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Enhanced tools necessary for managing a high distributed solar photovoltaic electricity system

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Abstract: Australia's energy transition to renewable energy sources has driven a significant uptake of distributed photovoltaic (DPV) energy systems. The increase in DPV can bring about operational challenges, such as the reduction of minimum operational demand, larger DPV induced demand ramps, and solar droughts. To manage a high DPV energy system, enhanced tools and insights are necessary to manage and operate energy systems and markets in a secure, reliable and affordable manner.

This paper covers the development of internal dashboards and visualisations, made within the Australian Energy Market Operator (AEMO) Operational Forecasting team, that have been instrumental in gaining a comprehensive understanding of DPV's behaviour and its corresponding impacts to Australia's National Electricity Market (NEM) under a variety of conditions. While these tools apply to the whole NEM, examples will focus on South Australia which has the highest proportion of DPV to demand.

A solar day classification tool has been developed, which summarises the solar characteristics of each day, capturing features such as the total energy generated by DPV, the impact of clouds, and the ramps in DPV observed. These collated metrics offer valuable insights into DPV behaviour and trends over time, building a stronger knowledge base to better manage current and emerging system challenges.

One key challenge is solar droughts which directly impacts DPV. Leveraging the solar day classification tool, historical solar droughts have been identified and used to provide detailed insights, which enable for the planning of possible future solar droughts that may eventuate in an energy system more reliant on renewables.

Tools have also been developed to better visualise and understand the relationship and interaction between DPV generation and operational demand and their forecasts, as changes in DPV generation and forecasts can directly influence operational demand, particularly during the middle of the day.

Developing the capability of these tools has made it easier to gain insights from the information currently available to support more informed energy system management, and to identify and increase awareness of emerging risks and challenges that high DPV uptake brings. The tools discussed also highlight the important role forecasting plays and the need to continually monitor and improve forecast performance.

Continuing to develop the features of these tools and applying the insights that they provide will be instrumental in ensuring that emerging risks and challenges are properly understood and effectively managed, thus securely operating high DPV energy systems now, and into the future.

Keywords: *Energy transition, photovoltaic electricity, PV, Power BI*

1. INTRODUCTION

Australia's energy systems are currently undergoing significant changes as part of the energy transition's shift to low emission sources. A major component of the transition has been the uptake of distributed solar photovoltaic (PV) energy systems, typically found on rooftops. To manage an energy system with a high uptake of distributed PV (DPV), new analytical tools are required to provide enhanced insights.

The Australian Energy Market Operator (AEMO) is Australia's independent system and market operator and system planner. AEMO's purpose is to ensure secure, reliable, and affordable energy, and enable the energy transition for the benefit of all Australians. AEMO operates a number of electricity and gas systems, and markets in Australia. The focus of this paper will be on electricity and the National Electricity Market (NEM).

AEMO's *Integrated System Plan* (ISP) is a roadmap for the transition of the NEM to meet future energy needs and enable a net zero economy by 2050. The ISP shows where new transmission, generation and storage is needed across the NEM. The 2024 ISP found that across the NEM, the capacity of DPV is forecast to rise from 21 gigawatts (GW) in 2024 to 36 GW by 2030, and 86 GW by 2050, as shown in Figure 1 (AEMO, 2024a). AEMO's *Quarterly Energy Dynamics* (QED), which details Australia's energy market dynamics, trends and outcomes, found that in quarter one (January 1 to March 31) of both 2024 and 2025, DPV contributed more electricity to the grid than grid-scale solar, wind, hydro or gas (AEMO, 2025e).

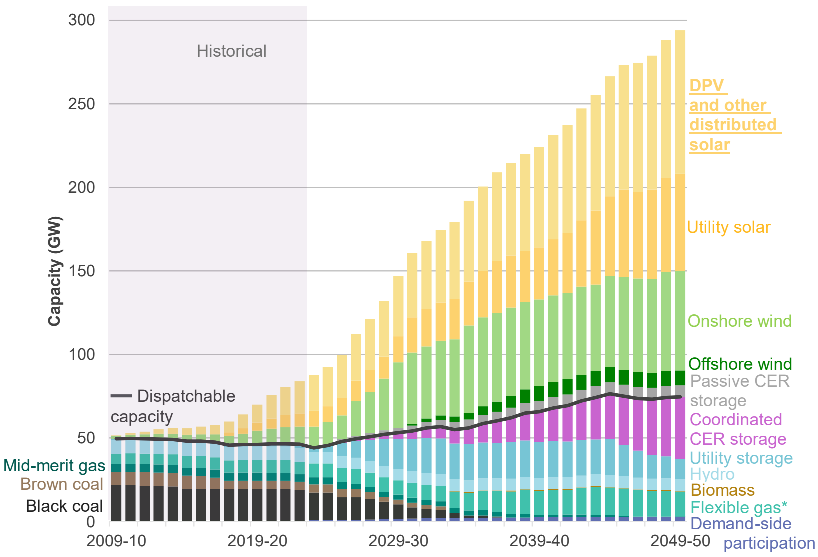

Figure 1 Capacity, NEM (GW, 2009-10 to 2049-50, Step Change) (AEMO, 2024a)

This paper is organised as follows: Section 2 outlines some of the emerging challenges in managing and operating a system with high DPV penetration. Section 3 describes key data sources described in this paper as well as some of the new analytical tools AEMO's Operational Forecasting team have developed. Section 4 concludes with a summary and suggestions for further work.

2. OPERATIONAL CHALLENGES

Operational demand is defined as demand met by scheduled, semi-scheduled and significant non-scheduled intermittent generation, typically greater than or equal to 30 megawatts (MW) in capacity (AEMO, 2025d). Importantly, operational demand does not include demand met by DPV. DPV generation is either consumed on-site or exported to the grid which reduces demand the grid needs to supply (operational demand). As a result, there is an inverse relationship between DPV and operational demand; as DPV generation increases, operational demand decreases and vice versa. This relationship, together with the increasing uptake of DPV, presents new and emerging challenges in managing and operating the NEM, not least of which to DPV and operational demand forecasting.

This section provides an overview of some of the current and emerging challenges in managing and operating an energy system with increasing levels of DPV. The examples shown in this paper are from a South Australia perspective, where world leading rates of DPV adoption have made these challenges most apparent (Renew Economy, 2025a; AEMO, 2025a).

2.1. Minimum System Load (MSL)

Australia's electricity systems were originally designed for one-way flows of power from utility generators to consumers. However, today, surplus energy from consumers is now flowing back into the electricity system.

Due to the uptake of DPV, minimum operational demand, also referred to as minimum system load (MSL) in the NEM, has been falling on average more than 1.2 GW per year across the NEM, and is projected to continue this downward trend (AEMO, 2024b). Decreasing MSL has been most evident in the NEM region of South Australia (SA), where DPV can at times generate more energy than the state requires, resulting in negative operational demand during the middle of the day (Renew Economy, 2025b).

Figure 2 shows the generation mix across the day on October 19, 2024, where the record minimum operational demand was -205 MW. This negative operational demand occurred due to DPV generating more than the underlying demand (operational demand plus DPV generation) in the region, leading to energy being exported from SA to the region of Victoria (AEMO, 2024c). The uptake of DPV has seen minimum demand records continue to be set across the NEM (AEMO, 2025e).

Decreasing MSL poses new challenges to the NEM. All mainland NEM regions are at or close to minimum secure levels of operational demand and action is required to maintain power system security during MSL periods (AEMO 2024b; AEMO, 2025b). Appropriately managing minimum operational demand levels is critical to ensuring the availability of required system security services (inertia, system restart, voltage management, reactive power management, ramping management), which have traditionally been served by large thermal synchronous generators (AEMO, 2024b; AEMO, 2024c).

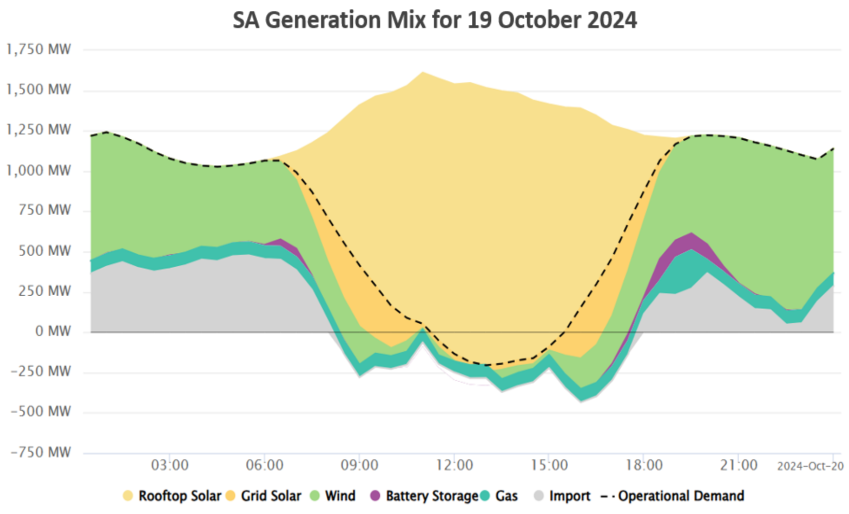

Figure 2 South Australia Electricity Generation Mix on October 19, 2024

2.2. DPV Induced Demand Ramping

Due to the inverse relationship between DPV and operational demand, the effect from transient clouds on DPV can cause sudden and dramatic changes in operational demand, herein referred to as demand ramping. The formation of clouds results in DPV generation ramping down, and in turn demand ramping up. Conversely, when clouds disperse, DPV generation ramps up and demand ramps down.

On October 17, 2024, SA experienced a significant operational demand ramping event between 1:30pm – 2:00pm when clouds dispersed over Adelaide's metropolitan area. This caused DPV generation to ramp up 781 MW over the half hour period, and a corresponding ramp down in operational demand of 598 MW. It is important to note that while the magnitude of this demand ramp, and more generally of demand ramps during the day, can largely be attributable to ramps in DPV, there are other drivers which impact demand, but are not discussed here.

Sudden and dramatic ramps in operational demand means scheduled, semi-scheduled and significant non-scheduled intermittent generators need to respond quickly. To manage large increases in operational demand, adequate head room from other fast-acting generators is required to maintain the demand-supply balance. Further details on the risks from demand ramps can be found in AEMO's *General Power System Risk Review Report* (AEMO, 2025a).

2.3. Solar Droughts

Renewable energy droughts, also known as *dunkelflaute* events, occur when there is low solar and wind generation for extended periods of time. Relevant to this paper is the solar aspect of renewable energy droughts and specifically solar droughts from a DPV perspective.

The key to managing an energy system with high amounts of renewable energy is through the operation of storage systems, most notably *deep storage*, to move energy from one period to the next. *Deep storage* systems can dispatch electricity for over 12 hours continuously to smooth out daily, weekly or seasonal variations in demand and renewable supply. That is, charging a storage system during periods of surplus renewables for discharging during periods of low renewable energy generation. An example of long duration storage is the Snowy 2.0 pumped-hydro battery project being developed in New South Wales (AEMO, 2024a).

To effectively plan and schedule the necessary amount of *deep storage,* a comprehensive understanding of both the intensity, and duration of solar droughts is needed.

3. DATA SOURCES AND ANALYTICAL TOOLS

The data presented in this paper can be publicly sourced from AEMO's NEMWEB market data site (AEMO, 2025c). The data specifically used in the tools described in this section includes 30-minute DPV estimated actuals and forecasts, and 30-minute operational demand actuals and forecasts.

The DPV estimated actuals and forecasts are produced by AEMO's Australian Solar Energy Forecasting System phase 2 (ASEFS2). ASEFS2 is designed to give visibility to small-scale DPV systems, defined as less than 100 kilowatt system capacity (AEMO, 2016). The resulting estimated actuals and forecasts for DPV assist AEMO in its forecasting processes and provide a basis for insights and tools on Australia's DPV.

To build the tools necessary to navigate the challenges discussed in Section 2, several software packages were used. These software packages include the R programming language, structured query language (SQL) and Power BI, Microsoft's business analytics platform. These tools extract, transform and visualise several years of data. This section presents three use cases of these tools: Solar Day Classification, Solar Droughts and Forecast Evolution.

3.1. Solar Day Classification

The Solar Day Classification tool uses DPV estimated actuals data to generate and visualise several DPV characteristics. These characteristics capture daily features including, but not limited to, total daily generation, daily maximum 30-minute absolute ramps, and daily volatility. Here, a ramp is defined as the absolute difference between two consecutive 30-minute periods, and daily volatility is defined as the sum of all 48 30-minute absolute ramps across the day. These characteristics capture various aspects of the impacts that cloud cover has on DPV generation, since cloud cover is the primary driver impacting DPV generation.

The daily maximum 30-minute ramp characteristic for SA is shown in Figure 3. Here the metric *CF_max_ramp_abs* is selected in the dropdown box (highlighted in the top left), which represents the ramp characteristic measured in capacity factor (CF). CF is a measure of DPV utilisation and is defined as the DPV generation for a particular period divided by the total nameplate installed capacity for the same period and region. Here *CF_max_ramp_abs* is used to normalise generation to account for changes in installed capacity over time. This means the impacts from clouds from previous years can be compared and translated to today's level of installed capacity. It can be seen from Figure 3 that the daily maximum 30-minute CF absolute ramp in SA occurred on October 17, 2024.

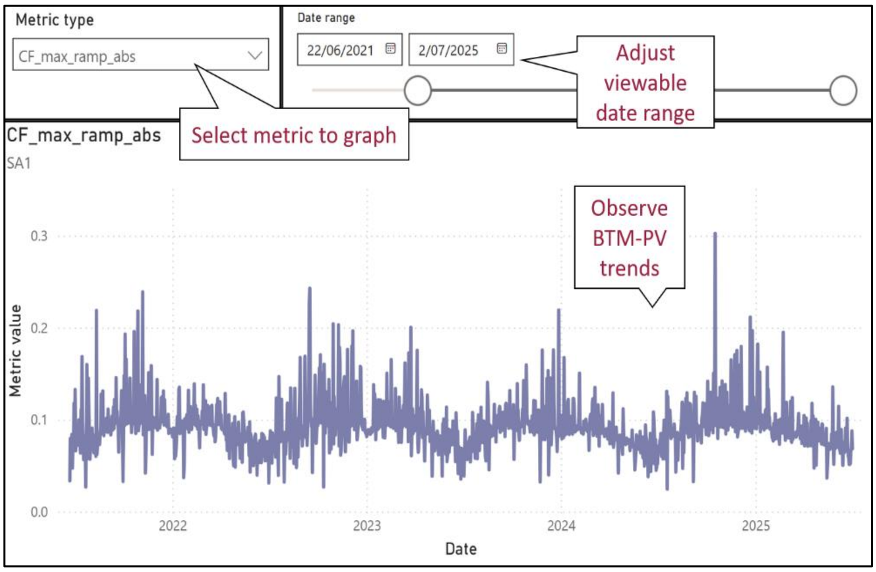

Figure 3 Solar Day Classification Tool (Power BI) – SA Capacity Factor Daily Maximum Distributed PV Absolute Ramps, 2021-2025

Having a tool to visualise various DPV characteristics provides a comprehensive picture of the behaviour and possible risks from DPV generation in managing and operating the energy system today and further into the energy transition.

3.2. Solar Droughts

The Solar Droughts tool utilises the Solar Day Classification's total daily generation characteristic to identify and visualise periods of consecutive days with low DPV *utilisation*. Utilisation is defined as the actual daily energy generated divided by the possible daily energy generation given clear sky conditions and time of year. Days with low utilisation translate to days with significant cloud cover.

Figure 4 shows the timeline of solar droughts along the x-axis, with each NEM region along the y-axis. Each dot represents a drought event where the colour and size relate to the intensity and duration respectively. The hover over text highlights a drought event for Queensland (QLD) that commenced on July 5, 2022. Here the drought event shows a period of two consecutive days where the daily DPV utilisation was less than 0.2 (20%), with a mean utilisation across the two days of 0.16 (16%).

The tool also includes a slider bar (at the bottom) to adjust the threshold level that defines a drought day. The ability to change the threshold allows for modelling of different use cases and changing characteristics of the energy system, thus facilitating detailed planning on how much energy storage is needed.

Work is underway to add DPV forecast data to this tool. This addition will identify any periods of solar droughts in the forecast horizon and will better inform the management and scheduling of *deep storage* systems as more DPV comes online.

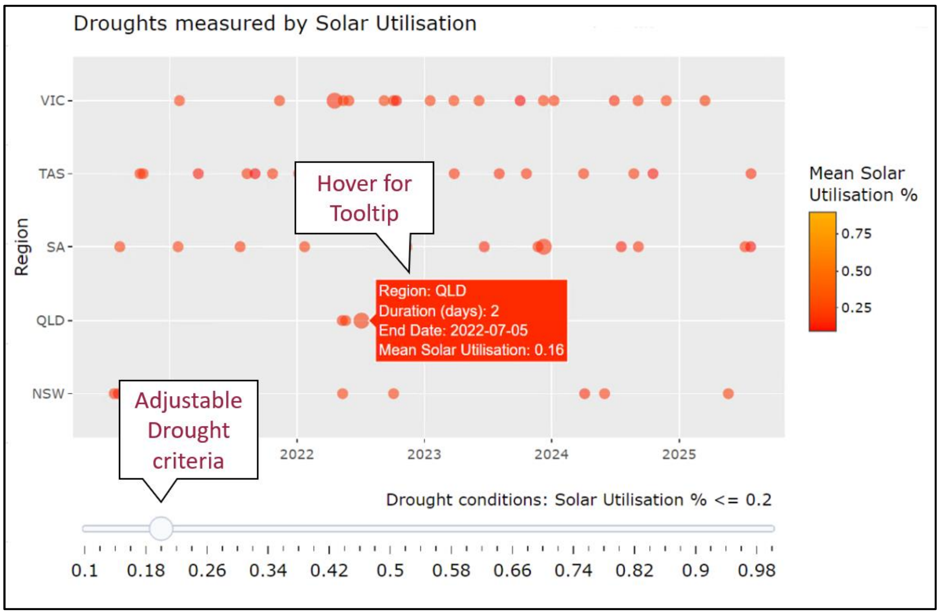

Figure 4 Solar Drought Tool (R Markdown) – Distributed PV Solar Utilisation, by Region, 2020-2025, with dot colour & size as intensity and duration of each drought, respectively.

3.3. DPV and Operational Demand Forecast Evolution and Relationship

The management and operation of an energy system is very reliant on forecast information. Because of the relationship between DPV actual generation and actual operational demand, as discussed in Section 2, it is also critical to understand the role DPV forecasts play in shaping operational demand forecasts.

A tool visualising DPV and operational demand actuals and forecasts has been created to assess how these forecasts evolve compared to what actually occurred. This tool allows for the selection of a day of interest, highlighting the observed MW values, along with each 30-minute forecast made throughout that day. This side-by-side view of DPV and operational demand allows for direct insights into how DPV affects operational demand, and how forecasts perform given different conditions.

Figure 5 shows October 17, 2024, a day where SA saw ramping and volatility in DPV generation due to the transient effects of clouds throughout the day. The DPV volatility resulted in operational demand volatility, with DPV (ASEFS2) on the left of the dashboard, and operational demand on the right. Actual values are shown by the purple lines, while point forecasts made at the chosen runtime are shown in teal. Demand ramping and volatility present a forecasting challenge as it is difficult to predict successive increases and decreases in DPV over a short period of time, particularly hours out from the event. The benefit of this tool to play through forecast runtimes, both statically and through animation, allows for the close monitoring of forecast performance as well as the relationship between DPV and operational demand, which ultimately informs forecast improvements.

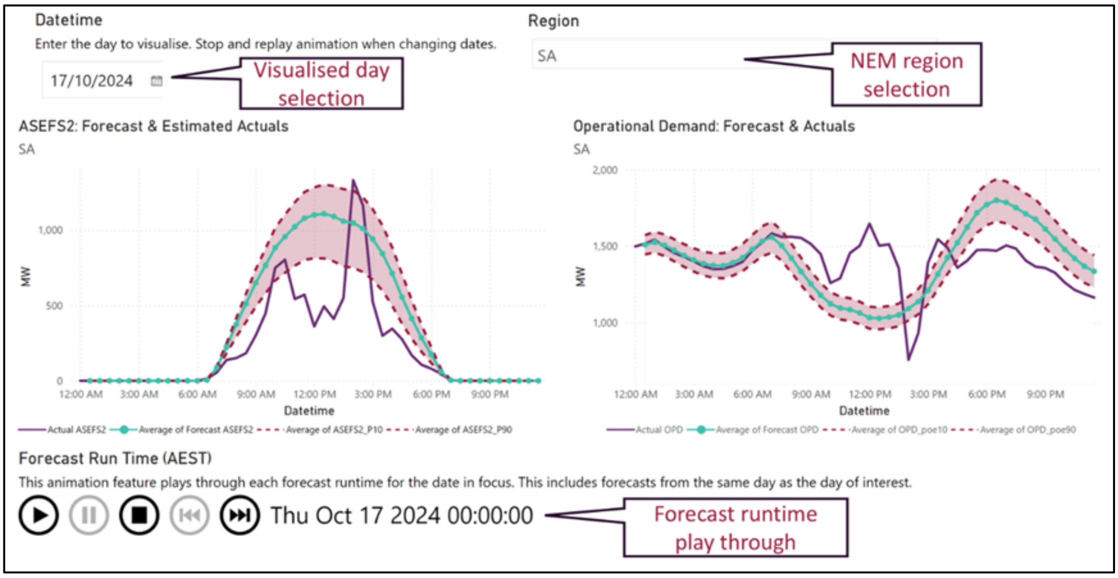

Figure 5 Forecast Evolution Tool (Power BI) – SA October 17, 2024, Distributed PV and Operational Demand Actuals with 12:00am Forecasts

To further assess the relationship between DPV and operational demand forecast accuracy, this tool has additional functionality to compare DPV and operational demand forecast deviations from actual values at different times of year and day. At a chosen forecast horizon or time, the correlation between these two deviations can be visualised, using interactive filters to adjust results shown. Figure 6 visualises the deviations of the forecasts made for 12:00pm (AEST), 12 hours ahead, for SA between the years 2020 and 2025. Here, the correlation between DPV and operational demand forecast deviations is -0.81. This strong negative correlation not only indicates the inverse relationship between DPV and operational demand, but also the relationship and role DPV forecasts play in forecasting operational demand for this time period in the middle of the day. Understanding and visualising the impact that DPV has on both operational demand and its forecasts in all NEM regions provides a basis for the proper management and operation of an increasingly high DPV energy system.

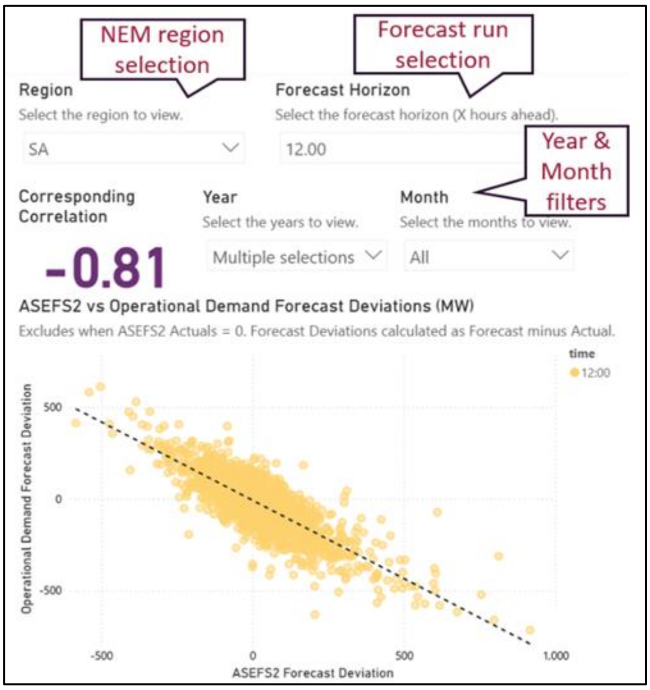

Figure 6 Forecast Deviation Correlation (Power BI) – SA 2020-2025, Distributed PV and Operational Demand 12 Hour Ahead Forecast Deviations from 12:00pm Actuals

4. DISCUSSION AND CONCLUSION

Australia's ongoing energy transition presents new challenges for managing and operating the NEM. Some of these challenges arise from the significant uptake to date, and predicted increased uptake, from DPV systems. The enhanced tools described in this paper have been instrumental in gaining a comprehensive understanding of DPV's behaviour and its corresponding impacts to Australia's NEM under a variety of conditions.

Whilst not discussed in this paper, additional tools have also been developed to look at DPV and operational demand forecast distributions, ramp trends and distributions, forecast performance and real-time monitoring. Developing the capability of these tools has made it easier to gain insights from the information currently available to support more informed energy system management, and to identify and increase awareness of emerging risks and challenges that high DPV uptake brings.

As the development of these dashboards and visualisations has been done internally within AEMO, they can easily be adjusted and developed with additional features and data that enhance the insights that they deliver. Conceptually, these tools could be applied to other relevant forecasting products, or developed for other time scales, such as five-minute, to more closely assess DPV and operational demand behaviour.

These tools, and others like them, provide the necessary insights to not only learn from history, but understand the important role forecasting plays and the need to continually monitor and improve forecast performance. Continuing to build on and apply the insights that these tools provide will be instrumental in ensuring that new and emerging challenges are properly understood and navigated to effectively manage an energy system with a high uptake of DPV.

REFERENCES

AEMO (2016) Australian Solar Energy Forecasting System, https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/nem-forecasting-and-planning/operational-forecasting/solar-and-wind-energy-forecasting/australian-solar-energy-forecasting-system, accessed 9 July 2025.

—— (2024a) 2024 Integrated System Plan (ISP), https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en, accessed 10 July 2025.

—— (2024b) NEM Electricity Statement of Opportunities (ESOO), https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/nem_esoo/2024/2024-electricity-statement-of-opportunities.pdf?la=en&hash=2B6B6AB803D0C5F626A90CF0D60F6374, accessed 10 July 2025.

—— (2024c) Supporting secure operation with high levels of distributed resources, https://aemo.com.au/-/media/files/initiatives/der/managing-minimum-system-load/supporting-secure-operation-with-high-levels-of-distributed-resources-q4-2024.pdf?la=en, accessed 30 July 2025.

—— (2025a) 2025 General Power System Risk Review, https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/2025-general-power-system-risk-review/2025-gpsrr.pdf?la=en, accessed 3 August 2025.

—— (2025b) Learnings from industry implementation of emergency backstop, https://aemo.com.au/initiatives/major-programs/nem-distributed-energy-resources-der-program/managing-distributed-energy-resources-in-operations/managing-minimum-system-load, accessed 6 August 2025.

—— (2025c) NEMWEB Market Data, https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/market-data-nemweb, accessed 22 July 2025.

—— (2025d) Operational Demand Data, https://aemo.com.au/energy-systems/electricity/national-electricity-market-nem/data-nem/operational-demand-data, accessed 10 July 2025.

—— (2025e) Quarterly Energy Dynamics (QED), https://aemo.com.au/energy-systems/major-publications/quarterly-energy-dynamics-qed, accessed 29 July 2025.

Renew Economy (2025a) Rooftop solar is a "burning platform," warns network boss: "Don't wait for the fire", https://reneweconomy.com.au/rooftop-solar-is-a-burning-platform-warns-network-boss-dont-wait-for-the-fire/, accessed 1 September 2025

—— (2025b) Rule change proposes paying big batteries to "charge as needed" when rooftop solar floods the grid, https://reneweconomy.com.au/rule-change-proposes-paying-big-batteries-to-charge-as-needed-when-rooftop-solar-floods-the-grid/, accessed 1 September 2025

