter due to persistently low electricity prices. South Australia became the lowest priced region in the NEM on a futures basis (Call 2022 swap contracts). Substantial increase in re-bidding by wind and solar farms using automated bidding software in order to reduce the risk to be dispatched at negative prices (AEMO, 2021_q1).

Q1, 12/03/2021: A major price volatility in SA due to outages in gas-powered generation, restricted import from Victoria and low renewable generation. The daily average price was $1,335/MWh.

Q1, Sunday, 14/03/2021 at 14:30: New record for SA half-hour Q1 minimum operational demand of 358 MW – just slightly above the 300 MW all-time record from October 2020. Due to a credible risk of separation, approximately 71 MW of residential and non-residential solar PV was curtailed, including 14 MW of residential PV under SA Government's Smarter Homes' initiative.

Q2, Monday, 26/04/2021, 13:30: new Q2 minimum demand of 523 MW. Several conditions contributed to the record: sunny and mild weather, low demand on the ANZAC day holiday and distributed solar PV providing 833 MW output (61% of underlying demand) (AEMO, 2021_q2).

Q2, April 2021: Wind output in SA declined to 594 MW, mainly due to very low wind speeds in April. The wind capacity factor during April was only 21%, the lowest in comparison to April 2019 (31%) and April 2020 (29%).

Q3, 22/07/2021: Maximum demand of 2,628 MW a new Q3 and winter record in South Australia (AEMO, 2021_q3).

Q3, 26/09/2021, 14:00h: Minimum demand record of 236 MW in SA. Distributed PV providing appx. 1,131 MW of generation, 83% of underlying demand.

Q3: Negative spot prices in South Australia reached 25% of the time. The negative prices were not so negative – 78% of them occurred in the interval $0/MWh and -$50/MWh. The negative prices in SA reduced the average spot price by $10.20/MWh. Gas-power generation in SA declined by 614 MW on average.

Q3: AEMO continued directing GPGs to generate and maintain system security. The total cost of the directions was $24 million, a record for the region. Key driver of increased time on direction was the reduction of the spot price, influenced by high wind output, low operational demand, and high gas prices, which led to gas generators decommitting from the market due to high running cost. The system strength curtailment of VRE in SA was substantial – 62 MW.

Q4, 14/11/2021: VRE curtailment in SA reached 1,307 MW at 13:55, which was 75% of potential semi-scheduled output in the region. The spot price in SA at that time was well below -$100/MWh. A record VCE curtailment in Victoria approximately at the same time (13:35), reaching 71% of potential output (AEMO, 2021_q4).

Q4, Sunday, 21/11/2021 at 13:00: New record for SA half-hour minimum operational demand of 104 MW, due mild sunny conditions, low weekend demand, reduced industrial load and increased distributed solar PV output (Figure 7, AEMO, 2022).

Q4, 14/12/2021: Stage 2 of Lincoln Gap Wind Farm (24 turbines of the 86MW) commenced generation into the national grid. Stage 2 is forecast to achieve full commercial operation in March 2022 (AEMO, 2022; http://lincolngapwindfarm.com.au/).

Q4, 2021: During this quarter AEMO continued to issue directions to gas generators in SA to maintain system security in the region. For Q4, SA generators time on directions reached 86%, the highest quarterly level on record with a total of 131 directions made (AEMO, 2022). The cost of these directions increased to $34 million ($16 million in Q4, 2020). With low spot prices in SA and high gas prices, SA gas generators avoided generation for economic reasons, so generation output under direction increased.

Q4, 2021: Negative spot prices set a record in SA reaching 28% of the time during the quarter. The reasons included: reduced daytime demand, due to mild weather conditions and high distributed PV output. While the frequency of negative prices increased in SA, approximately 40% of these negative prices were in -$50-$35/MWh price band (not so negative as before the introduction of the 5-min settlement) related to change in VRE bidding behaviour.

Q4, November 2021: Successful testing and commissioning of four synchronous condensers in SA, which allows to operate the grid with reduced number of synchronous generators (at least two gas generators in SA) and leading to lower system strength curtailment.

WHOLESALE SPOT PRICE BANDS IN SOUTH AUSTRALIA

The following section contains charts with monthly spot electricity data in SA for the last seven calendar years – 2015-2021 (see Figure 1 - Figure 3). The price data is extracted from aggregated price and demand data published by AEMO on a regular basis since the beginning of the NEM in December 1998.

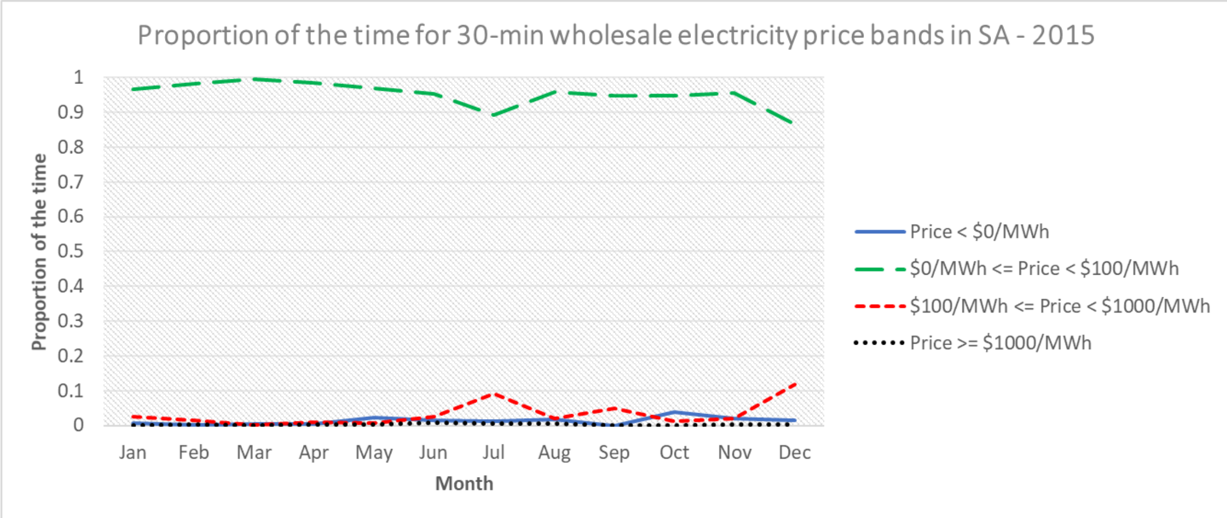
Four price bands are specified according to the following price intervals:

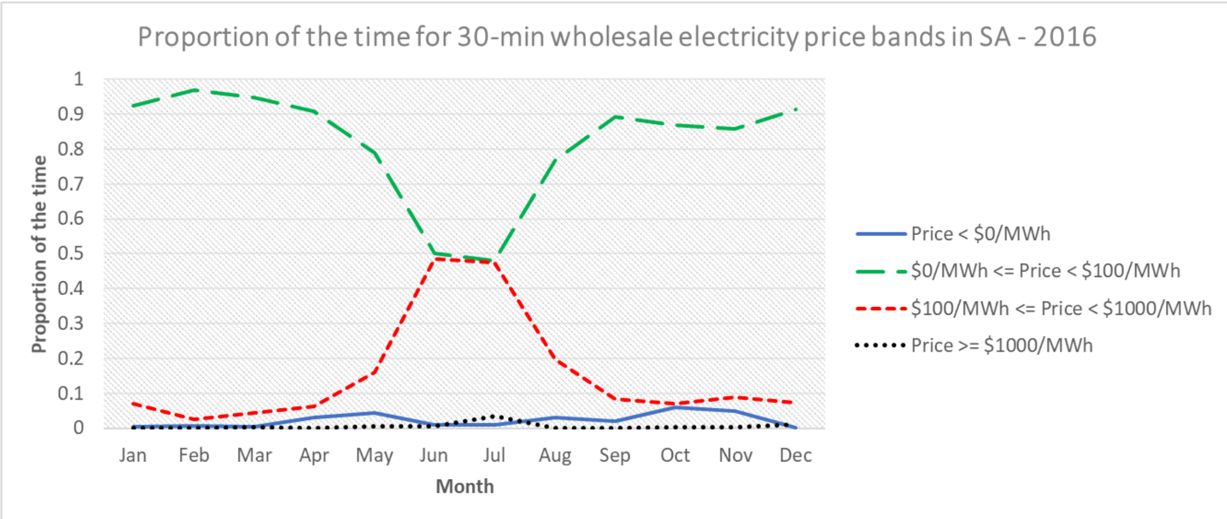
- P1: Regional reference price (RRP) < $0/MWh
- P2: $0/MWh <= RRP < $100/MWh
- P3: $100/MWh <= RRP < $1,000/MWh
- P4: $1,000/MWh <= RRP

For each price band the number of instances of 30-min price data within a given month are counted and then the proportion of prices for each band is calculated. The last three months of 2021 contain 5-min demand and price data due to the introduction of 5-min settlement procedure by AEMO. For these three months (October, November, and December 2021) 30-min average price data is calculated for six 5-min intervals.

The following observations from the charts in Figure 1, Figure 2 and Figure 3 can be listed here:

1. The prices in P2 (more or less “normal” prices between $0/MWh and $100/MWh) are dominant for 2015.
2. From 2016 to 2020 the price bands P2 and P3 are dominant and inverted to each other, for example when the frequency of prices in P2 drops, the frequency in P3 grows with a similar number. In 2021 negative prices (in P1) become more substantial and start to play this “complementary” role to prices in P2.
3. The frequency of negative prices (P1) for the years 2015-2018 were very low (one or two percent) and approaching 5% only in 3-4 months for the whole four-year period. The frequency of negative prices starts to grow from the middle of 2019 and exceeds 37% for September and October in 2021.
4. The frequency of very high prices (P4, >= $1,000/MWh) is in the range of 0.1% - 0.5% on average. This frequency was a bit higher in 2015 and 2016 (in comparison with the following years), exceeding 3.5% for July 2016.





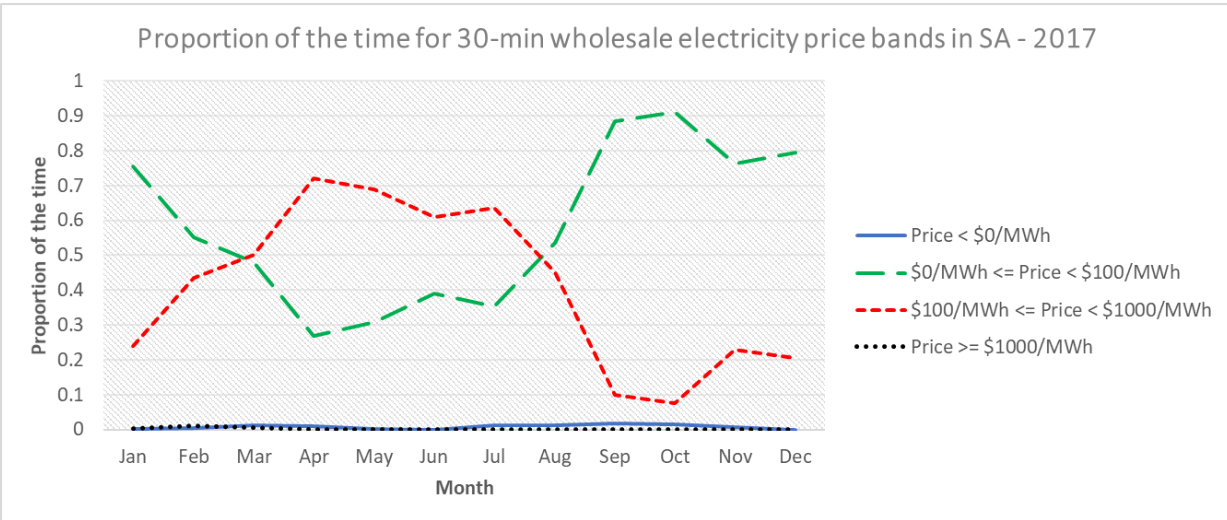
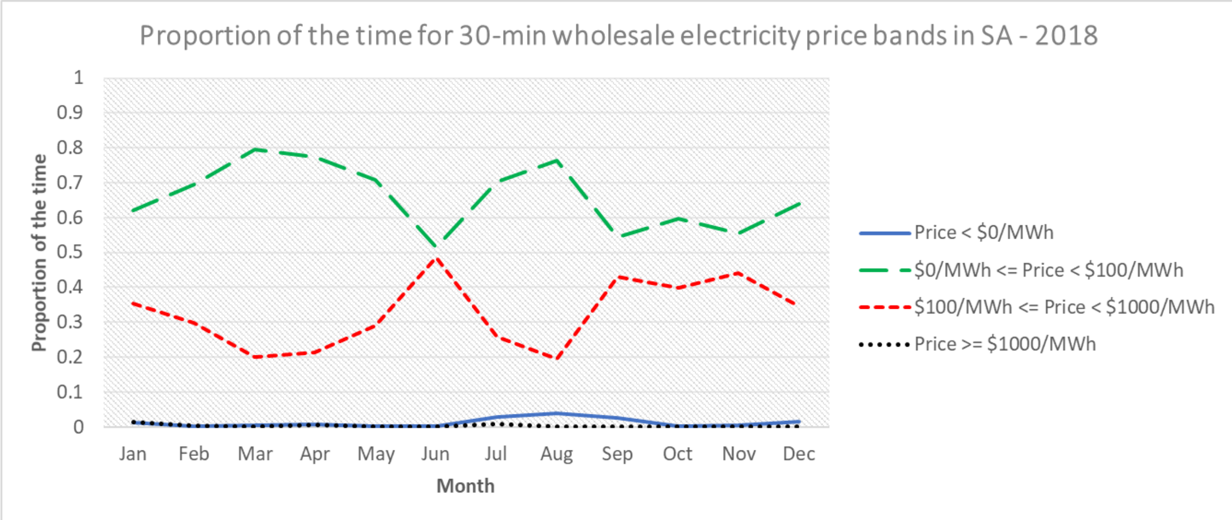
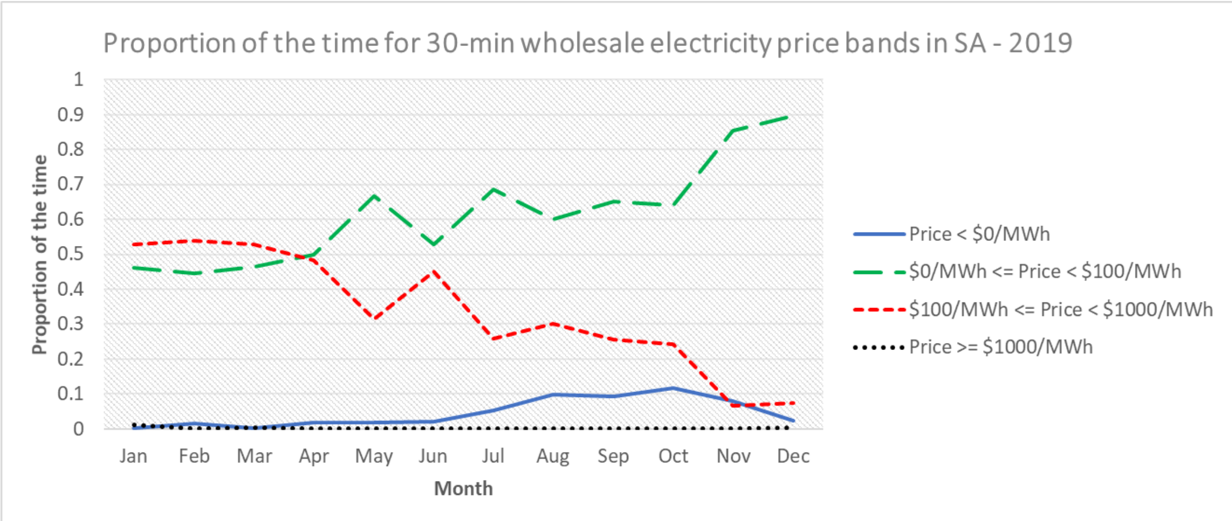


Figure 1. Proportion of time for 30-min wholesale spot price bands in SA: 2015, 2016 and 2017 (monthly data)





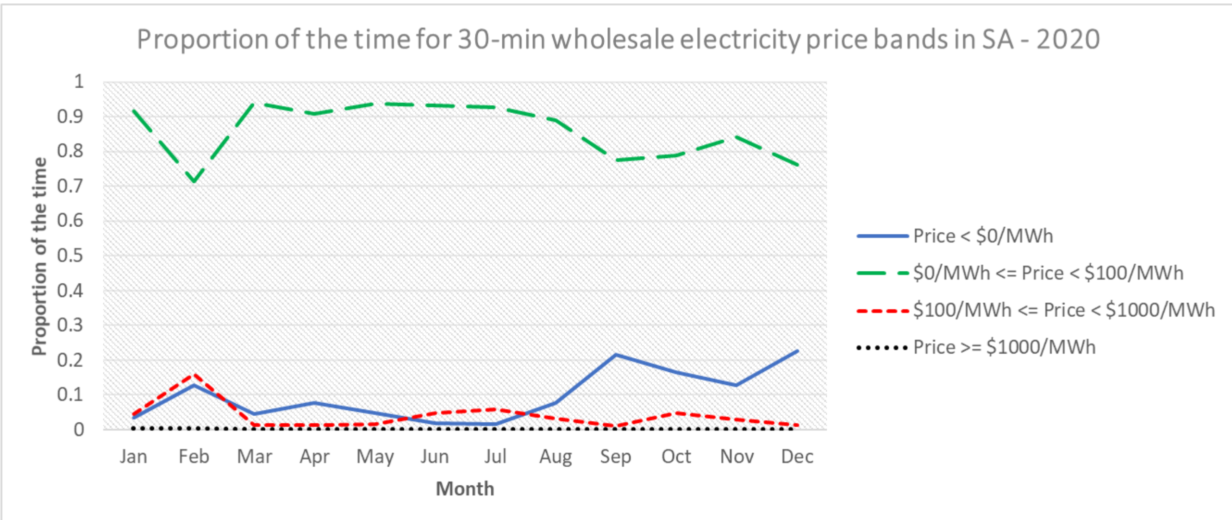


Figure 2. Proportion of time for 30-min wholesale spot price bands in SA: 2018, 2019 and 2020 (monthly data)

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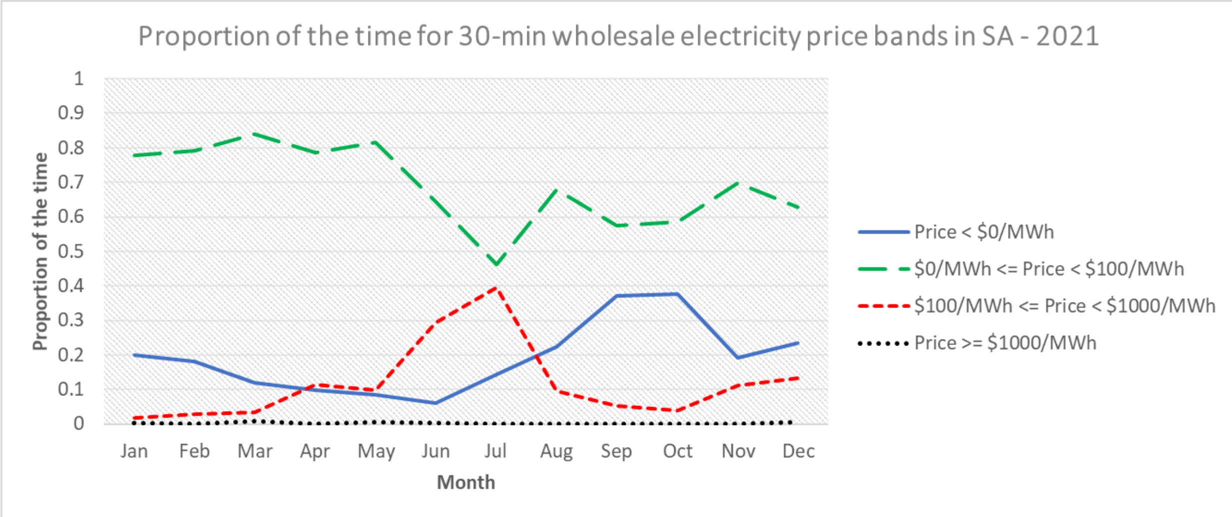

Figure 3. Proportion of time for 30-min wholesale spot price bands in SA: 2021 (monthly data)

DAILY FREQUENCY OF SPOT PRICES IN SOUTH AUSTRALIA

It is essential to understand the time distribution of negative and other price bands in South Australia. Figure 4 presents the daily frequency of negative spot prices in SA for the period October – December 2021. This is the first quarter in which the NEM operated with the 5-minute settlement rule. The frequency of negative spot prices in Figure 4 is based on 5-minute intervals. The most likely periods with negative spot prices are during peak solar production time (10:00 – 15:30), when distributed solar PV and utility-scale solar generate significant power reducing operational demand. The next likely period with negative prices is during the off-peak, early in the morning (3:00 am - 4:00 am), when the operational demand is very low and when there are good conditions for wind generation.

The frequency of negative spot prices has increased substantially in the last several years in all regions of the NEM with biggest increases in the southern regions of South Australia, Victoria, and Tasmania. Key drivers for negative prices included low operational demand, due to mild weather conditions, high renewable generation and interconnector constraints preventing export of excess generation.

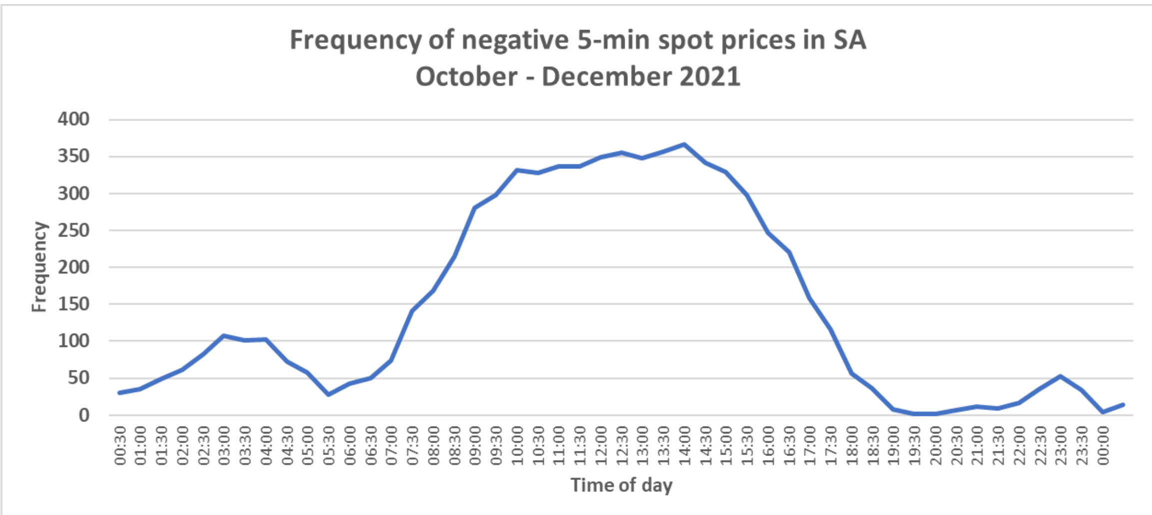

Figure 4. Daily frequency of negative spot prices in South Australia based on 5-min settlement periods, October-December 2021

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Daily frequencies for the studied price bands P1-P4 are shown in Figure 5 and Figure 6 for 2019 and 2020. These are 30-min average spot prices. 2019 is a pre-COVID-19 pandemic year and 2020 is perhaps most impacted by the pandemic. We can see very different daily patterns in these two neighbouring years. For both years the price band P2 ($0/MWh <= RRP < $100/MWh) is dominant and expected most of the time. In 2019 the price band P3 ($100/MWh <= RRP < $1000/MWh) is very complementary to P2, it is significant during the morning and evening peak and dominating during the evening peak. In 2020 P3 is very suppressed, with some distinctions during the morning and evening peak, however, at much lower values than in 2019. The frequency of negative spot prices (P1) in 2020 is higher than in 2019, with the peaks nearly double the peaks from 2019. P1 was the second dominant price band in 2020, complementing P2 for most of the time, except for the evening peak, when P3 was noticeable.

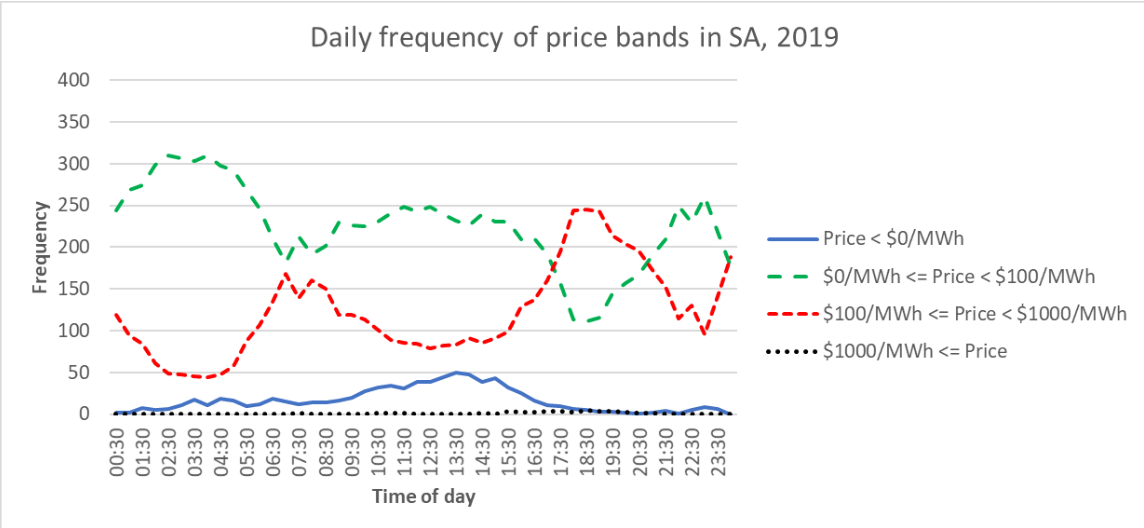

Figure 5. Daily frequency of 30-min wholesale spot price bands in South Australia, 2019

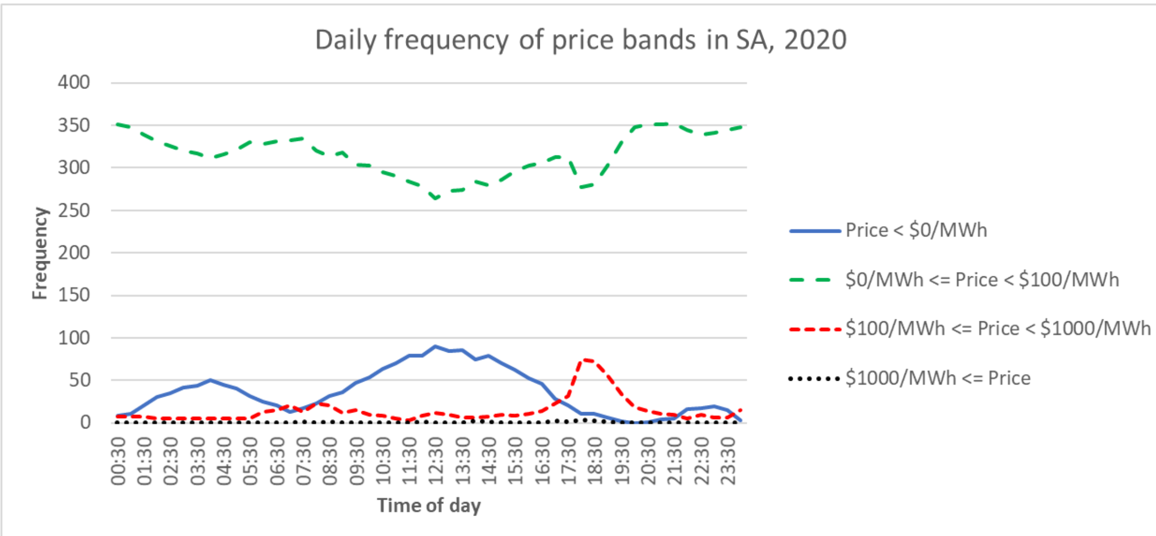

Figure 6. Daily frequency of 30-min wholesale spot price bands in South Australia, 2020

SPOT PRICE AND DEMAND

Figure 7 presents a relationship between spot price bands and operational demand in South Australia for 2019. While the different y-axis scales for each price band on this Figure distort the overall picture, it is clear that higher prices are more likely to happen when the operational demand is higher.

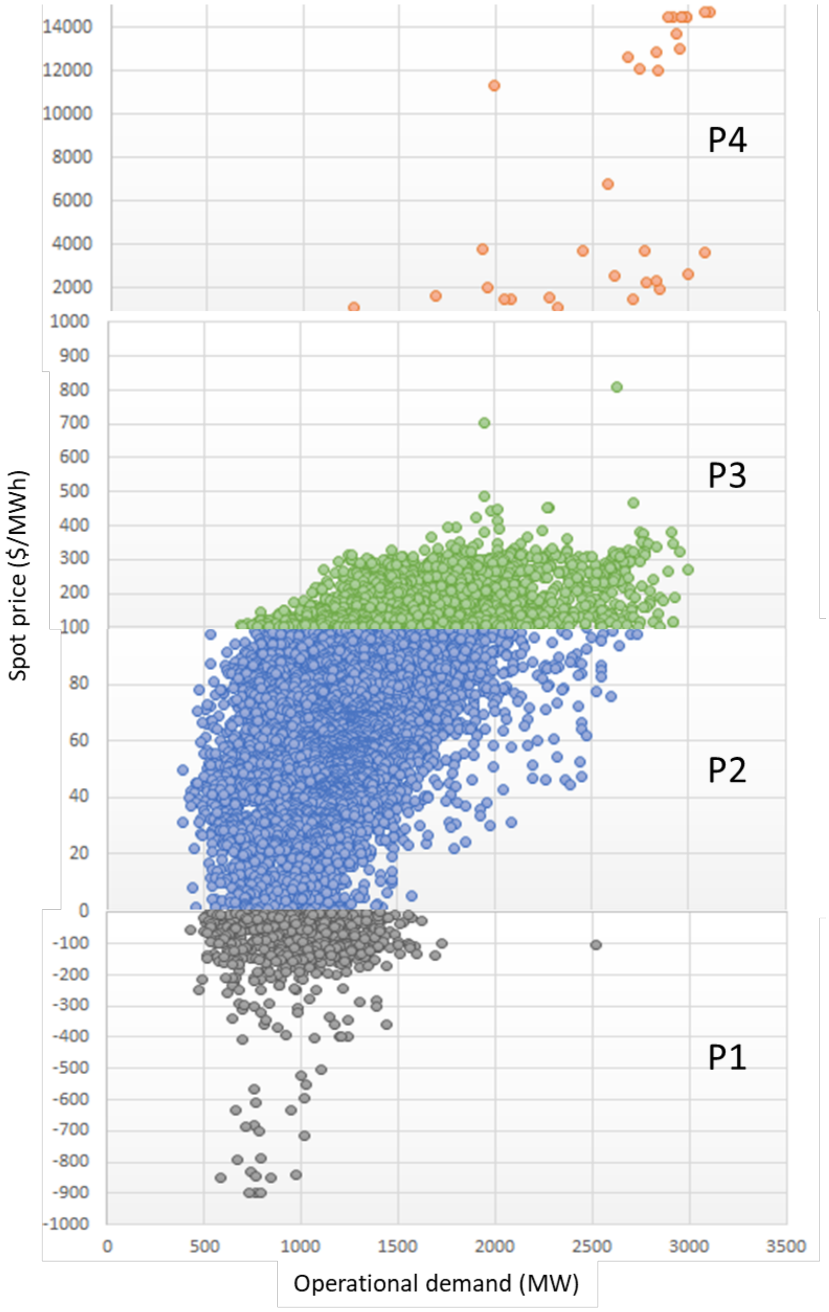

Figure 7. 30-min wholesale spot price dependence on 30-min operational demand in SA, 2019[1]

[1] Please note that the y-axis scales are different for each price band

WHOLESALE SPOT PRICE BANDS IN THE REGIONS OF THE NEM

Appendix B (see Figure 15 and Figure 16) includes several charts with proportion of time for 30-min wholesale spot price bands in the regions of the NEM – Queensland, New South Wales, Victoria, South Australia, and Tasmania. The data is for recent years – 2019 (before the COVID-19 pandemic) and 2021 (the second year of the pandemic). Each chart compares regional proportions for a specified price band P1 – P4 as described in the previous section.

The following observations from the charts in Figure 15 and Figure 16 can be listed here:

1. The dominant wholesale electricity prices in SA and Victoria ($0/MWh - $100/MWh) were closely aligned for most of the time in 2019 (see Figure 8). This indicates that the interconnectors Vic – SA were not congested most of the time this year.
2. Price separation between Northern regions (Queensland and NSW) and Southern regions (Victoria and SA) can well be observed for both 2019 and 2021 for prices in the band $0/MWh - $100/MWh (see Figure 8 and Figure 16). The spot prices in Tasmania transitioned between the prices in these two groups, being closer to prices in Queensland and NSW during the winter of 2021 and for the rest of the time – closer to prices in Victoria and SA (see Figure 8). Most likely this behaviour of Tasmanian spot prices is related to specifics of hydro generation, dominant in the region. The dependence price structure of the southern regions of the NEM (South Australia, Victoria, and Tasmania) is closely related to their geographical co-location and the performance of the transmission interconnections (Apergis, 2020).
3. The frequencies of negative spot prices in SA, Victoria, and Tasmania in 2021 were similar, except for summer, when the frequency of negative prices in Tasmania was significantly lower (see Figure 9). The frequency of negative prices was higher in SA and Victoria in comparison with the Northern regions – Queensland and NSW. As negative prices are frequently associated with more VRE available, which for wind and solar generation is dependent on the weather, it could be proposed that the weather patterns (wind speed and solar irradiation) in these three regions are somewhat correlated. This hypothesis needs further investigation as South Australia, Victoria and Tasmania are well connected by three transmission interconnectors and in Tasmania hydro generation historically is lower in summer than the rest of the year.
4. The frequency of very high spot prices (>= $1000/MWh) in 2019 was much higher during the summer months, while in 2021 it was the opposite – the frequencies were higher in the winter months. There were at least two differences between 2019 and 2021 – 2021 was impacted by the COVID-19 pandemic and 2021 was a mild year. At the same time, very high spot prices may start to occur in periods of low supply due to low solar PV generation (as in winter), instead of high demand due to use of air-conditioning in hot days (as in summer).

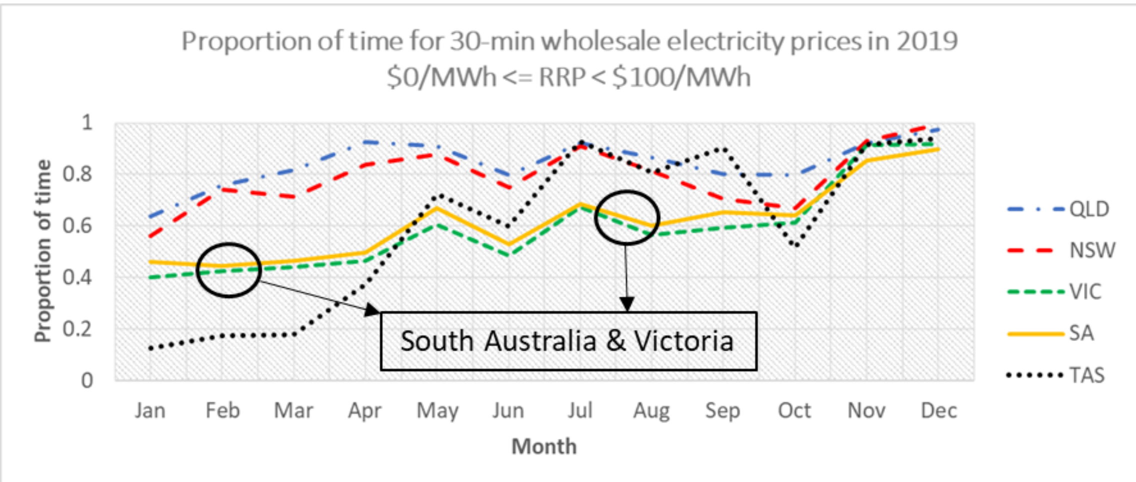

Figure 8. Proportion of time for 30-min wholesale electricity prices in the range $0/MWh - $100/MWh in the regions of the NEM in 2019

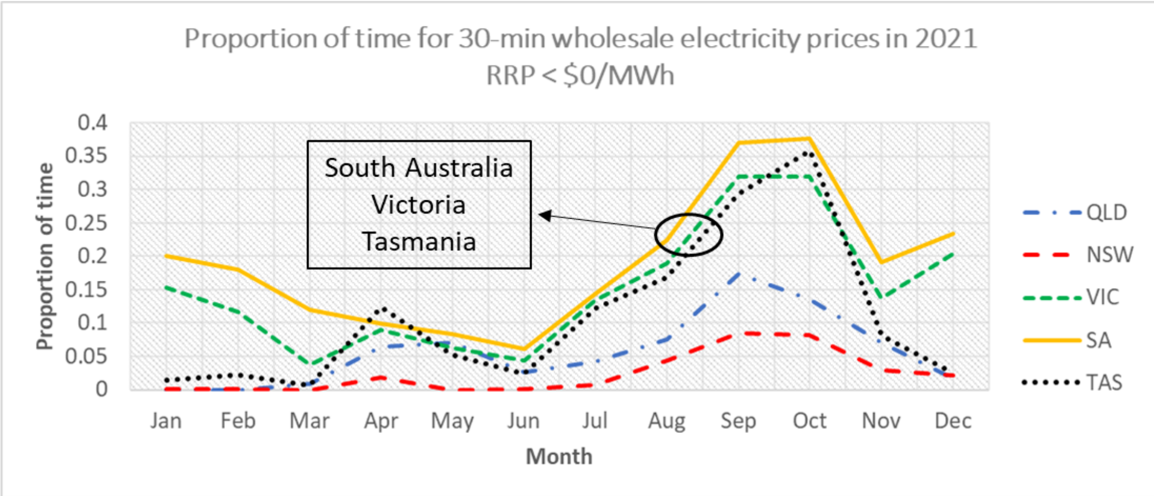

Figure 9. Proportion of time for 30-min negative wholesale electricity prices in the regions of the NEM in 2021

Assumptions and development paths for SA according to the AEMO Draft 2022 Integrated System Plan (ISP) description of the Step Change and Hydrogen Superpower scenarios

In December 2021 AEMO published its document "Draft 2022 Integrated System Plan for the NEM" [AEMO, 2021a]. The final version of the document is intended to be published in the middle of 2022 after completing an extensive consultation with energy stakeholders. The Integrated System Plan (ISP) is one of the main AEMO's planning publications for the NEM. It aims to describe an optimal development path for the NEM for 20 years into the future and to inform all relevant energy stakeholders. The ISP document is updated every two years.

AEMO uses a scenario modelling approach to outline a range of plausible development paths into the future. The Draft 2022 ISP considers four scenarios for the power system transformation [AEMO, 2021a]:

- *Slow Change* (slow economic recovery, continued PV uptake by households)
- *Progressive Change* (to meet the national emission goals)
- *Step Change* (with a focus on energy efficiency, DER, digital energy, and step changes in global policy)
- *Hydrogen Superpower* (with a focus on Australian competitive advantage to export hydrogen)

The four scenarios span a range of electricity demand and decarbonisation as shown in Figure 10. The scale of electricity demand is affected by the magnitude to which other sectors electrify and the scale of decentralisation is affected by the magnitude to which consumers (households and businesses) produce and manage their own electricity instead of importing from the electricity grid. The analysis in this report is relevant to the two most ambitions and transformational scenarios, depicted with the green colour:

- *Step Change*
- *Hydrogen Superpower*

Table 1 and Table 2 summarise energy resource use indicators for the selected two scenarios by 2030 and 2040 respectively [AEMO, 2021b; AEMO, 2021c]. Some data for 2030 indicators was not available in these reports and was estimated assuming that the developments from 2020 to 2040 are not linear but accelerating with time to a degree.

Table 3 provides several important generation capacity related indicators for the two scenarios under consideration.

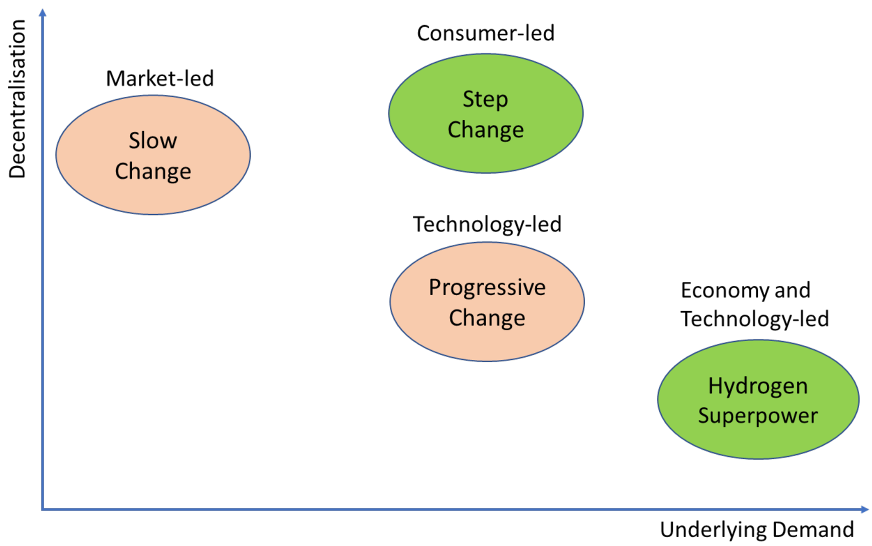

Figure 10. Scenarios used in the 2022 Draft ISP

Table 1. Development indicators for the Step Change and Hydrogen Superpower scenarios by 2030

Indicators by 2030	Step Change Scenario	Hydrogen Superpower Scenario
Transforming agents	Consumers	Goverments, Companies, Research and Development
Electricity use	Relatively large use of electricity, generated with near zero carbon emissions	Relatively large use of electricity, generated with near zero carbon emissions
Rooftop solar capacity	Extra 160% increase from 2020; Extra 120% of households with rooftop solar in comparison with 2020	Extra 200% increase from 2020
Household use of gas	34% of 2020	36% of 2020
Household use of hydrogen	Not substantial	22% of the necessary heating and cooking energy
Industry use of gas	8% less than in 2020	26% less than in 2020
Industry use of coal	12% less than in 2020	Not specified, assumed at least 12% less than in 2020
Industry use of oil	36% less than in 2020	Not specified, assumed at least 36% less than in 2020
Industry use of hydrogen	Some	Over 13% of industry use of gas in 2020 shifting to hydrogen
Percentage of electric cars	Almost 24%	Almost 30%
Heavy vehicles fuelled by hydrogen	Almost 13%	Almost 20%
Hydrogen export	None	About 20% of Australia's LNG export in 2020

Table 2. Development indicators for the Step Change and Hydrogen Superpower scenarios by 2040

Indicators by 2040	Step Change Scenario	Hydrogen Superpower Scenario
Transforming agents	Consumers	Goverments, Companies, Research and Development
Electricity use	Wide use of electricity, generated with near zero carbon emissions	Wide use of electricity, generated with near zero carbon emissions
Rooftop solar capacity	Extra 400% increase from 2020; Extra 300% of households with rooftop solar	Extra 500% increase from 2020
Household use of gas	15% of 2020	10% of 2020
Household use of hydrogen	Not substantial	54% of the necessary heating and cooking energy
Industry use of gas	20% less than in 2020	65% less than in 2020
Industry use of coal	30% less than in 2020	Not specified, assumed at least 30% less than in 2020
Industry use of oil	90% less than in 2020	Not specified, assumed at least 90% less than in 2020
Industry use of hydrogen	Some	Over 33% of industry use of gas in 2020 shifting to hydrogen
Percentage of electric cars	Almost 60%	Almost 75%
Heavy vehicles fuelled by hydrogen	Almost 33%	Almost 50%
Hydrogen export	None	About half of Australia's LNG export in 2020

Table 3. Supply-related indicators of the Step Change and the Hydrogen Superpower scenarios

Indicator	Region	Step Change Scenario				Hydrogen Superpower Scenario			
SUPPLY [MW]		2023-24	2029-30	2039-40	2049-50	2023-24	2029-30	2039-40	2049-50
Mid-merit gas	SA	1,329	1,329	0	0	1,329	529	0	0
Peaking Gas+Liquids	SA	1,584	1,584	927	435	1,584	1,584	1,983	3,037
Utility-scale storage	SA	473	473	829	1,355	473	702	1,283	15,137
Coordinated distributed storage	SA	89	397	1,649	2,891	103	540	2,330	3,758
Distributed storage	SA	213	551	1,392	1,373	235	659	1,689	1,548
Wind	SA	2,342	4,265	5,707	8,575	2,342	8,125	22,677	55,636
Utility-scale solar	SA	566	566	2,361	7,226	566	3,321	18,625	69,164
Distributed PV	SA	2,721	3,959	5,743	7,145	2,947	4,657	6,996	8,811

UNIVERSITY OF WOLLONGONG AUSTRALIA

Analysis of scenario impact on future electricity prices in South Australia

Many simulation and optimization models have been created to address the complexities of electricity market studies. Widely used parameter-rich models aim to cope with technical, economic, and environmental aspects of these models (Beran, 2019; Grozev, 2005; Batten, 2006). Many of these types of models have evolved to cope with increasing complexities of renewable generation and different policies as well. However, the operation of these types of models required a substantial amount of effort, rich amount of input data and it is susceptible to errors in data processing, and it may deliver biased results if input data is inaccurate (Beran, 2019). Testing of simulation and optimization models is a real challenge, frequently avoided, because of the substantial effort required.

As developing or utilising a full-scale simulation or optimization model is outside of the scope of this research, for the purposes of this report only a very basic, structural modelling approach is followed, analysing the impacts of both supply and demand influencing factors on negative or very high spot electricity prices. It is coupled well with the "What-if" scenario modelling approach for long future periods when there are many uncertainties to consider.

BRIEF DESCRIPTION OF IMPORTANT INFLUENCING FACTORS OF ELECTRICITY PRICE VOLATILITY IN SOUTH AUSTRALIA

The special nature of electricity markets is the necessity to balance instantaneously (in very short periods of time) electricity demand with electricity supply. In the NEM this balancing function is supported by a gross-pool spot market where cheaper offers from generators are dispatch first according to varying demand and subject to technical and security constraints. The wholesale spot electricity prices are results from a dispatch algorithm that runs every 5 minutes. For every dispatch interval, supply (an aggregation of outputs from different generators), demand (an aggregation of different consumers' loads) and variety of market rules have influences which ultimately define the wholesale spot price. These are the three main groups of influencing factors considered in this report to evaluate their impact on negative and very high spot prices (see Figure 11 and Figure 12):

- Supply-related influencing factors
- Demand-related influencing factors
- Market rules and procedures.

The market rules and procedures do not directly impact the electricity prices, except for some administrative price provisions and price modifiers. The Administrative Price Cap (APC) and Administrative Floor Price (AFP), for example, are invoked to limit the spot price after a period of sustained high prices. For the purposes of this report, we assume that the market rules and procedures affect the wholesale electricity prices through the dispatch process (see Figure 11 and Figure 12).

The dispatch process may restrict or modify supply or demand due to different reasons. For example, Wholesale Demand Response Mechanism (WDRM) allows consumers to participate in the wholesale electricity market, reducing their demand during high electricity prices and electricity supply scarcity (AEMO, 2020a). Demand Response Service Providers (DRSP) must register as market participants, and they can offer aggregated demand capability through the standard bidding and scheduling operations of the NEM. In Figure 11 and Figure 12 there is an arrow from the "Dispatch & Pre-dispatch" box leading to the "Demand" box to account for demand response. The demand response mechanism usually reduces the demand, and it is depicted with a minus sign next to the arrow in these charts.

Another example for the Dispatch modifying the Supply is VRE curtailment. The dispatch algorithm may restrict the output from semi-scheduled renewable generators in order to maintain system security. Additionally, ElectraNet, the transmission operator in South Australia, can reduce the output of small solar PV installations to maintain minimum demand for system security, based on SA's "Smarter Homes" program (AEMO, 2021d). In 2020, the South Australian Government established this program setting new requirements for small business and residential solar PV installations. This required that consumers with new or upgraded rooftop solar PV system allow a remote-control functionality to curtail generation in rare events threatening the security of the NEM. On 11/10/2020 ElectraNet curtailed 10 MW power from small PV installations for the first time to maintain minimum demand in SA.

The impact of growing supply is positive in terms of creating more favourable market conditions for negative spot prices as it increases the available generation capacity. This is depicted with the '+' symbol next to the linking arrow in Figure 11. Vice versa - for the very high spot prices this impact of growing supply is negative as it mitigates conditions for high prices. This is depicted with the '+' symbol next to the linking arrow in Figure 12.

When demand is growing this creates less favourable conditions for negative prices and more favourable conditions for very high prices (see Figure 11 and Figure 12).

Electricity markets are complex adaptive systems in which market participants adapt their decision making based on feedback from the market, learning from their own interactions with the market as well as from competitors' activities. Price volatility is just one of many aspects of these complex adaptive systems. Usually, every market condition for unusually high or low prices is created based on many influencing factors.

Supply-related influencing factors

Supply-related influencing factors on volatile electricity prices can be grouped in several clusters – generation, transmission, weather & climate, market rules and procedures. They include (but not limited to) the following factors, which can overlap:

- Wind generation
- Utility-scale solar
- Distributed solar PV
- Gas generation (peaking and mid-merit)
- Storage (utility-scale, distributed, coordinated distributed)
- Firming capacity
- Low renewable generation (wind and solar)
- Fast changes in supply
- Generation plant outages (specifically unplanned but also planned; partial and full)
- New or upgraded transmission links
- Transmission outages, congested interconnectors, and other transmission links
- Weather, extreme weather, seasons, climate change
- Security constraints imposed on generators
- Security constraints imposed on interconnectors
- VRE curtailment
- Wind and solar generation forecasting
- New energy services
- Bidding and rebidding (economic withholding)

Demand-related influencing factors

Demand-related influencing factors on volatile electricity prices can also be grouped in several clusters – loads, weather & climate, market rules and procedures. They include (but not limited to) the following factors, which can overlap:

- Residential use of electricity
- Commercial use of electricity
- Industrial use of electricity
- Charging electric vehicles
- Level of household use of gas
- Level of industry use of gas
- Hydrogen production and use
- Energy efficiency
- Demand-side participation
- Demand forecasting inaccuracies
- Weather (temperature, humidity, wind speed, solar radiation)
- Extreme weather, seasons, climate change
- Time of the day
- Day of the week

Here we comment only on a few of these demand- or supply-changing factors with greater impact on spot prices in the context of South Australia.

Weather (season, temperature, humidity, wind speed, solar radiation)

> A large amount of the variability of electricity demand is dependent on the weather [Thatcher, 2007]. It is well understood that the electricity demand patterns vary significantly with seasons, mainly dependent on temperature and humidity, but also influenced by the wind speed and the solar radiation. These variations are associated with energy required for heating or cooling in buildings. At high temperatures, as it happens in South Australia and most other places in Australia during summer, electricity demand usually grows due to wide use of air conditioning. At low temperatures, such as in winter, the electricity demand starts to grow as well, as more heating appliances are switched on. At pleasant temperatures, say around 18 °C, but dependent on location, season, etc., the electricity demand associated with heating and cooling trends to a minimum as no heating or cooling devices are used by residents and businesses.
>
> Heatwaves significantly affect peak electricity demand [Burillo, 2017]. They are low-probability but high-impact events in many Australian cities and in particular in Adelaide and Melbourne. During several extremely hot days the heat accumulates in the building materials and the heat stress of population grows as well. Heatwaves usually lead to very high electricity demand due to wide-ranging use of air conditioning. Cold spells of several days may impact electricity demand as well, however, low temperatures in Australia are not so likely and critical and while have an impact on electricity demand it is not so big as during the heatwaves.

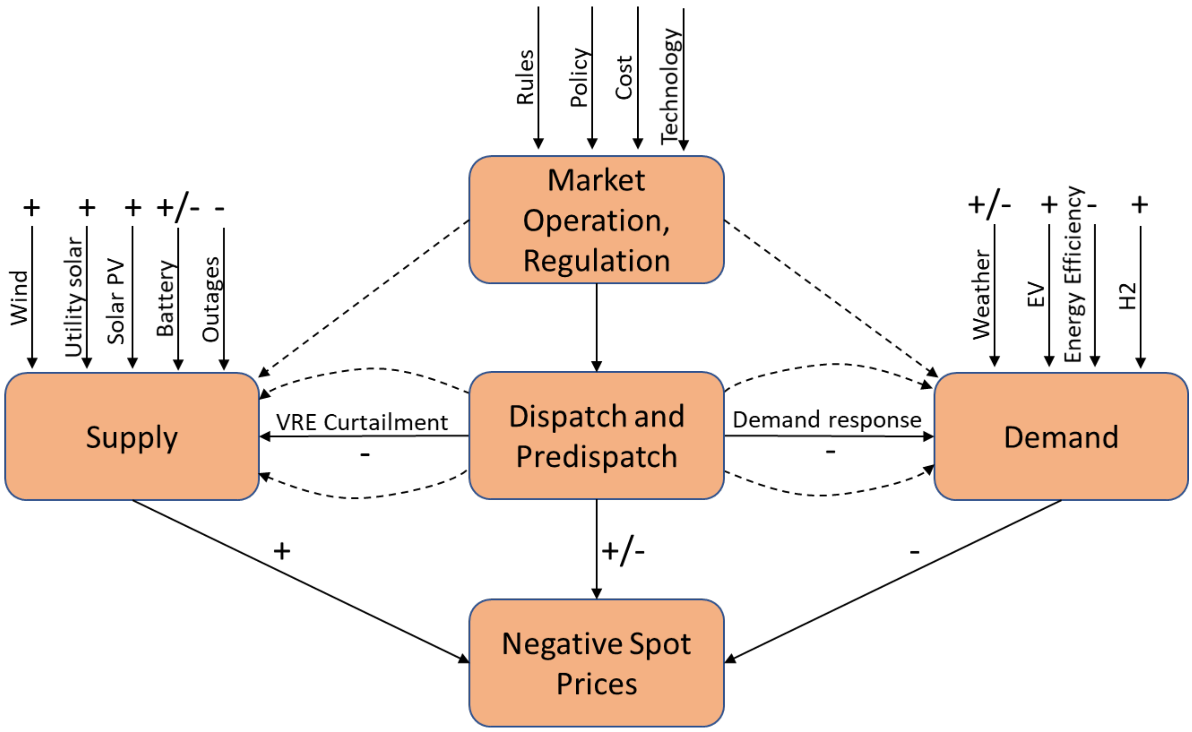

Figure 11. Summary of influencing factors on negative spot prices

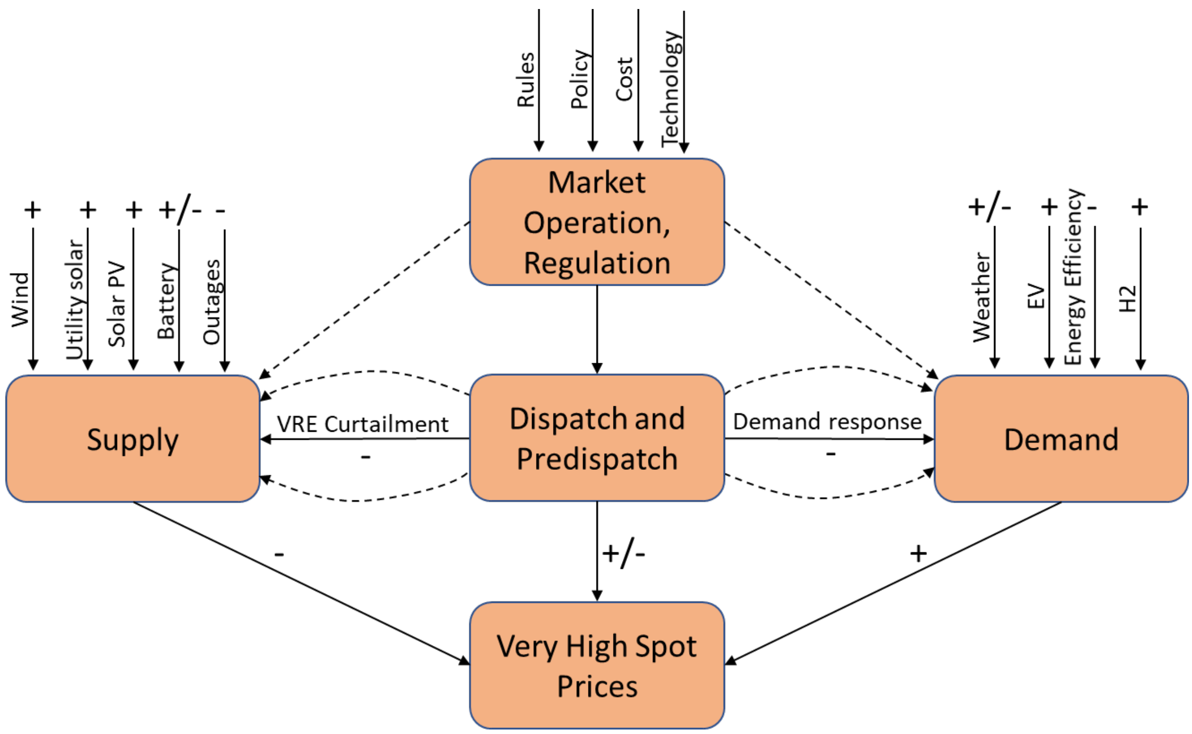

Figure 12. Summary of influencing factors on very high spot prices

ASSESSMENT OF POTENTIAL SCENARIO IMPACT ON NEGATIVE SPOT PRICES IN SOUTH AUSTRALIA

As depicted in Figure 11, both electricity supply and demand together may create conditions for negative spot prices. When supply is growing, more favourable conditions for negative prices are created because more generation capacity is available to satisfy demand, which leads to dispatching of cheaper generation offers. For some dispatch periods the price-setting generation quantity may have a negative price and it defines a negative regional price. Every influencing factor that helps to increase the electricity supply will create more favourable conditions towards negative prices or having a “positive” potential impact on likelihood of negative prices. For example, more wind generation, more utility-scale solar PV generation, or battery discharging – all help to increase available supply and may help in creating conditions for negative prices. On the other hand, if there are more planned or unplanned outages of generators or transmission links, they will reduce the available supply and will create less favourable conditions for negative prices. For demand-related influencing factors the logic is reversed – if demand is increased, less favourable conditions for negative spot prices are created and the potential impact is “negative”; if demand is decreased – more favourable conditions are created.

Table 5 and Table 7 list a variety of influencing factors for negative spot prices for Step Change and Hydrogen Superpower. The supply-related influencing factor has the symbol ‘↑’ in the column “Currently/2021” if it increases supply and the symbol ‘↓’ if it decreases supply. For demand-related factors it is the opposite.

Every upward or downward arrow (‘↑’ or ‘↓’) in this assessment is considered to have approximately equal weight on the outcome for negative prices. Of course, this is a strong assumption as we know that some influences are more important than others when creating conditions for negative prices. At the same time, it is very difficult to quantify the contribution of each factor without applying complex statistical methods such as principal component analysis, Bayesian networks, etc. Even if we established the weights of these influencing factors for a past period, there is no guarantee that the same will be true in the future transformation of the energy system, under many new conditions.

The percentage of positive and negative influencing factor for the current period (2021) is calculated based on the number of upward and downward arrows and it is shown at the bottom of each column with arrows (see Table 5 and Table 7).

The next step is to estimate “the number of arrows” for 2030 and 2040 for each influencing factor, based on information provided in the scenario description. For example, if the wind generation capacity in SA is expected to double by 2030 in comparison with the current capacity (2021), we put two arrows in the column for 2030. The changes are approximate and not always linear. Some effort is taken not to overblow a growth of a factor when starting from a very low initial position. Once all arrows for 2030 and 2040 are estimated, the next step is to calculate the percentage of upward and downward arrows to evaluate how the balance of “positive” and “negative” influences will potentially change into the future. The last step is to estimate relative changes for each scenario in comparison with the current situation. For example, in Table 5 the percentage of 37.50% for positive impacts on current negative prices in 2021 is accepted as an index of value 1.0 and the changes for 2030 and 2040 are calculated relative to this value: they are 1.07 and 1.14 respectively.

Figure 13 presents a chart for a potential growth of negative spot prices in South Australia in 2030 and 2040, relative to 2021, and according to the selected scenarios – Step Change and Hydrogen Superpower. In both scenarios a slightly increase of the frequency of negative prices is expected. For Step Change this increase is in the order of 7% over a decade (from 2021 to 2030 and from 2030 to 2040). For Hydrogen Superpower this increase is a bit more distinct – it is approximately 18% - 19% over a decade. In summary, given the qualitative nature of this estimation, the negative spot prices are expected to continue exist into the future and slightly grow under the Step Change Scenario. Under the Hydrogen Superpower scenario, the estimated growth will be bigger in comparison with Step Change.

One important influencing factor supporting negative prices is VRE curtailment. According to AEMO, curtailment of renewable energy will be necessary into the future and its percentage will grow (AEMO, 2021a). This percentage will grow to more than 20% of all renewable generation in 2050 for the Step Change scenario. It is more efficient to "waste" some generation output instead of building a very expensive network and storage capacity to capture every kWh generated. AEMO indicates that the VRE curtailment will be most likely during periods when utility-scale solar and wind become direct competitors for dispatch, rather than pricing out other types of generation (AEMO, 2021a).

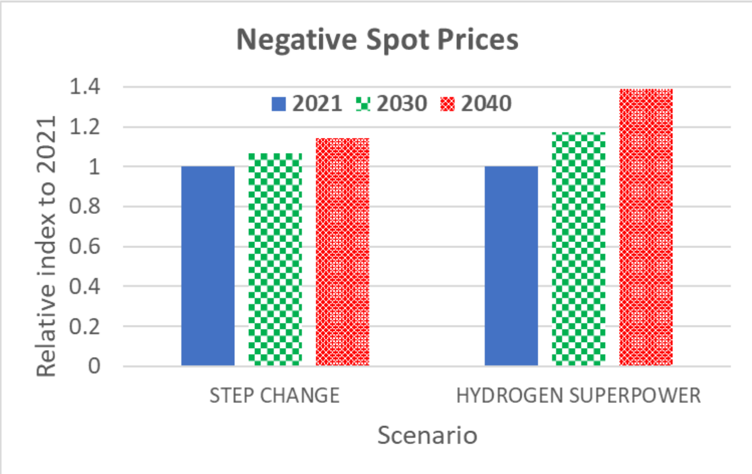

Figure 13. Potential growth of negative spot prices in SA in 2030 and 2040

ASSESSMENT OF POTENTIAL SCENARIO IMPACT ON VERY HIGH SPOT PRICES IN SOUTH AUSTRALIA

The assessment of influences on very high spot prices follows the logic from the previous section, dealing with negative prices, however, changing the type of influence (negative to positive and vice versa). Very high prices occur when demand is very high, and supply is scarce. "Negative" supply-related influencing factors are those that reduce supply and for demand "negative" influencing factors are those that increase demand. It is not a surprise that a change of an influencing factor that creates more favourable conditions for negative prices at the same time creates less favourable conditions for very high spot prices and vice versa.

Figure 14 presents a chart for a potential decrease of very high spot prices in South Australia in 2030 and 2040, relative to 2021, and according to the selected scenarios – Step Change and Hydrogen Superpower. In both scenarios it is expected there will be a slight decrease of the frequency of very high prices. For Step Change this decrease is in the order of 4% - 5% over a decade (from 2021 to 2030 and from 2030 to 2040). For Hydrogen Superpower this decrease is a bigger – it is approximately 11% - 12% over a decade. In summary, given the qualitative nature of this estimation, the very high spot prices are expected to continue exist into the future and slightly decrease under the Step Change Scenario. Under the Hydrogen Superpower scenario, the estimated decrease will be bigger in comparison with Step Change.

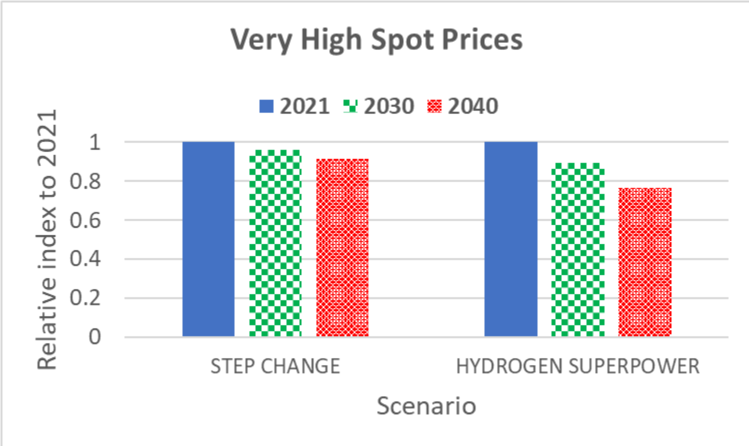

Figure 14. Potential reduction of very high spot prices in SA in 2030 and 2040

Table 4. Influence factors for Very High Spot Prices in Step Change

		Influence factors	Comment	Currently Very High Spot Prices 2021	STEP CHANGE Very High Spot Prices 2030	 2040
Demand	Loads	More residential use of electricity (+)		↑	↑	↑
		More commercial use of electricity (+)		↑	↑	↑↑
		More industrial use of electricity (+)		↑	↑	↑↑
		More charging of electric vehicles (+)		↑	↑↑	↑↑↑↑
		Less household use of gas (+)	Some gas usage replaced by electricity	↑	↑↑↑	↑↑↑↑
		Less industry use of gas (+)	Some gas usage replaced by electricity	↑	↑	↑↑
		More hydrogen production (+)	More electricity for hydrogen production	↑	↑↑	↑↑
		Better energy efficiency (-)		↓	↓	↓↓
	Weather & climate	Extreme weather increasing demand (+)		↑	↑	↑↑
		Climate change increasing demand (+)		↑	↑	↑↑
	Market	Demand-side participation (-)		↓	↓	↓↓
		Demand forecast inaccuracies (+/-)		↑	↑	↑
		Time of day/week/season increasing demand (+)	Peak demand depends on these daily, weekly and seasonal patterns	↑	↑	↑↑
Supply	Generation	More mid-merit gas (+)		↓	↓	
		More peaking gas + liquids (+)		↓	↓	↓
		More utility-scale storage (+)		↓	↓	↓↓
		More coordinated distributed storage (+)		↓	↓↓↓	↓↓↓↓↓
		More distributed storage (+)		↓	↓↓	↓↓↓↓↓
		More wind (+)		↓	↓↓	↓↓↓
		More utility-scale solar (+)		↓	↓	↓↓↓
		More distributed solar PV (+)		↓	↓↓	↓↓↓
		More firming capacity (+)		↓	↓	↓
		More generation plant outages (-)		↑	↑	↑↑
	Transmission	New transmission links and capacity (+)		↓	↓↓	↓↓↓
		More tranmission line outages (-)		↑	↑	↑↑
	Weather & climate	Extreme weather reducing supply (-)		↑	↑	↑↑
		Climate change reducing supply (-)		↑	↑	↑↑
	Market	Bigger curtailment of VRE (-)		↑	↑↑	↑↑
		Wind and solar generation forecasting (+/-)		↑	↑	↑
		Bigger utility profit/Bidding (-)		↑	↑↑	↑↑
		Security constraints imposed on generators (-)		↑	↑↑	↑↑
		Security constraints imposed on transmission links (-)		↑	↑	↑
		Percentage (negative impact)	↓	37.50%	40.00%	42.86%
		Percentage (positive impact)	↑	62.50%	60.00%	57.14%
		Index of positive impact		1.00	0.96	0.91

Table 5. Influence factors for Negative Spot Prices in Step Change

		Influence factors	Comment	Currently Negative Spot Prices 2021	STEP CHANGE Negative Spot Prices 2030	 2040
Demand	Loads	More residential use of electricity (+)		↓	↓	↓
		More commercial use of electricity (+)		↓	↓	↓↓
		More industrial use of electricity (+)		↓	↓	↓↓
		More charging of electric vehicles (+)		↓	↓↓	↓↓↓↓
		Less household use of gas (+)	Some gas usage replaced by electricity	↓	↓↓↓	↓↓↓↓
		Less industry use of gas (+)	Some gas usage replaced by electricity	↓	↓	↓↓
		More hydrogen production (+)	More electricity for hydrogen production	↓	↓↓	↓↓
		Better energy efficiency (-)		↑	↑	↑↑
	Weather & climate	Extreme weather increasing demand (+)		↓	↓	↓↓
		Climate change increasing demand (+)		↓	↓	↓↓
	Market	Demand-side participation (-)		↑	↑	↑↑
		Demand forecast inaccuracies (+/-)		↓	↓	↓
		Time of day/week/season increasing demand (+)	Peak demand depends on these daily, weekly and seasonal patterns	↓	↓	↓↓
Supply	Generation	More mid-merit gas (+)		↑	↑	
		More peaking gas + liquids (+)		↑	↑	↑
		More utility-scale storage (+)		↑	↑	↑↑
		More coordinated distributed storage (+)		↑	↑↑↑	↑↑↑↑↑
		More distributed storage (+)		↑	↑↑	↑↑↑↑↑
		More wind (+)		↑	↑↑	↑↑↑
		More utility-scale solar (+)		↑	↑	↑↑↑
		More distributed solar PV (+)		↑	↑↑	↑↑↑
		More firming capacity (+)		↑	↑	↑
		More generation plant outages (-)		↓	↓	↓↓
	Transmission	New transmission links and capacity (+)		↑	↑↑	↑↑↑
		More tranmission line outages (-)		↓	↓	↓↓
	Weather & climate	Extreme weather reducing supply (-)		↓	↓	↓↓
		Climate change reducing supply (-)		↓	↓	↓↓
	Market	Bigger curtailment of VRE (-)		↓	↓↓	↓↓
		Wind and solar generation forecasting (+/-)		↓	↓	↓
		Bigger utility profit/Bidding (-)		↓	↓↓	↓↓
		Security constraints imposed on generators (-)		↓	↓↓	↓↓
		Security constraints imposed on transmission links (-)		↓	↓	↓
		Percentage (negative impact)	↓	62.50%	60.00%	57.14%
		Percentage (positive impact)	↑	37.50%	40.00%	42.86%
		Index of positive impact		1.00	1.07	1.14

Table 6. Influence factors for Very High Spot Prices in Hydrogen Superpower

		Influence factors	Comment	Currently Very High Spot Prices 2021	HYDROGEN SUPERPOWER Very High Spot Prices 2030	 2040
Demand	Loads	More residential use of electricity (+)		↑	↑↑	↑↑↑↑
		More commercial use of electricity (+)		↑	↑↑	↑↑↑
		More industrial use of electricity (+)		↑	↑↑	↑↑↑↑
		More charging of electric vehicles (+)		↑	↑↑↑	↑↑↑↑
		Less household use of gas (+)	Some gas usage replaced by electricity	↑	↑↑↑	↑↑↑↑
		Less industry use of gas (+)	Some gas usage replaced by electricity	↑	↑↑	↑↑↑↑
		More hydrogen production (+)	More electricity for hydrogen production	↑	↑↑↑	↑↑↑↑↑↑
		Better energy efficiency (-)		↓	↓	↓↓
	Weather & climate	Extreme weather increasing demand (+)		↑	↑	↑↑
		Climate change increasing demand (+)		↑	↑	↑↑
	Market	Demand-side participation (-)		↓	↓↓	↓↓↓
		Demand forecast inaccuracies (+/-)		↑	↑	↑
		Time of day/week/season increasing demand (+)	Peak demand depends on these daily, weekly and seasonal patterns	↑	↑	↑↑
Supply	Generation	More mid-merit gas (+)		↓	↓↓	
		More peaking gas + liquids (+)		↓	↓	↓↓
		More utility-scale storage (+)		↓	↓↓	↓↓↓↓
		More coordinated distributed storage (+)		↓	↓↓↓	↓↓↓↓↓↓↓
		More distributed storage (+)		↓	↓↓	↓↓↓↓↓
		More wind (+)		↓	↓↓↓↓	↓↓↓↓↓↓↓↓ ↓↓↓
		More utility-scale solar (+)		↓	↓↓↓↓↓	↓↓↓↓↓↓↓↓ ↓↓↓↓↓↓↓↓ ↓↓↓↓
		More distributed solar PV (+)		↓	↓↓	↓↓↓
		More firming capacity (+)		↓	↓	↓↓
		More generation plant outages (-)		↑	↑	↑↑
	Transmission	New transmission links and capacity (+)		↓	↓↓	↓↓↓↓
		More tranmission line outages (-)		↑	↑	↑↑
	Weather & climate	Extreme weather reducing supply (-)		↑	↑	↑↑
		Climate change reducing supply (-)		↑	↑	↑↑
	Market	Bigger curtailment of VRE (-)		↑	↑↑	↑↑↑↑
		Wind and solar generation forecasting (+/-)		↑	↑	↑↑
		Bigger utility profit/Bidding (-)		↑	↑↑	↑↑↑
		Security constraints imposed on generators (-)		↑	↑↑	↑↑↑
		Security constraints imposed on transmission links (-)		↑	↑	↑↑
		Percentage (negative impact)	↓	37.50%	44.07%	52.07%
		Percentage (positive impact)	↑	62.50%	55.93%	47.93%
		Index of positive impact		1.00	0.89	0.77

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Table 7. Influence factors for Negative Spot Prices in Hydrogen Superpower

		Influence factors	Comment	Currently Negative Spot Prices 2021	HYDROGEN SUPERPOWER Negative Spot Prices 2030	2040
Demand	Loads	More residential use of electricity (+)		↓	↓↓	↓↓↓↓
		More commercial use of electricity (+)		↓	↓↓	↓↓↓
		More industrial use of electricity (+)		↓	↓↓	↓↓↓↓
		More charging of electric vehicles (+)		↓	↓↓↓	↓↓↓↓
		Less household use of gas (+)	Some gas usage replaced by electricity	↓	↓↓↓	↓↓↓↓
		Less industry use of gas (+)	Some gas usage replaced by electricity	↓	↓↓	↓↓↓↓
		More hydrogen production (+)	More electricity for hydrogen production	↓	↓↓↓	↓↓↓↓↓↓
		Better energy efficiency (-)		↑	↑	↑↑
	Weather & climate	Extreme weather increasing demand (+)		↓	↓	↓↓
		Climate change increasing demand (+)		↓	↓	↓↓
	Market	Demand-side participation (-)		↑	↑↑	↑↑↑
		Demand forecast inaccuracies (+/-)		↓	↓	↓
		Time of day/week/season increasing demand (+)	Peak demand depends on these daily, weekly and seasonal patterns	↓	↓	↓↓
Supply	Generation	More mid-merit gas (+)		↑	↑↑	
		More peaking gas + liquids (+)		↑	↑	↑↑
		More utility-scale storage (+)		↑	↑↑	↑↑↑↑
		More coordinated distributed storage (+)		↑	↑↑↑	↑↑↑↑↑↑↑
		More distributed storage (+)		↑	↑↑	↑↑↑↑↑
		More wind (+)		↑	↑↑↑↑	↑↑↑↑↑↑↑↑ ↑↑↑
		More utility-scale solar (+)		↑	↑↑↑↑↑	↑↑↑↑↑↑↑↑ ↑↑↑↑↑↑↑↑ ↑↑↑↑
		More distributed solar PV (+)		↑	↑↑	↑↑↑
		More firming capacity (+)		↑	↑	↑↑
		More generation plant outages (-)		↓	↓	↓↓
	Transmis	New transmission links and capacity (+)		↑	↑↑	↑↑↑↑
		More tranmission line outages (-)		↓	↓	↓↓
	Weather & clima	Extreme weather reducing supply (-)		↓	↓	↓↓
		Climate change reducing supply (-)		↓	↓	↓↓
	Market	Bigger curtailment of VRE (-)		↓	↓↓	↓↓↓↓
		Wind and solar generation forecasting (+/-)		↓	↓	↓↓
		Bigger utility profit/Bidding (-)		↓	↓↓	↓↓↓
		Security constraints imposed on generators (-)		↓	↓↓	↓↓↓
		Security constraints imposed on transmission links (-)		↓	↓	↓↓
		Percentage (negative impact)	↓	62.50%	55.93%	47.93%
		Percentage (positive impact)	↑	37.50%	44.07%	52.07%
		Index of positive impact		1.00	1.18	1.39

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Conclusion

This report contains the findings from research conducted by UOW into research Question C, as specified by the South Australian Productivity Commission. Research Question C seeks to forecast the frequency of low or negative and high (above $1,000/MWh) wholesale electricity spot price events in 2030 and 2040 under two energy market development scenarios published by AEMO: Step Change and Hydrogen Superpower.

Negative prices

The frequency of negative spot prices has increased substantially in the last several years in all regions of the NEM with biggest increases in the southern regions of South Australia, Victoria, and Tasmania. Key drivers for negative prices included low operational demand, high renewable generation and interconnector constraints preventing export of excess generation with wind generation being the dominant factor. The most likely periods with negative spot prices in SA are during peak solar production time (10:00 – 15:30), when distributed solar PV and utility-scale solar generate significant power, reducing operational demand. The next likely period with negative prices is during the off-peak, early in the morning (3:00 am - 4:00 am), when the operational demand is very low and when there are good conditions for wind generation. Generators that have output during negative price periods must pay for their generation. The reasons to bid at negative prices could be different. A generator may be willing to pay for generating electricity for having higher chances of winning a certain volume of production (the case mainly for VRE generators – wind and solar) or to avoid start/stop as it is the case for baseload generators. Since the introduction of 5-min settlement since 1st of October 2021 the bidding behaviour of some generators has modified and as a result the amplitude of the negative prices has reduced (not the frequency).

Very high electricity spot price

Very high spot prices (>= $1000/MWh) usually occur when there is scarce generation and growing electricity demand. More and more expensive generation offers must be accepted and dispatched by the market operator during these conditions. Key drivers for very high spot prices include high temperature when extra demand is created by air-conditioning use, generator outages reducing available generation, low wind output, and network outages reducing import of cheaper electricity from other regions. Extreme temperatures, heat waves and coincidence of conditions for high prices in other regions of the NEM – all increase the likelihood of very high prices.

The AER is required to publish a report whenever the electricity spot price exceeds $5000/MWh in accordance with the National Electricity Rules. A list of events with spot prices exceeding $5000/MWh for the last three years (2019-21) is included as an appendix to this report.

The Step Change and Hydrogen Superpower scenarios

Recently AEMO published its document “Draft 2022 Integrated System Plan for the NEM”. AEMO uses a scenario modelling approach to outline a range of plausible development paths into the future, considering four scenarios. This report analyses the potential impact of the two most ambitions and transformational scenarios - Step Change and Hydrogen Superpower - on very high and negative spot prices in South Australia.

Research findings

- Negative spot prices - due to excessive supply from renewable generation with zero fuel cost, associated to low demand - will continue to be persistent in the market in South Australia. In the Step Change and Hydrogen Superpower scenarios the frequency of negative spot prices is expected to increase slightly in comparison with recent market trends. The Hydrogen Superpower scenario will provide a more significant change compared with the Step Change one.

- With significant new generation capacity planned over the next two decades in South Australia, it is expected that market conditions for very high spot prices (more than $1,000/MWh) will occur less frequently in comparison with events recorded over the last two years. Therefore, under the Step Change and Hydrogen Superpower scenarios, the frequency of very high prices will decrease only marginally, with the latter scenario providing a more significant change.

These findings are based on many assumptions, which are considered more qualitatively than quantitively in a consistent modelling approach. Because of the many uncertainties associated with studied scenario projections, these research finding should be used only as a "what-if" guide to inform our understanding of the complex evolution of the power grid and the electricity market.

Recommendations

While more studies are necessary for greater understanding of price volatility across the NEM, some initial recommendations are provided.

Significant work has been done by market participants and other stakeholders for better integration of renewables into the market, however, there are still many issues which require further attention and new solutions, including very high and very low spot prices. One significant issue is better integration or coupling of renewable generators and battery storage. There are options both for utility-based and distributed generation and storage.

A significant opportunity perhaps exists for coupling of renewable generators and hydrogen production plants. Electrolysis plants for green hydrogen which are able to follow closely the output from renewable generators may mitigate the stability issues resulting from the intermittence of renewable output and when connected to the grid, mitigate the price volatility.

In general, improving the climate resilience and climate adaptation of the electricity grid in relation to failures, heatwaves, flooding, bushfires, and other disasters impacted by climate change is a significant issue that must be further address by stakeholders.

More research on some of these topics is recommended which includes advanced modelling and simulation.

References

AEMO (2022). Aggregated price and demand data. Available online: https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/data-nem/aggregated-data

AEMO (2021a). Draft 2022 Integrated System Plan. Available online: draft-2022-integrated-system-plan.pdf (aemo.com.au)

AEMO (2021b). 2021 Inputs, Assumptions and Scenarios Report (IASR). Overview. Available online: https://aemo.com.au/-/media/files/major-publications/isp/2021/2021-inputs-assumptions-and-scenarios-report.pdf?la=en

AEMO (2021c). Draft 2022 Forecasting Assumptions Update. Available online: https://aemo.com.au/-/media/files/major-publications/isp/2022/iasr/draft-2022-forecasting-assumptions-update.pdf?la=en

AEMO (2021d). Solar PV curtailment initiative by SA Government supports the NEM. Available online: https://aemo.com.au/newsroom/media-release/solar-pv-curtailment-initiative-by-sa-government-supports-the-nem

AEMO, 2021_q1. Quarterly Energy Dynamics Q1 2021. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2021/q1-report.pdf?la=en

AEMO, 2021_q2. Quarterly Energy Dynamics Q2 2021. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2021/q2-report.pdf?la=en

AEMO, 2021_q3. Quarterly Energy Dynamics Q3 2021. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2021/q3-report.pdf?la=en

AEMO, 2021_q4. Quarterly Energy Dynamics Q4 2021. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2021/q4-report.pdf?la=en

AEMO (2020a). Wholesale demand response: High-level design. Available online: https://aemo.com.au/-/media/files/initiatives/submissions/2020/wdrm/wdrm-high-level-design-june-2020.pdf

AEMO, 2020_q1. Quarterly Energy Dynamics Q1 2020. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q1-2020.pdf?la=en

AEMO, 2020_q2. Quarterly Energy Dynamics Q2 2020. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q3-2020.pdf?la=en

AEMO, 2020_q3. Quarterly Energy Dynamics Q3 2020. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q4-2020.pdf?la=en

AEMO, 2021_2020q4. Quarterly Energy Dynamics Q4 2020. Available online: https://aemo.com.au/-/media/files/major-publications/qed/2020/qed-q4-2020.pdf?la=en

AEMO, (2017). Black system South Australia, 28 September 2016. Available online: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf

Apergis N., Gozgor G., Lau, CKM., Wang S. (2020). Dependence structure in the Australian electricity markets: New evidence from regular vine copulae. *Energy Economics* 90, 104834. https://doi.org/10.1016/j.eneco.2020.104834

Batten D., Grozev G. (2006). NEMSIM: Finding Ways to Reduce Greenhouse Gas Emissions using Multi-Agent Electricity Modelling. Chapter 11 in: Pascal P, Batten B (Editors), *Complex Science for a Complex World: Exploring Human Ecosystems with Agents*. Australia National University Press, Canberra, ACT, Australia.

Beran, P., Pape, C., Weber, C. (2019). Modelling German electricity wholesale spot prices with a parsimonious fundamental model – Validation & application. *Utilities Policy*, 58, 27-39. https://doi.org/10.1016/j.jup.2019.01.008

Burillo, D., Chester, MV., Ruddell, B., Johnson, N. (2017). Electricity demand planning forecasts should consider climate non-stationarity to maintain reserve margins during heat waves. *Applied Energy*, 206, 267-277. http://dx.doi.org/10.1016/j.apenergy.2017.08.141

Grozev G., Batten D., Anderson M., Lewis G., Mo J., Katzfey J. (2005). NEMSIM: Agent-based Simulator for Australia's National Electricity Market. In: *SimTecT 2005 Conference Proceedings*. Sydney, NSW, Australia.

Mwampashi, MM., Nikitopoulos, CS., Konstandatos, O., Rai, A. (2021). Wind generation and the dynamics of electricity prices in Australia. *Energy Economics* 103, 105547. https://doi.org/10.1016/j.eneco.2021.105547

Do, H., Nepal, R. and Smyth, R. (2020). Interconnectedness in the Australian National Electricity Market: A Higher-Moment Analysis, *Economic Record*, Vol. 96 (315), pp. 450-469. doi:10.1111/1475-4932.12563

Nepal, R. and Foster, J. (2016). Testing for Market Integration in the Australian National Electricity Market, *The Energy Journal*, Vol. 37 (4), pp. 215-237. http://dx.doi.org/10.5547/01956574.37.4.rnep

Thatcher, M. (2007). Modelling changes to electricity demand load duration curves as a consequence of predicted climate change for Australia. *Energy* 32, 1647–1659. doi:10.1016/j.energy.2006.12.005

Appendix A

ELECTRICITY SPOT PRICES ABOVE $5,000/MWH IN SOUTH AUSTRALIA

Table 8. Electricity spot prices above $5,000/MWh in South Australia[2]

Region	Date	Trading interval	Price [$/MWh]	Reasons
SA	18/01/2018	16:30	6,256	High temperatures in both regions - VIC & SA; Loy Yang B unit 1 in Victoria tripped - stop generating unexpectedly;
SA	18/01/2018	17:00	14,167	As above
SA	18/01/2018	17:30	13,136	As above
SA	18/01/2018	18:00	5,693	As above
SA	19/01/2018	14:30	11,864	High temperatures in both regions - VIC & SA; Special pricing arragements;
SA	19/01/2018	15:00	13,408	As above
SA	19/01/2018	17:00	5,413	As above
SA	19/01/2018	18:00	5,332	As above
SA	07/02/2018	16:00	8,001	High temperatures in both regions - VIC & SA; Material reduction of available capacity in both regions;
SA	09/07/2018	12:30	8,824	Network outage reducing the ability for low-priced electricity to flow from Vic to SA; Relatively low wind; Relatively high initial bids.
SA	24/01/2019	16:00	12,844	Extreme heat in Victoria and SA; Outages of generators in Vic; Low wind in both regions; Special intervention pricing arrangements.
SA	24/01/2019	16:30	13,711	As above
SA	24/01/2019	17:00	13,025	As above
SA	24/01/2019	17:30	14,500	As above; Market Price Cap (MPC) reached;
SA	24/01/2019	18:00	14,500	As above
SA	24/01/2019	18:30	14,500	As above
SA	24/01/2019	19:00	14,500	As above
SA	24/01/2019	19:30	14,500	As above
SA	24/01/2019	20:00	14,500	As above
SA	24/01/2019	20:30	14,500	As above
SA	24/01/2019	21:00	12,000	As above
SA	25/01/2019	11:30	11,340	Extreme heat in Victoria for a second day and high demand; Extreme heat in Adelaide on the previous day; Generator outages in Victoria; Low wind output; Special pricing arrangements from AEMO; Demand forecast not accurate; Customer load shedding in Victoria - 250 MW;

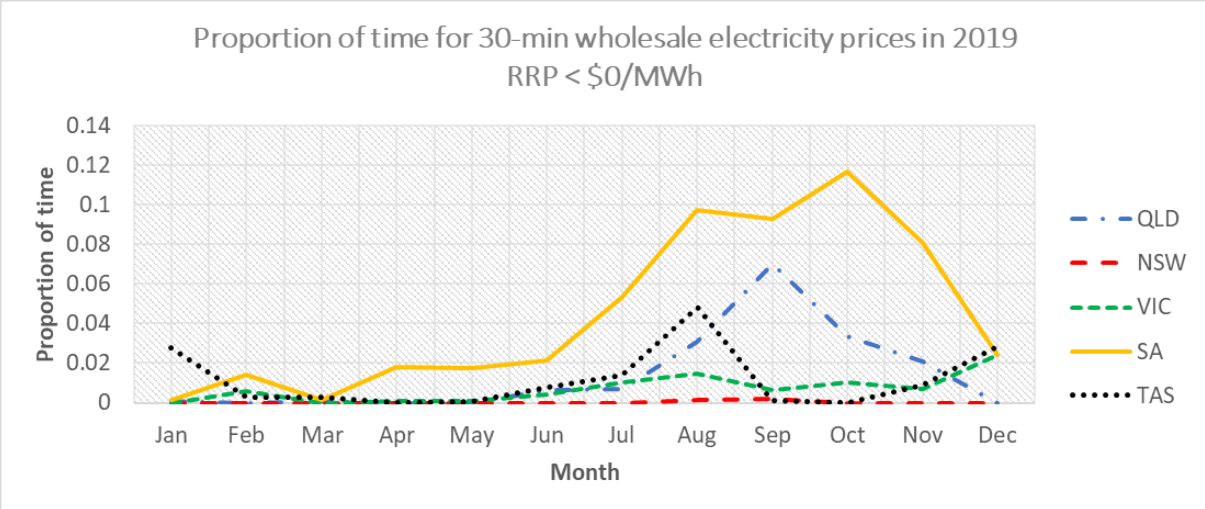
[2] From 1/10/2021 the rule that requires AER to publish a report whenever the electricity 30-min price exceeds $5,000/MWh was amended for 5-min settlement. The reporting is still for 30-min interval. The 30-min price now is calculated as an average of 6 trading intervals (previously 6 dispatch intervals).

Table 8 – continued

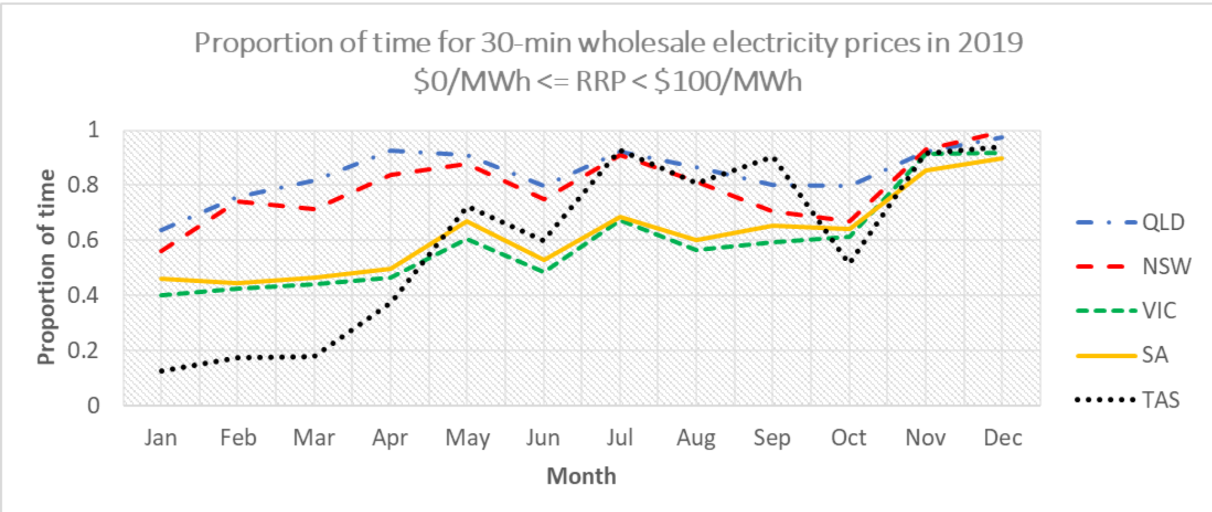
Region	Date	Trading interval	Price [$/MWh]	Reasons
SA	01/03/2019	16:00	6,765	High temperatures in Melbourne and Adelaide; Reduced availability of wind generators;
SA	01/03/2019	16:30	12,609	As above
SA	01/03/2019	17:00	12,067	As above
SA	19/12/2019	19:00	14,700	Maximum temperature in Adelaide exceeded 45°C, leading to very high demand and market cap for the price; Import from Victoria was limited; Some small errors in forecasting leading to significant swings in price outcome.
SA	19/12/2019	19:30	14,700	As above
SA	30/01/2020	18:30	11,204	Very high demand due to high temperatures; Unplanned outage of a generating unit in Victoria; Low wind generation.
SA	30/01/2020	19:00	12,217	As above
SA	31/01/2020	14:00		Failure of the Heywood interconnector due to local storm; Invoking constraints which limited the output of generators.
SA	02/03/2020	14:00	5,603	Unplanned outage of the Heywood interconnector; Invoking constraints on generators in SA to maintain power system security; Rebidding to high prices.
SA	02/03/2020	14:30	7,027	As above
SA	22/01/2021	04:00	5,031	Pelican Point PS outage; Interconnector capacity restricted for system protection.
SA	12/03/2021	19:30	5,010	Disconnected power station (Barker Inlet PS) due to fire; limited output from another PS - Torrens Island PS; Rebidding; Low wind generation - as low as 12 MW; Planned transmission outage in Vic, which limited cheaper import from Vic.
SA	12/03/2021	20:00	14,348	As above
SA	12/03/2021	20:30	5,066	As above
SA	12/03/2021	23:00	12,223	As above
SA	12/03/2021	23:30	5,309	As above
SA	13/03/2021	00:00	7,885	As above
SA	17/05/2021	18:00	5,673	Reduced supply due to planned and unplanned maintenance; Low wind generation; High demand due to cooler weather, increasing heating.
SA	18/05/2021	18:00	5,420	As above
SA	18/05/2021	18:30	7,039	As above
SA	18/12/2021	01:00	5,715	Low available capacity due to low wind generation; Unplanned outage on Murraylink prevented import from Victoria; rebidding from low to high prices.
SA	30/12/2021	19:30	8,456	High demand due to high temperature; very low wind generation - 50 MW; Interconnector capacity restricted to avoid voltage collapse.
SA	30/12/2021	20:00	5,279	As above
SA	31/12/2021	19:00	6,368	As above
SA	10/01/2022	12:30	11,489	Restricted import from Victoria on the Heywood interconnector; Demand was higher than forecast due to reduction in roof solar generation and high temperature; Available generation capacity was lower than forecast due to fall in wind and solar generation.
SA	31/01/2022	18:00	14,239	High demand driven by hot temperatures both in SA (2,400 MW) and Victoria (8,300 MW); Planned outage of 720 MW in Victoria; A network constraint forcing flow from Victoria to NSW; Wind generation lower than forecast in SA; Generating units in Victoria witdrawing capacity due to technical reasons.

Appendix B

PROPORTION OF TIME FOR 30-MIN WHOLESALE SPOT PRICE BANDS IN THE REGIONS OF THE NEM



a/



b/

Figure 15. Proportion of time for 30-min wholesale electricity price bands in 2019:

a/ Price < $0/MWh

b/ $0/MWh <= Price < $100/MWh

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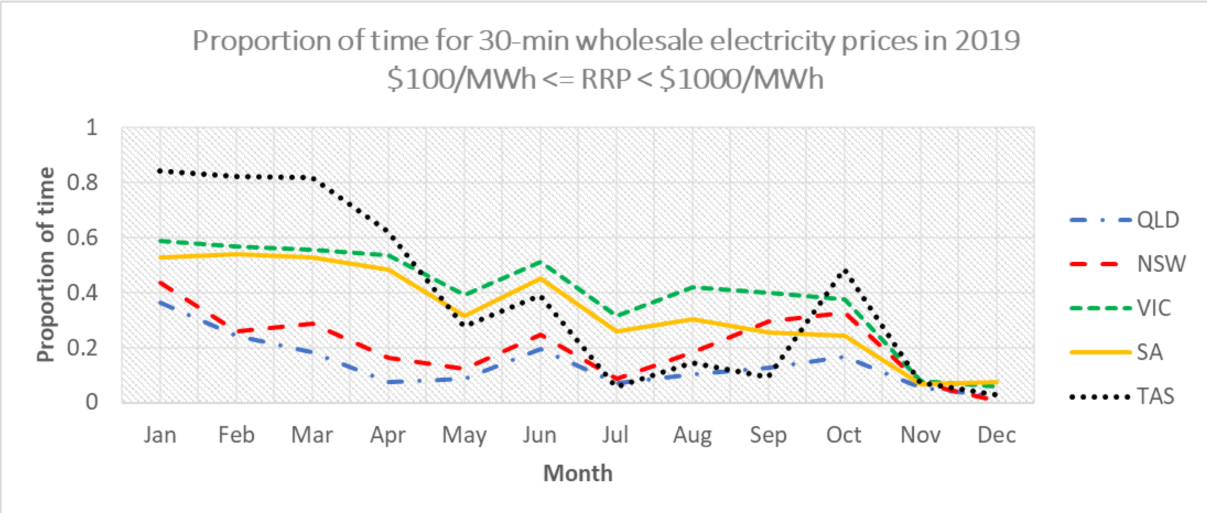
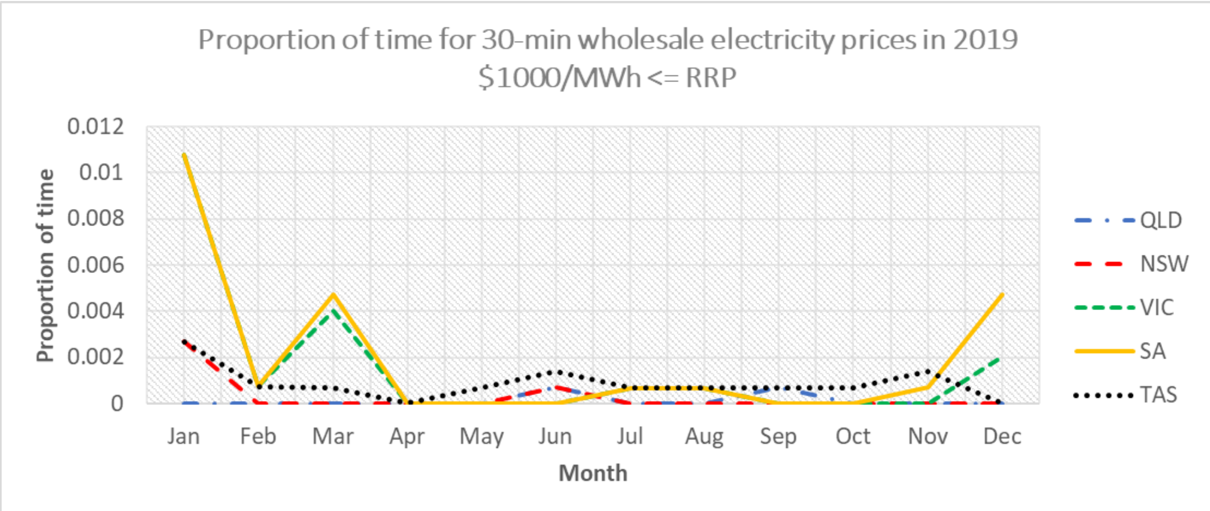


c/



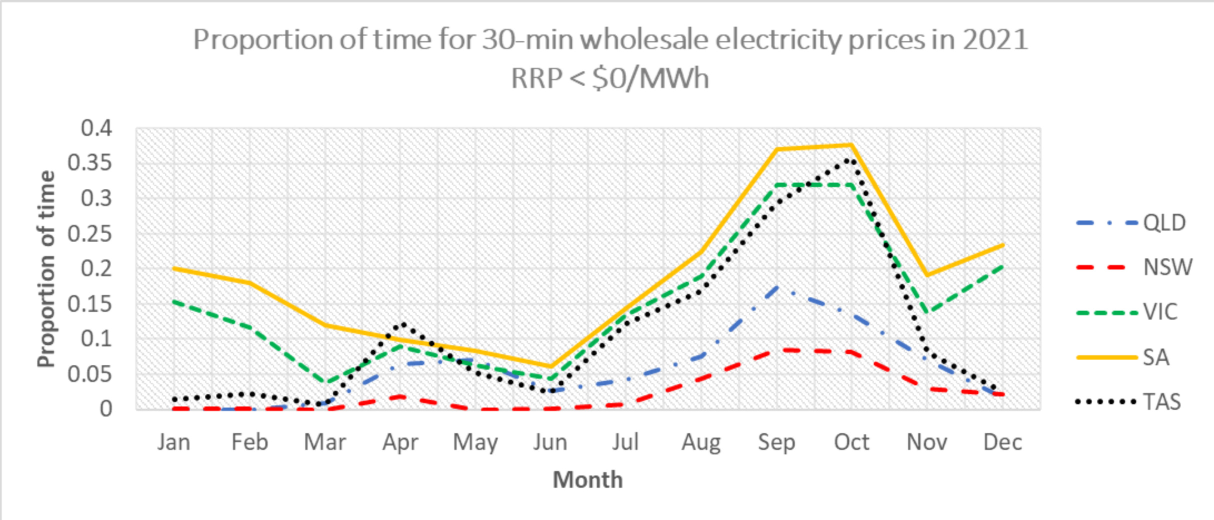
d/

Figure 15 - continued.

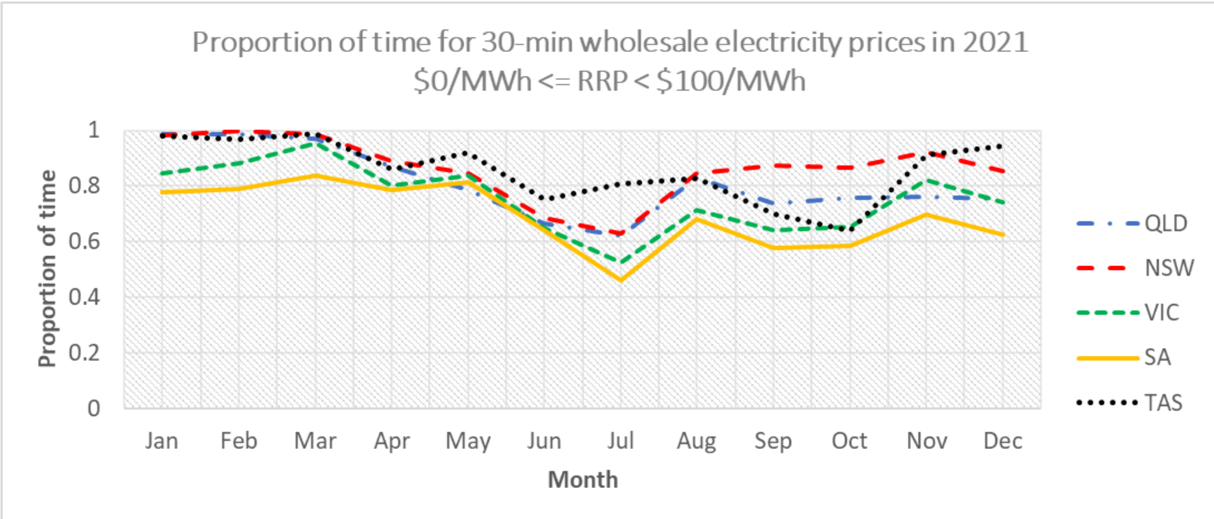
Proportion of time for 30-min wholesale electricity price bands in 2019:

c/ $100/MWh <= Price < $1000/MWh

d/ $1000/MWh <= Price



a/



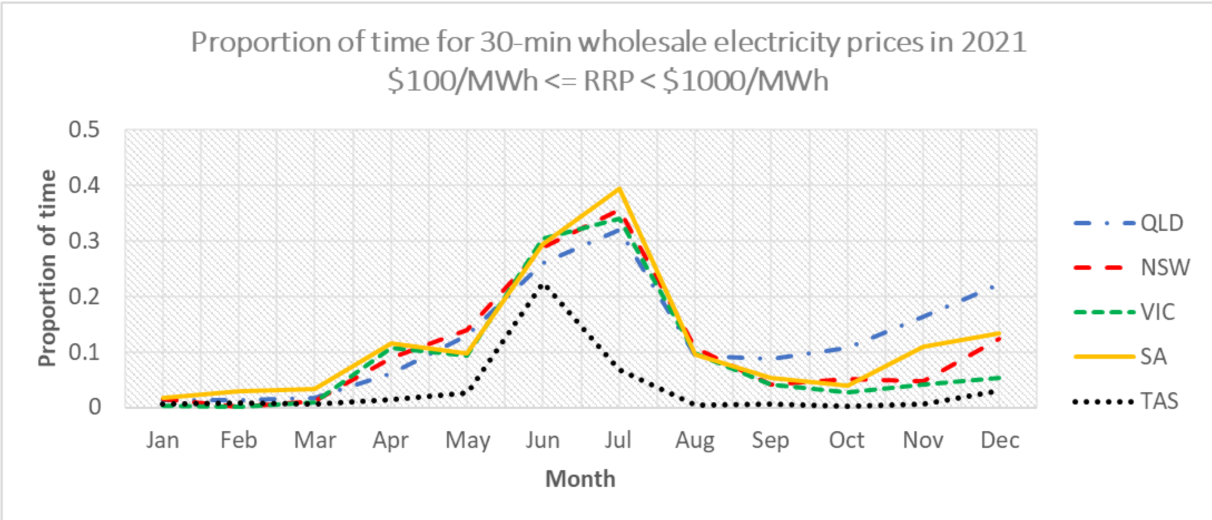
b/

Figure 16. Proportion of time for 30-min wholesale electricity price[3] bands in 2021:

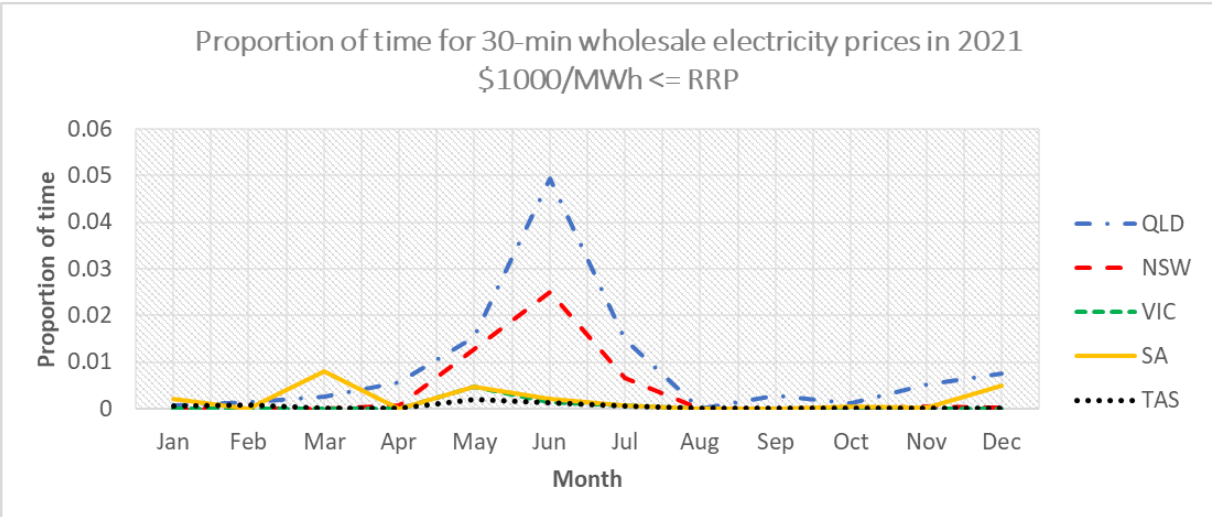
a/ Price < $0/MWh

b/ $0/MWh <= Price < $100/MWh

[3] For October, November and December 2021, when the NEM was using the 5-min settlement rule for the first time, the 30-min prices are calculated as average of the corresponding six 5-min settlement periods.



c/



d/

Figure 16 - continued.

Proportion of time for 30-min wholesale electricity price bands in 2021:

c/ $100/MWh <= Price < $1000/MWh

d/ $1000/MWh <= Price

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