THE GENERATOR OPERATIONS SERIES

Report Two: Ramp Rates for Solar and Wind Generators on the NEM

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Australian Government
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ARENA

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EXECUTIVE SUMMARY

Understanding how quickly solar and wind farms can "ramp" their generation up or down in response to variable weather conditions is relevant to understanding how a high penetration renewables grid (from off-grid applications to the NEM) can best operate, and the requirements for storage or backup generation to account for intra-day weather variability. Ramp rates are one of the factors in determining whether a grid will remain stable after a sudden drop and then increase in generation due to thick cloud cover passing quickly over a solar farm or change in wind speed at a wind farm.

This new empirical analysis on wind and solar "ramp rates" will assist developers and operators in being able to better optimise the design of hybrid power systems and the appropriate storage, forecasting and other strategies required to best manage generation variability. This study analyses high frequency (i.e., 4 second) dispatch data from 2020 at 54 grid-connected solar and wind generators to improve the understanding of the relationship that exists between size (i.e., geographical footprint and capacity) and ramp rates. We report on the probability distributions of 4-second, 6-second, 60-second and 5-minute ramp rates.

The findings can help to inform on-grid and off-grid applications; however, developers of off-grid hybrid power stations have the most to gain from the presented outcomes. Off-grid power stations can achieve higher renewable energy fractions if their design accounts for ramp rates at short time intervals (i.e., sub 5-minute). Previously, there has been limited analysis of empirical evidence that quantifies ramp rates for variable renewable energy (VRE) generators at short time intervals.

The new knowledge presented in this study can directly inform decisions made in the design stage for off-grid hybrid power stations and allow for better integration of renewable energy generation with diesel and/or gas generators, leading to higher renewable energy fractions.

Where possible, periods of curtailment unrelated to weather were filtered out from generator dispatch data so that the analysis focussed on understanding how weather alone impacts ramp rates. The geographical footprints of generators have been calculated as an approximation of the area encompassing all generation units using manually sourced geospatial data.

The solar farms included in this analysis range from 10 to 180 MW of registered AC capacity, that occupy anywhere between 22 to 560 ha of land. The wind farms range from 29 to 452 MW of registered AC capacity, where the estimated area surrounding individual turbines takes up anywhere between 749 to 13,453 ha of land.

This study presents several new insights on the behaviour of ramp rates at variable renewable energy generators:

- The 4-second 0.01 per cent probability of exceedance for solar PV (i.e., the 1 in 1000 probability of exceeding a normalised ramp rate) reduces by 0.046 per cent for every additional MW of capacity installed. This value increases to 0.065 per cent when considering the 5-minute 0.01 per cent probability of exceedance ramp rate.
- The 4-second 0.01 per cent probability of exceedance for wind reduces by 0.011 per cent for every additional MW of capacity installed. This value increases to 0.034 per cent when considering the 5-minute 0.01 per cent probability of exceedance ramp rate.
- Prior studies have demonstrated that normalised ramp rates reduce as the geographical area of variable renewable energy generators increase. This study demonstrates that this relationship remains valid at higher time resolutions of 4-seconds and 6-seconds, as well as at one-minute and 5-minute frequencies, and can be empirically quantified based on generation and geospatial data collected at a large number of generators.
- Solar generators experience a greater reduction in variability due to geographical dispersion than wind generators. This is made evident by the greater percentage reduction for solar ramp rates when compared with wind ramp rates in the rules of thumb set out above.
- Increasing the geographical footprint of generators has a greater effect on reducing variability over longer time frequencies than shorter time frequencies.

Title page image: Clouds pass over Moree Solar Farm

TABLE OF CONTENTS

Image: EDL Coober Pedy Hybrid Renewable Project

INTRODUCTION

This report is the second in a series of analyses of the detailed operational data from utility-scale renewables on the National Electricity Market (NEM). The increased uncertainty in electricity supply due to the rapid growth of solar and wind generators[1] presents challenges for both owners of generators and, when considering the combined impact of ramping, grid operators. By improving the understanding of the relationship between the size[2] of solar and wind generators and the expected ramp rate distribution, developers and operators can optimise the design of hybrid power systems and the appropriate storage, forecasting and other strategies to best manage variability.

One of the three challenges identified in AEMO's report titled 'Managing Variability and Uncertainty' was that there is a limit to the accuracy of deterministic forecasts of expected ramps, even using current best practice approaches. Forecasting limitations increase uncertainty and the need for greater ramping reserves[3] [3]. In the NEM, uncertain forecasts can also negatively impact asset owners by imposing higher causer pays factors.

While the lessons learned from this analysis inform both on-grid and off-grid applications, developers of off-grid hybrid power stations have the most to gain from the outcomes in this study. In order to strive for significant renewable energy fractions in off-grid applications, developers need confidence on the magnitude and frequency of ramp rates to be expected from power systems. This study quantifies the relationship existing between the size of variable renewable energy generators and ramp rates at short time intervals. This information can directly inform decisions made in the design stage for off-grid hybrid power stations and allow for better integration of renewable energy generation with diesel and/or gas generators.

Ekistica and ARENA have historically analysed variability and the impact it has on power systems and networks. In 2015, Ekistica and ARENA published a report outlining the impact solar irradiance variability has on PV power ramp rates by comparing data from nine weather stations spread out across Alice Springs [1]. Additionally, ARENA and Ekistica published another knowledge sharing report in 2018, which analysed solar PV ramp rates for geographically dispersed PV arrays at Yulara [2]. These reports quantified how geographically distributing solar PV mitigates weather variability, and that in some scenarios, load variability can be of greater concern.

1 Note that "solar and wind generators", "variable renewable energy generators", and "semi-scheduled generators" are terms often used throughout this study. Unless otherwise stated and within the on-grid context, all terms generally refer to large-scale grid-connected solar and wind generators.

2 The term "size" is often referred to throughout the study. Unless explicitly stated, the size of a generator refers to both the power capacity and geographical footprint (area). As proven in this study, the power capacity and geographical footprint of a generator are strongly correlated with one another.

3 Ramping reserve is defined by the United States' National Renewable Energy Laboratory as capacity available for assistance in active power balance during infrequent events that are more severe than balancing needed during normal conditions and are used to correct non-instantaneous imbalances [1].

BACKGROUND

A key objective in delivering electricity securely and reliably is ensuring the supply of electricity meets demand. Solar PV and wind generators are fast outpacing demand as the key drivers of variability and uncertainty in the NEM and Western Australia's South-West Interconnected System (SWIS) [3]. As variable renewable energy (VRE) continues to account for more of the electricity generation mix, the uncertainty of electricity supply across time intervals increases and becomes harder to predict. Operators, such as the Australian Energy Market Operator (AEMO), are responsible for managing this uncertainty associated with all generation technologies to ensure the electricity supply is reliable and secure.

The consequences of failures to manage abrupt changes in VRE generation are magnified in fringe-of-grid and off-grid applications where there is often limited energy resource diversity and availability. These regions of the grid are generally more susceptible to blackouts. This can place pressure on developers to design power stations more conservatively and strive for relatively small renewable energy fractions (REFs) [4]. This is especially true in the mining industry where avoiding expensive downtime in mining operations is paramount and blackouts can have health and safety implications if underground mining operations rely on power. In order to instil confidence in striving for higher REFs, developers are looking to more accurately quantify VRE ramp rates at short time intervals (i.e., sub-5-minute). Developers want better knowledge around the relationship that exists between the size of solar and wind generators and ramp rates to inform the design of hybrid power stations (i.e., renewable energy generation integrated with other energy generation technologies).

Previous analysis conducted by AEMO [3] focussed on assessing VRE ramping across time intervals of 5-minutes to 90-minutes. This study aims to assist industry in overcoming the challenge of forecasting limitations by sharing new knowledge from analysis on solar and wind ramp rates at shorter time scales (e.g., 4 second, 6 second, 60 second). This study also discusses the relationship existing between the size of VRE generators and their respective ramp rates.

Previous research demonstrates that for both solar and wind farms, increased geographical dispersion of solar modules or wind turbines reduces the variability of total farm output [5]. However, studies to date ([6], [7], [2], [8]) have tended to rely on data from a limited number of plants or on simulations of plant behaviour. By using the high frequency (4 second) data published by AEMO at 54 VRE generators on the NEM, this study provides an empirical basis for characterising the relationship between size and variability. A better understanding of the typical distributions of ramp rates will assist VRE plant developers and operators in assessing the feasibility of investments in forecasting, storage or other technologies or strategies for managing output variability ([9], [10]).

EXAMPLE - OPERATIONAL MATERIALITY OF RAMP RATES

Designers and developers of off-grid and microgrid systems need confidence on what ramp rates can be expected from solar and wind generators at short timescales (e.g., sub 5-minute) to ensure the gas and/or diesel generators can respond quickly enough. They may need to consider installing alternative enabling technologies (e.g., battery, cloud forecasting technology) if the diesel and/or gas generators cannot adequately provide support to manage system ramp rates.

While installing a battery is a proven solution to managing ramp rates at short timescales, it is expensive. In the design stage, developers are questioning whether a cheaper alternative to installing a battery might be to increase the capacity, and therefore geographical footprint, of a solar and/or wind farm to reduce normalised ramp rates (i.e., with respect to the power capacity installed) to levels that fall within the risk appetite for the client.

One developer indicated that 52 minutes per year at risk is material when designing off-grid hybrid power stations. In other words, nominal ramp rates must not fall outside allowable boundaries for more than 52 minutes per year to satisfy the risk appetite of clients. This risk appetite equates to a 0.01 per cent probability of exceedance (POE). Sometimes the risk appetite can require even fewer at-risk intervals per year. This is because a single interval where the thermal generation is unable to ramp up fast enough to replace a sudden fall in renewable generator output can cause outages which last up to several hours. These can be extremely costly particularly for off-grid mine sites, and have safety implications for personnel. POEs are explained in more detail in the Methodology section of this study.

Typically, increasing the capacity of solar and/or wind farms will result in larger ramp rates from a power generation point of view. However, reducing nominal ramp rates might allow for a different combination of alternative generator technologies in some circumstances, potentially removing the need to install other, more expensive, enabling technologies. Similarly, better understanding the combined ramp rates from co-locating solar and wind generators might change what enabling technologies are installed to support overall system ramp rates. Note, this study does not assess ramp rates from co-locating solar and wind farms.

Developers have indicated that limited empirical analysis has been completed to date to help inform some of the decisions above. This study conducts empirical analysis on grid-connected assets to broaden the literature in this space to better inform developers designing hybrid power stations for off-grid applications.

Image: Emu Downs Solar Farm and Emu Downs Wind Farm

METHODOLOGY

REMOVING PERIODS OF CURTAILMENT

AEMO's four second public dispatch data for the year 2020 was downloaded and analysed for the solar and wind farms included in this analysis (see Figure 3 and Figure 4). As described in ARENA's first report in the Generator Operations Series [11], large-scale generators are subject to many external factors before being dispatched. Curtailment of generators can occur through binding constraints applied by AEMO, negative pricing events, or limits on the capacity of the generator at the inverter level. Curtailment has significant impact on ramp rates for most large-scale generators. In some instances a generator may be operating at full capacity only to be completely shut off in the next time interval.

For many VRE generators, periods of curtailment cause the greatest individual ramping events. Where possible, periods where a semi-dispatch cap signal was sent from AEMO and the energy cleared during that period was less than the plant availability (i.e., non-weather related curtailment) were filtered out from generator dispatch data. This was so the analysis focussed on understanding how weather alone impacts VRE ramp rates. Not all periods of curtailment[4] were able to be removed and the results may therefore be slightly skewed to include some periods where ramping was a result of external factors (e.g., thermal constraints, local voltage limits, avoiding negative pricing) outside of weather.

Prior to analysis of the ramp rate distributions, a number of filtering steps were performed to exclude ramping events not due to natural resource variability. Past studies using grid data to analyse VRE ramp rates have identified the necessity for excluding sudden falls in output due to curtailment or outages from the analysis [12]. For solar, irradiance levels below 100 W/m^2, and resultant plant output below 10 per cent of rated capacity, are unlikely to be the result of a cloud event ([13], [14]).

On this basis, three filters were applied to the 4 second generation data from AEMO:

1. Periods where a binding constraint was operating to curtail output through AEMO's NEM Dispatch Engine (NEMDE) or where the 5-minute regional reference price (RRP) fell below 0 were excluded.
2. Periods where the farm generation fell below 5 per cent of the rated capacity were excluded.
3. Generators missing significant portions of data were removed entirely from the analysis.

Figure 1 visually demonstrates discarding undesirable periods of data from the analysis for a solar (left) and wind (right) generator. For the day represented in Figure 1, significant amounts of data have been removed for the solar farm (left), indicating the large number of periods where AEMO sent a semi-dispatch cap signal and the energy cleared was less than the energy available. These are periods where the generator's output was ramping, but not as a result of changes in weather.

4 Note that in the context of this study, and unless otherwise stated, periods of curtailment refer to periods where a semi-dispatch cap signal was sent from AEMO and the energy cleared was less than the plant availability at the time (i.e., non weather related curtailment).

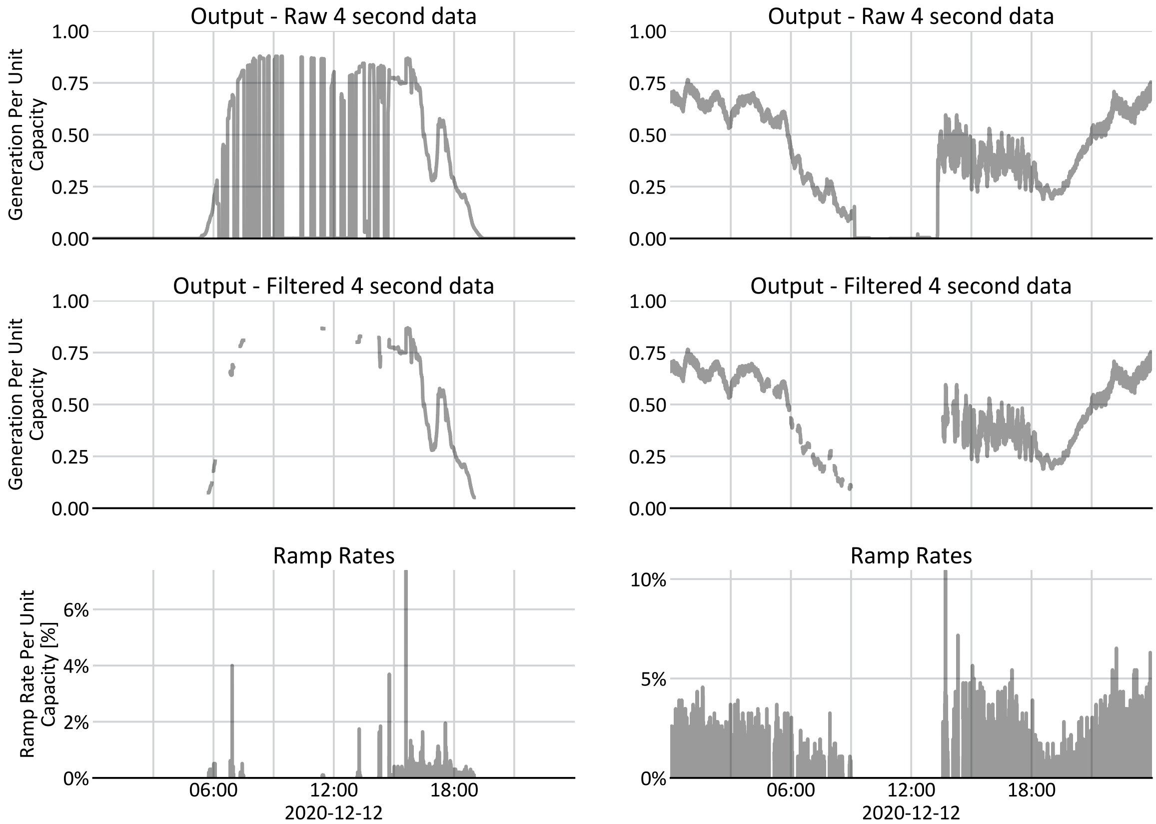

Figure 1. Process of filtering normalised ramp rate data and calculating 4-second ramp rates for solar (left) and wind (right) farms

PROBABILITY OF EXCEEDANCE

Developers and network operators are often most interested in understanding what maximum ramping events can be expected from VRE generation. A previous study [6] reports on the 1-minute maximum ramping events across four different solar farms and comments on the importance for future studies to conduct similar analysis on a wider dataset at shorter time intervals (e.g., sub-1-minute). This study does not comment specifically on maximum VRE ramping events due to the uncertainty outlined above in distinguishing weather-related ramping events from those due to other external factors. This study instead reports on probability distributions of VRE ramp rates and probability of exceedances at 4-second, 6-second, 60-second and 5-minute resolutions. The probability of exceedance (POE) is the probability that a certain value will be exceeded in a future time interval.

EXAMPLE - POE

If the value of the 1 per cent POE 4-second ramp rate is 50 per cent of nominal capacity, this can be interpreted as: In any given 4-second interval, there is a 1 per cent chance that the ramp rate will exceed 50 per cent of the farm's nominal capacity. Alternatively, and perhaps more intuitively, this can be interpreted as: Over a year, it can be expected that 86 hours of operation will experience normalised ramp rates exceeding 50 per cent. A 0.1 per cent POE corresponds to 8.6 hours per year, while a 0.01 per cent POE corresponds to 52 minutes. One developer indicated that a significant risk is deemed to exist when ramp rates operate outside their allowable boundaries for more than 52 minutes per year (i.e., 0.01 per cent POE), and an even lower POE may be unsatisfactory in some circumstances.

For example, let us assume that a 100 MW solar farm has a 0.1 per cent POE 4-second ramp rate equal to 50 per cent of nominal capacity. This means that each year, on average, will have 7776 4-second intervals where the solar farm ramps up or down by 50 MW or more. In total, 8.6 hours across the year are at risk of having ramp rates exceeding 50 MW over 4 seconds.

RAMP RATES OVER DIFFERENT TIME INTERVALS

The interval of 4-seconds corresponds to the maximum resolution data published by AEMO. The intervals of 6 seconds, 60 seconds and 5 minutes have been selected to correspond to the three contingency event durations for which a contingency Frequency Control Ancillary Services (FCAS) market exists on the NEM [15].

Variable generation can result in significantly different ramp rates being calculated depending on the time interval they are calculated over. Figure 2 is a simple example demonstrating how over the period of approximately one hour, a generator's output varies anywhere from 25 per cent to 80 per cent of maximum output. Over this period, the four second normalised ramp rate does not exceed a few percent, while the five-minute normalised ramp rate reaches almost 40 per cent.

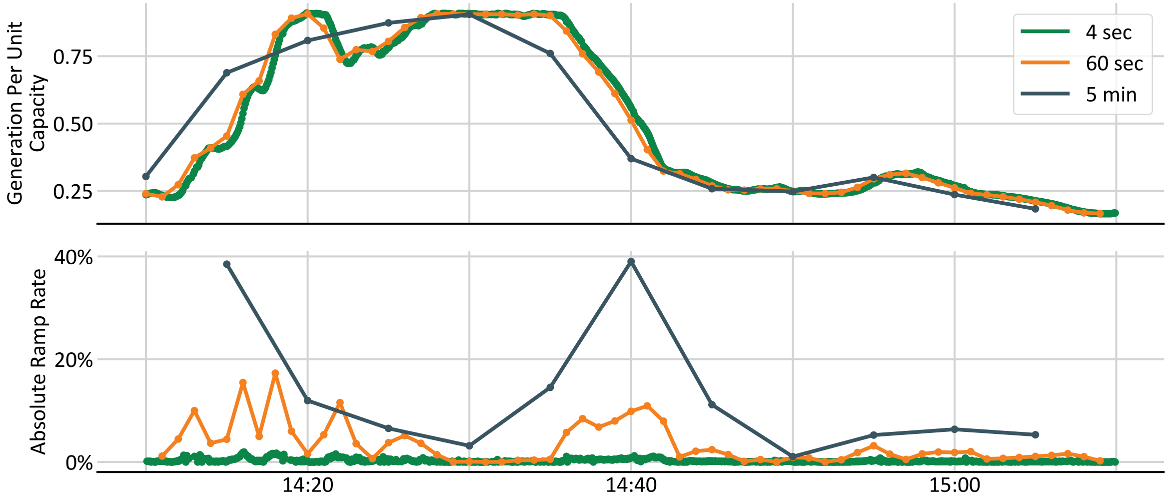

Figure 2. Ramp rates at four second, one minute and five minute frequencies over a one hour period for a solar farm

GEOGRAPHICAL FOOTPRINT

At higher time resolutions, the ramp rate for solar farms is determined by the time required for a cloud to cast a shadow across the modules at the farm. The highest ramp rates observed in [6] were some function of the area of the solar farm, the size and density of the cloud, and the speed at which the cloud is travelling.

For wind farms, ramp rates are dependent on local fluctuations in wind speed. However, as the distance between turbines increases, the correlation between wind speeds decreases, which smooths the output of the farm as a whole [16]. Therefore, it is expected that for both solar and wind VRE generators, the POE ramp rates will decrease as the footprint of the farm increases. Ultimately the geographical footprint, shape, and orientation with reference to weather fluctuations (e.g., cloud movement and wind direction) will influence POEs, however for simplicity the modelling undertaken only considers geographical footprint area.

Geospatial data was manually obtained and collated for solar and wind farms connected to the NEM. Generators were omitted from this analysis where geospatial data was unobtainable. Geographical footprints of VRE generators have been calculated using the geospatial data. The relationship between size of generators and respective ramp rates (i.e., quantify how geographically dispersing solar farms impact ramp-rates) have been established and discussed.

The geographical footprint for solar farms in this study are represented by either the solar array footprint or the convex hull footprint. The solar array footprint represents the area covered by the arrays of solar PV modules, which excludes the spacing between arrays, inverter, transformers, and access roads. The convex hull footprint approximates the area surrounding and including all solar PV modules (i.e., a border/perimeter drawn around the solar PV arrays). This surrounding area includes land space situated between individual solar PV arrays, which can be significant for generators where arrays are situated far apart.

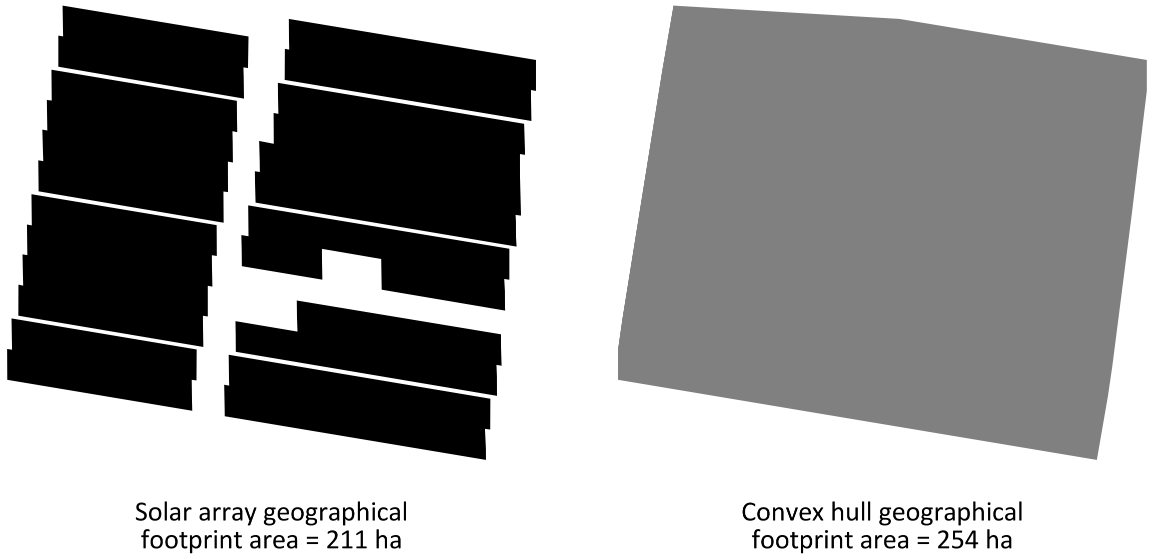

Figure 3. Comparing the solar array and convex hull geographical footprint area for Parkes Solar Farm

Figure 4 displays the solar array geographical layout for 39 of the 45 large-scale solar farms connected to the NEM. The geospatial data was not attainable for two projects.

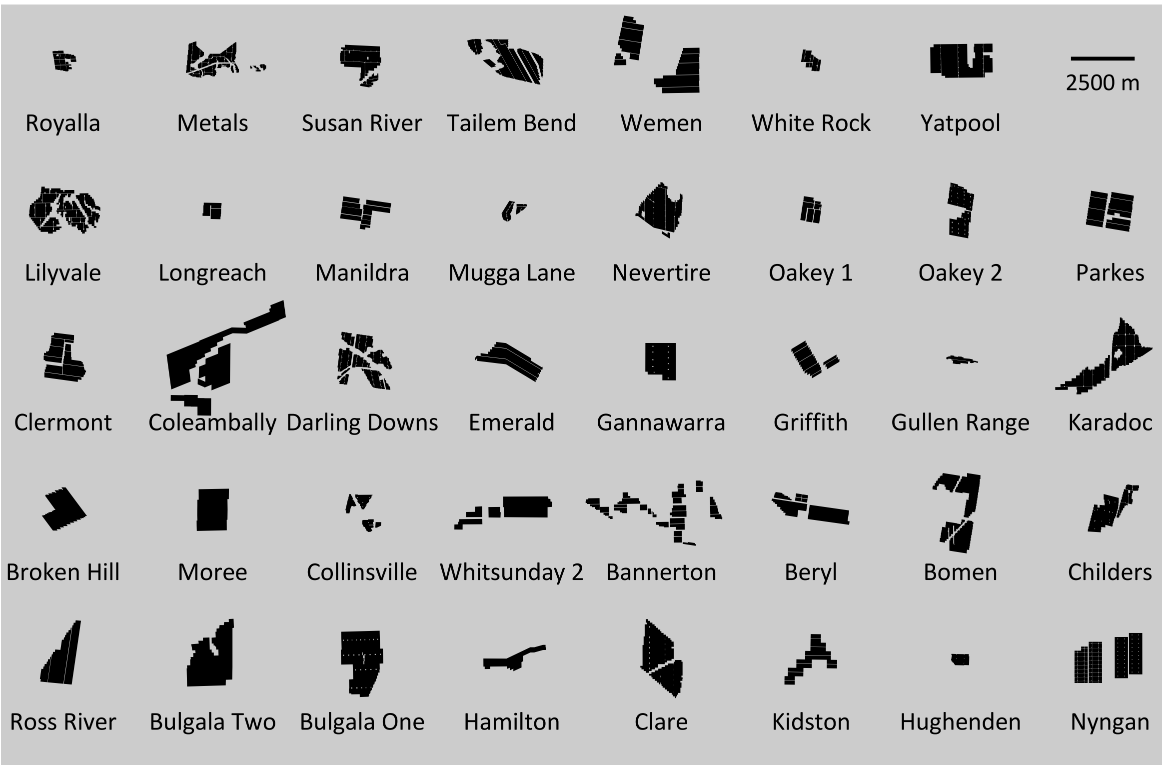

Figure 4. Geographical footprint for solar farms connected to the NEM. Note: Not all solar farms connected to the NEM have been included in this figure. Note that North is to the top of the page.

The geographical footprints for 15 of the 56 wind farms connected to the NEM are represented in Figure 5 by the convex hull footprint. The convex hull footprints are the shaded regions surrounding the individual wind turbines, which are represented by black dots. The 15 projects below span a wide range of sizes (i.e., both power capacity and geographical footprint) and were chosen to be included in this analysis as they are a relatively fair representation of the 56 wind generators connected to the NEM.

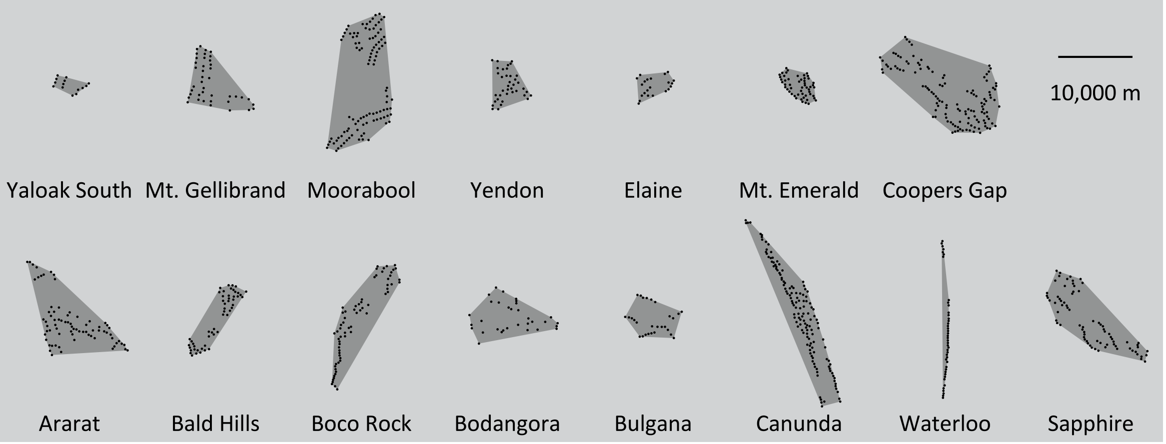

Figure 5. Geographical footprint for wind farms connected to the NEM, where points indicate wind turbine locations. Note: Not all wind farms connected to the NEM have been included in this figure. Note that North is to the top of the page.

GEOGRAPHICAL FOOTPRINT OF SOLAR AND WIND ON THE NEM

The solar farms included in this analysis range from 10 to 180 MW of registered AC capacity, where the solar PV arrays take up anywhere between 22 to 560 ha of land. The wind farms included in this analysis range from 29 to 452 MW of registered AC capacity, where the estimated convex hull area surrounding individual turbines takes up anywhere between 749 to 13,453 ha of land.

Figure 6 shows boxplot distributions comparing geographical footprint densities for solar and wind farms on the NEM. On average for solar, approximately 445 kW of registered PV AC capacity resides within 1 ha of land consisting only of solar PV arrays. This number falls to 313 kW per 1 ha of land when including land that encompasses spacing between arrays, inverters, transformers, access roads etc. While individual wind turbines require relatively small amounts of land, the convex hull area that encompasses all individual turbines is relatively large on a per MW basis when compared to solar. On average for wind, approximately 43 kW of registered AC capacity resides within 1 ha of land, which is 6 times the convex hull area required for the same installed capacity when compared to solar.

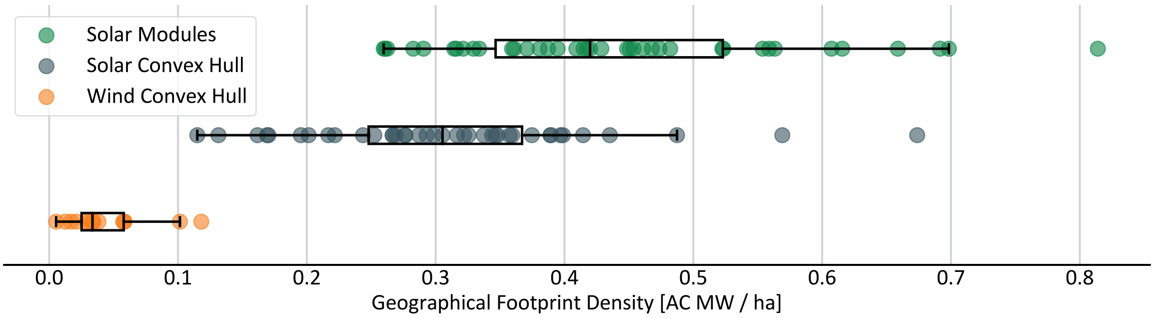

Figure 6. Boxplots representing the geographical footprint density for solar and wind farms on the NEM

RAMP RATES FOR SOLAR AND WIND GENERATORS ON THE NEM

Figure 7 shows ramp rate histograms at different time scales for a solar and wind farm of comparable capacity, where the probabilities of exceedance are represented by vertical dashed lines. All probabilities of exceedance increase as the time interval over which ramp rates are calculated increases. For both the solar and wind farm represented in Figure 7, the 0.1 per cent exceedance probability can be interpreted as there being a probability of 1 in 1000 that a four second ramp rate will exceed approximately 3 per cent of the total registered AC capacity, which equates to 4 MW. When considering five-minute ramp rates on the solar farm and wind farm, this value changes to 47 per cent and 19 per cent of total registered AC capacity, or approximately 60 MW and 25 MW, respectively.

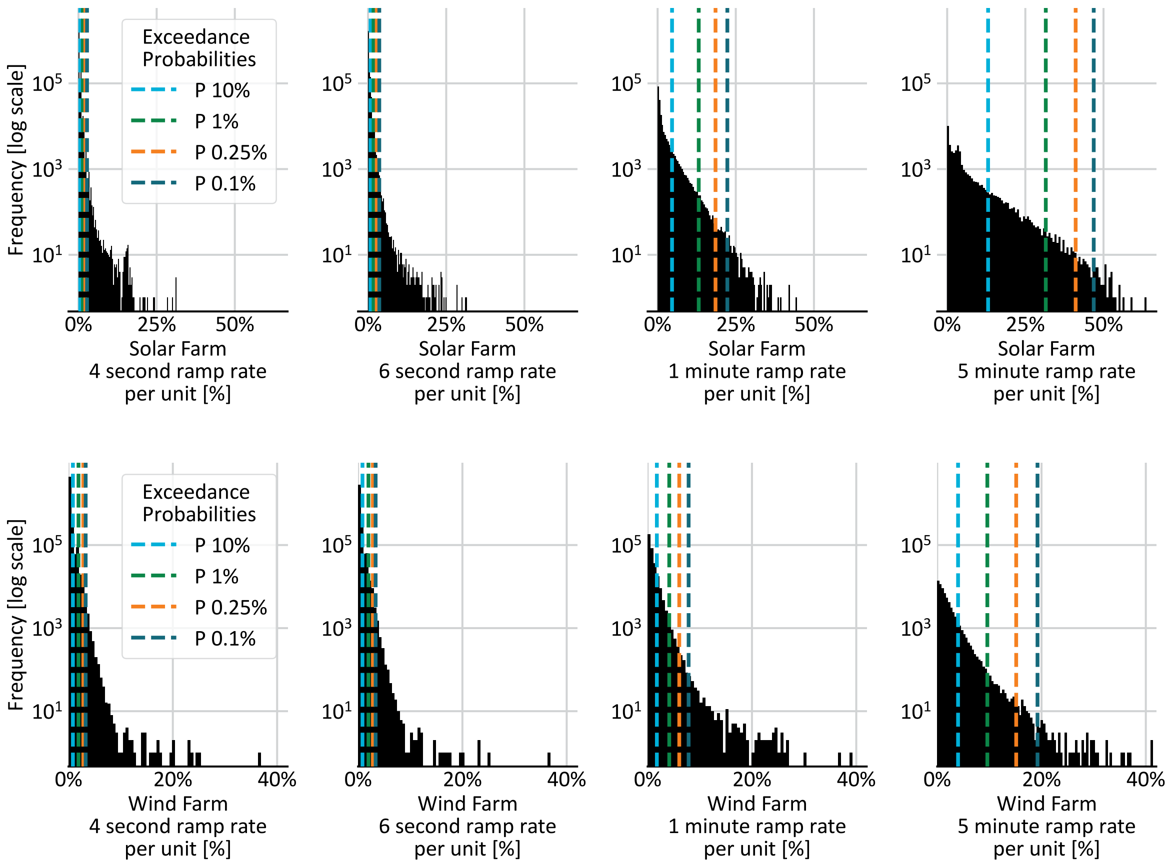

Figure 7. Histogram comparing the frequency of ramp rates at different time intervals for a solar and wind farm of comparable capacities on the NEM. Coloured lines indicate the different probability of exceedances. The x-axis is the normalised ramp rate, the y-axis is the number of occurrences represented with a log scale.

To put some of the above numbers in perspective, from March to May 2019, AEMO increased the regulation FCAS capacity from 130/120 MW (raise/lower) to 220/210 MW (raise/lower), which is used to balance supply and demand when actual generator output differs from forecasts. Contingency FCAS volumes have also increased [17]. AEMO appears to work with a maximum credible contingency equal to 750 MW (loss of Kogan Creek) [18]. However, regional or local ramp rates can be significant in less connected parts of the network over shorter time frames [3].

Figure 8 compares ramp rate occurrences across two solar farms and two wind farms of different nameplate capacities. Figure 8 shows the benefit that geographical dispersion can have on reducing ramp rates for both solar and wind. It also shows that solar farms tend to experience higher normalised ramp rates for longer periods of time when compared to wind. The smaller solar and wind farms experienced 5-minute normalised ramp rates greater than 30 per cent almost 3 times and 4 times as frequently as their larger counterparts. It is important to recognise that the ramp rates measured here are normalised, i.e., they are expressed as a percentage of nominal capacity. Larger actual ramp rates will likely be experienced on larger generators.

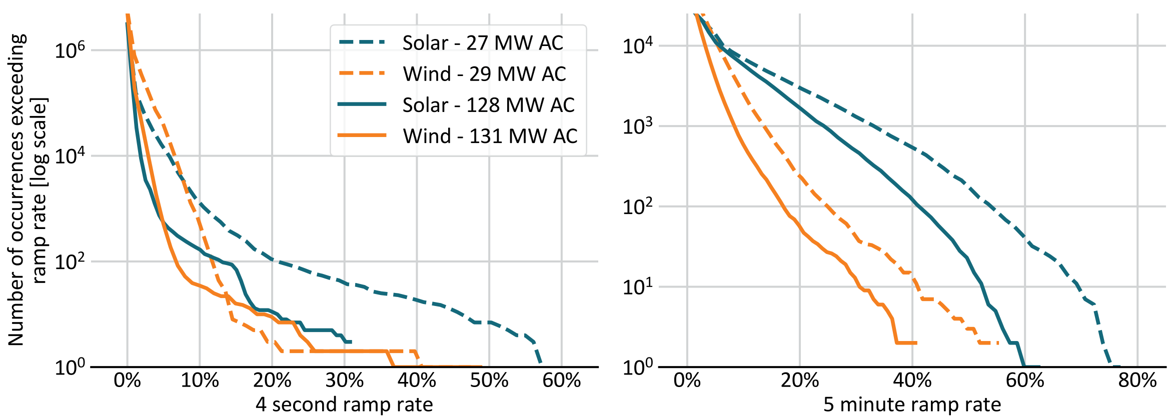

Figure 8. Comparing how ramp rate occurrences change with technology and nameplate capacity

Fitting a straight line to the data in Figure 9 demonstrates a relationship existing between geographical footprint and exceedance probabilities for solar and wind normalised ramp rates. For every additional hectare of land (i.e., convex hull) taken up by solar and wind farms, the 0.1 per cent exceedance probability (i.e., the 1 in 1000 probability of exceeding a normalised ramp rate) for four-second normalised ramp rates falls by 0.015 per cent and 0.00017 per cent, respectively. These values change to 0.025 per cent and 0.00092 per cent with respect to five-minute ramp rates for solar and wind generators. The key takeaways from this analysis are:

1. The magnitude of ramp rates at low probabilities of exceedance reduce as geographical footprints of solar and wind farms increase.
2. Increasing the geographical footprint (i.e., hectares of land) has a bigger impact on reducing solar ramp rates than it does compared to reducing wind ramp rates.
3. Increasing the geographical footprint (i.e., hectares of land) of solar and wind farms has a bigger impact reducing low POE ramp rates at lower time resolutions compared to ramp rates measured over shorter periods of time (i.e., 5-minute compared to 4-second).

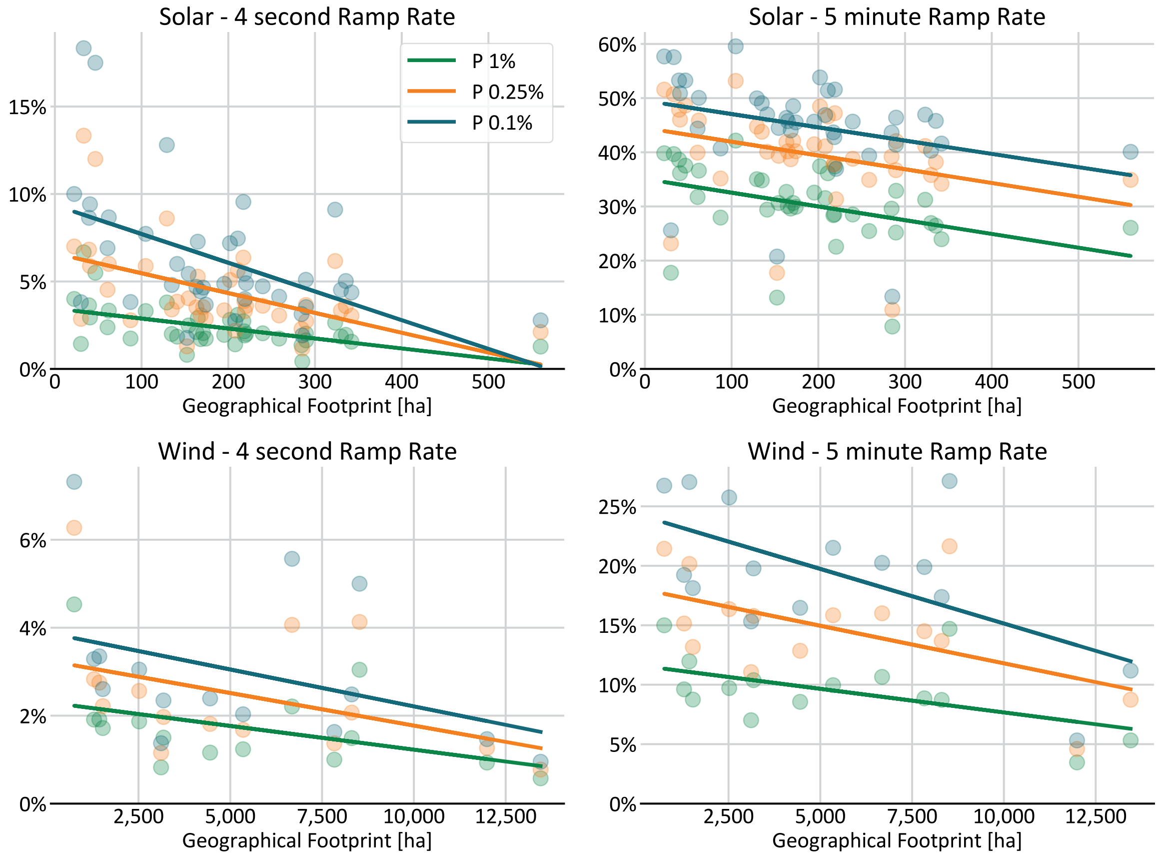

Figure 9. The relationship between normalised ramp rate exceedance probabilities and geographical footprints (convex hull)

The analysis above demonstrates the relationship between farm area and the magnitude of peak ramp rates, which is consistent with the established literature. However, the results also provide the basis for an analysis to determine the significance of area as opposed to capacity for characterising the ramp rate distribution. Figure 10 shows that for both solar and wind farms, the area of the farms is correlated with their registered capacities.

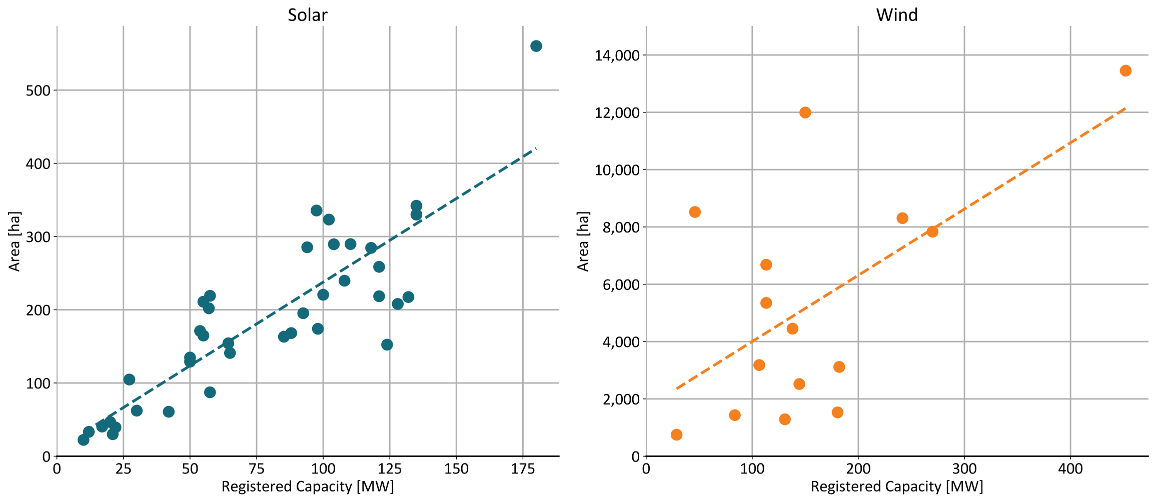

Figure 10. Correlation between registered capacity and area of solar and wind generators with line of best fit

A linear regression analysis was performed of the ramp rate magnitude at 1 per cent, 0.25 per cent and 0.1 per cent probabilities of exceedance against farm capacity, farm area and farm capacity and area. This analysis indicated that models using farm capacity alone performed better than models which used farm area or a combination of area and capacity as independent variables, with performance measured by the leave-one-out cross-validated root-mean-square error and the adjusted-R2 value. This result held for both solar and wind farms at 4-second and 6-second resolution, and at higher temporal resolutions, the performance of the capacity-only and capacity-area combination models was very similar.

While this analysis is based on a relatively small sample size (n=39 for solar, n=15 for wind), it indicates that VRE generator capacity is sufficient to approximate the expected peak ramp rates.

Image: DeGrussa Copper Mine Solar Hybrid Project

SUMMARY

The increased uncertainty in electricity supply due to the rapid growth of solar and wind generators presents challenges for both owners of generators and, when considering the combined impact of ramping, grid operators. This study analyses AEMO's public dispatch data from 2020 at 54 grid-connected variable renewable energy generators to improve the understanding of the relationship that exists between the size of solar and wind generators (i.e., geographical footprint and capacity) and ramp rates. This new empirical analysis conducted on high frequency (i.e., 4 second) datasets assists developers and operators in being able to better optimise the design of hybrid power systems and the appropriate storage, forecasting and other strategies required to best manage variability.

This study presents several new insights on the behaviour of ramp rates at VRE generators:

- It is worth noting that the relationship between normalised ramp rates and capacity will continue to change as technology efficiencies continue to change. The conclusions below reflect analysis conducted on dispatch data in 2020 from 54 VRE generators connected to the NEM. Acknowledging the limitations of the sample size within this study and the fact that not all periods of curtailment[5] were able to be excluded from the analysis, the following rules of thumb can be deduced.
    - The 4-second 0.01 per cent probability of exceedance for solar PV reduces by 0.051 per cent for every additional MW of capacity installed. This value increases to 0.098 per cent when considering the 5-minute 0.01 per cent probability of exceedance ramp rate. The 0.01 per cent probability of exceedance ramp rate for a 10 MW solar generator is approximately 9.76 per cent of installed capacity at 4-second resolution and 51.55 per cent at 5-minute resolution.
    - The 4-second 0.01 per cent probability of exceedance for wind reduces by 0.011 per cent for every additional MW of capacity installed. This value increases to 0.034 per cent when considering the 5-minute 0.01 per cent probability of exceedance ramp rate. The 0.01 per cent probability of exceedance ramp rate for a 10 MW wind generator is approximately 4.65 per cent of installed capacity at 4-second resolution and 24.47 per cent at 5-minute resolution.
- The relationship existing between ramp rates and the size of solar and wind generators has been reported in previous studies, specifically the fact that normalised ramp rates reduce as the size of VRE generators increase. The above rules of thumb confirm these relationships to exist and for the first time, quantify this relationship based on empirical generation and geospatial data collected from a large number of generators. The relationship exists because as the geographical dispersion of an individual VRE generator increases, the renewable resource relied upon is sourced from a larger area. This larger area results in a natural smoothing of resource variability and ultimately results in reducing ramp rates. This study demonstrates that this result remains valid at higher time resolutions of 4-seconds and 6-seconds, as well as at one-minute and 5-minute frequencies.
- Solar generators experience a greater reduction in variability due to geographical dispersion than wind generators. This is made evident by the greater percentage reduction for solar ramp rates vs. wind ramp rates in the rules of thumb above.
- Increasing the geographical footprint of generators has a greater effect on reducing variability over longer time frequencies than shorter time frequencies. The greater percentage reduction for VRE ramp rates at 5-minute intervals vs. 4-second intervals demonstrates this.
- In developing a model for estimating expected ramp rates at 0.1 per cent, 0.25 per cent and 1 per cent probability of exceedance, total generator capacity is an effective proxy for total geographical footprint.

5 Periods where a semi-dispatch cap signal was sent from AEMO and the energy cleared was less than the plant availability at the time (i.e., non weather related curtailment).

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