Operational Impacts of DER Integration in the SWIS

Energy Transition Hub Webinar – 21 April 2021

Julius Susanto, Principal Engineer, WA System Management Planning

Acknowledgement of Country - Perth

I would like to acknowledge that this meeting is being held on Aboriginal land, the land of the **Whadjuk** people of the Noongar Nation. I pay my respects to their Elders past, present and future.

Outline

Section	Topics
The South West Interconnected System (SWIS)	• Introduction to the SWIS • Rooftop PV integration in the SWIS
Operational Impacts of DER Integration	• Low load issues • System load volatility • Ramping and cycling • Emerging contingency risks • Impact on Under Frequency Load Shedding (UFLS) • Impact on system restart

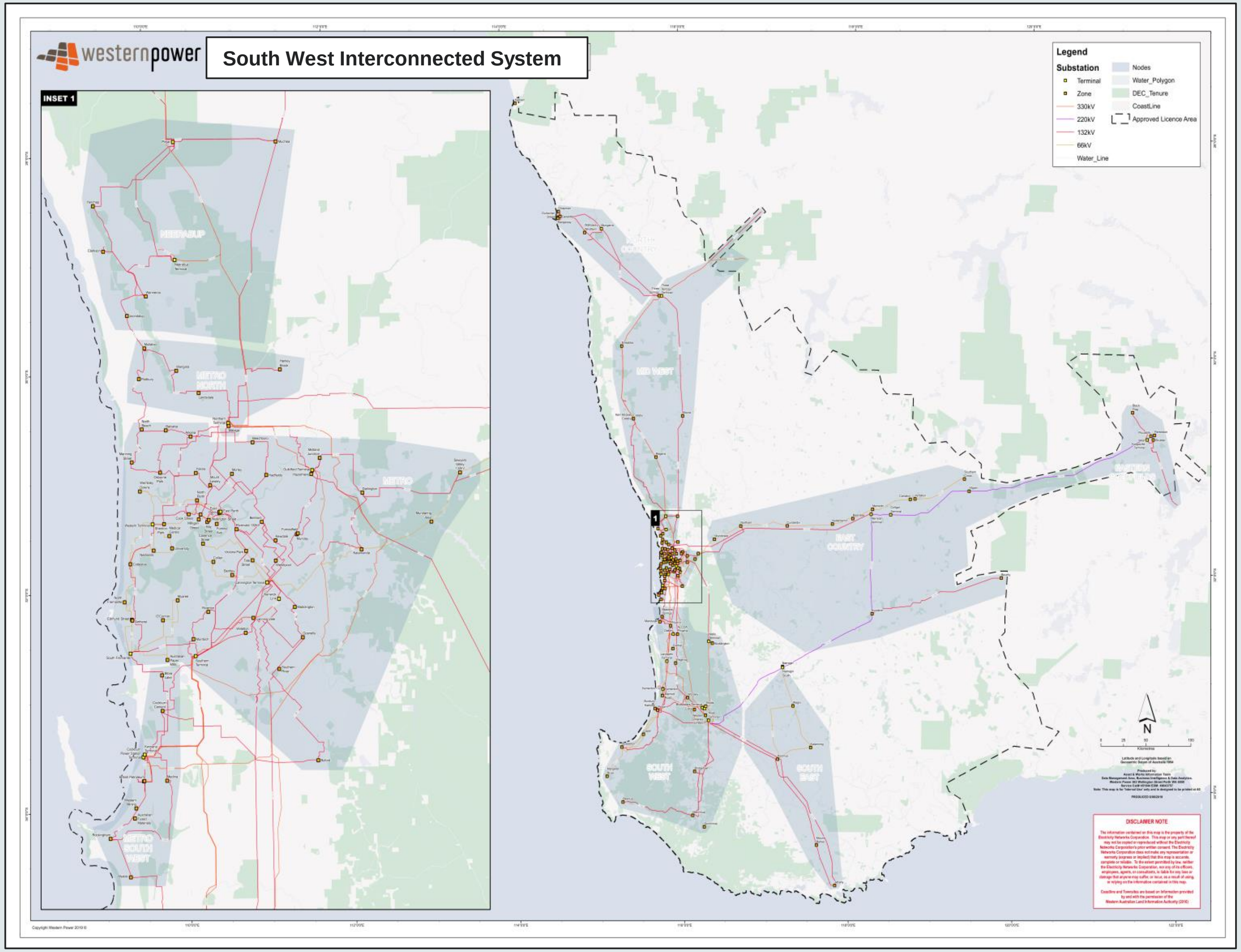
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

The South West Interconnected System (SWIS)

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

South West Interconnected System (SWIS)

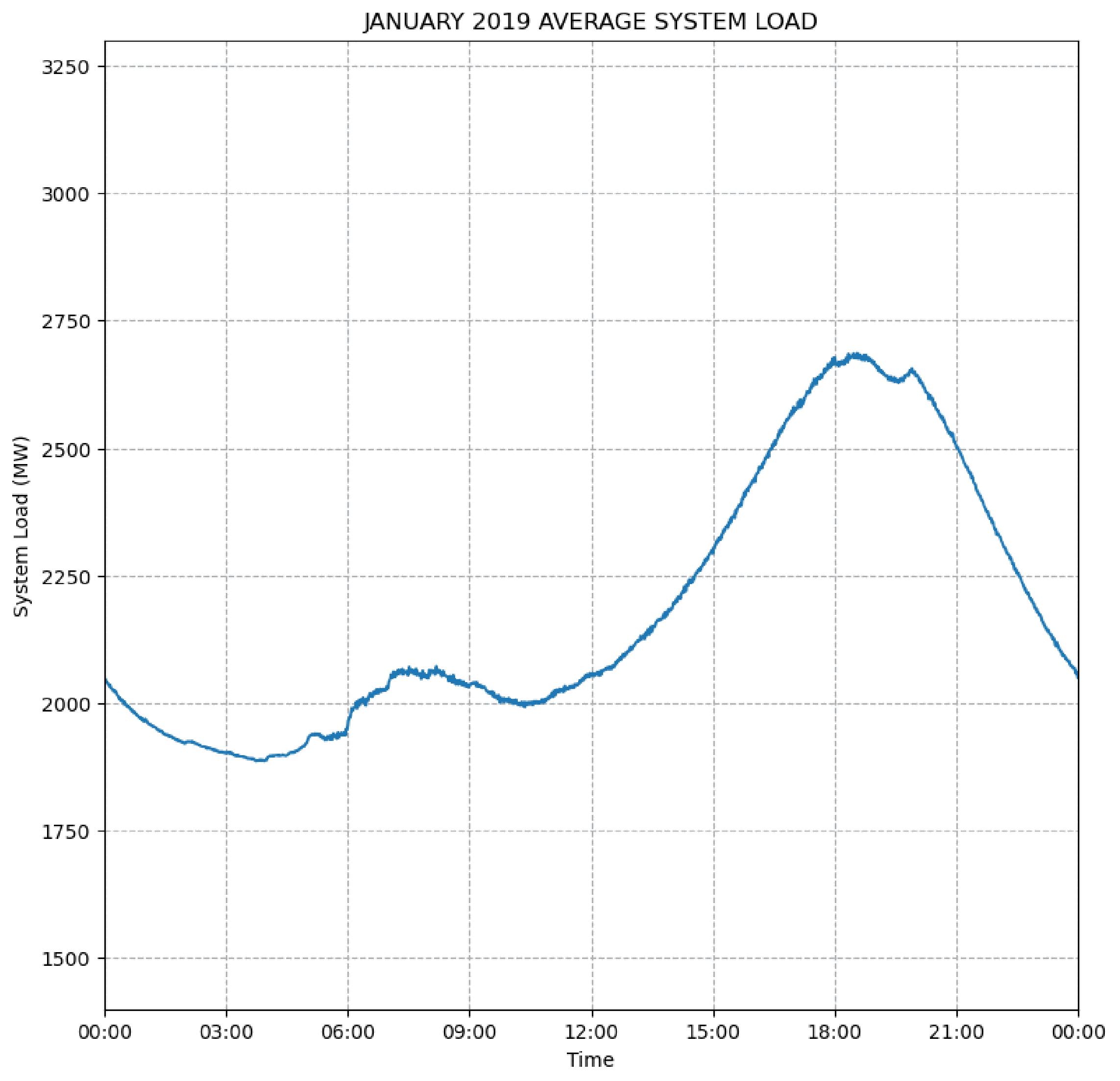
- The **South West Interconnected System (SWIS)** is a medium-scale islanded power system that serves ~1.2 million customers in the southwest of Western Australia.
- Peak demand in the SWIS is only 4,300 MW, but the grid covers a geographic area of ~261,000 km^2 (greater than the land area of the UK, which has a power system with a peak demand of ~59,000 MW).
- There are >6,000 km of transmission lines and >64,000 km of distribution lines.



AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

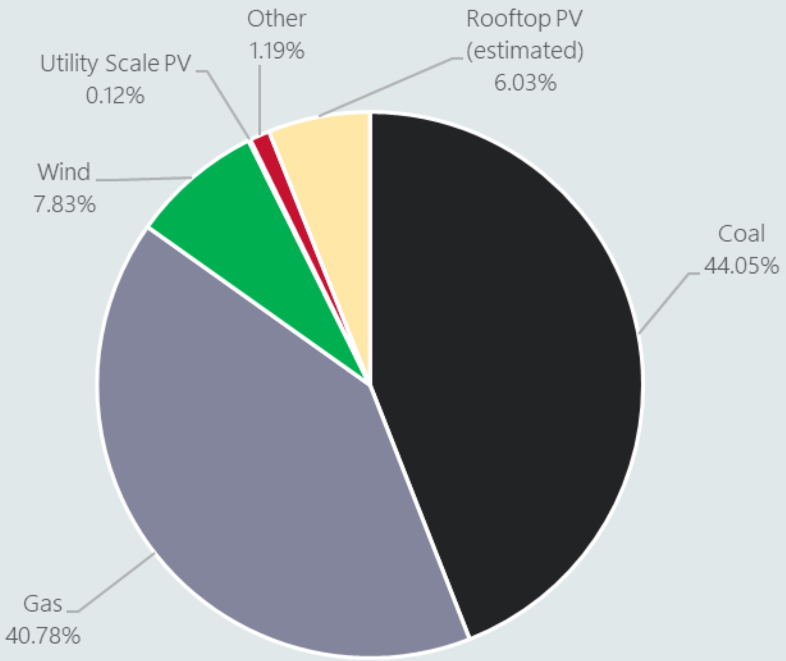
SWIS System Load

- The average daily System Load profile for the SWIS is shown in the animation on the right from January 2019 to December 2020
- Daily load profiles change throughout the year and are highly dependant on temperature
- Distinct seasonal variations in system load, i.e. moving between single-peak (Summer) and two-peak (Winter)
- Duck curve effects are most prominent over the Spring months (September to November)

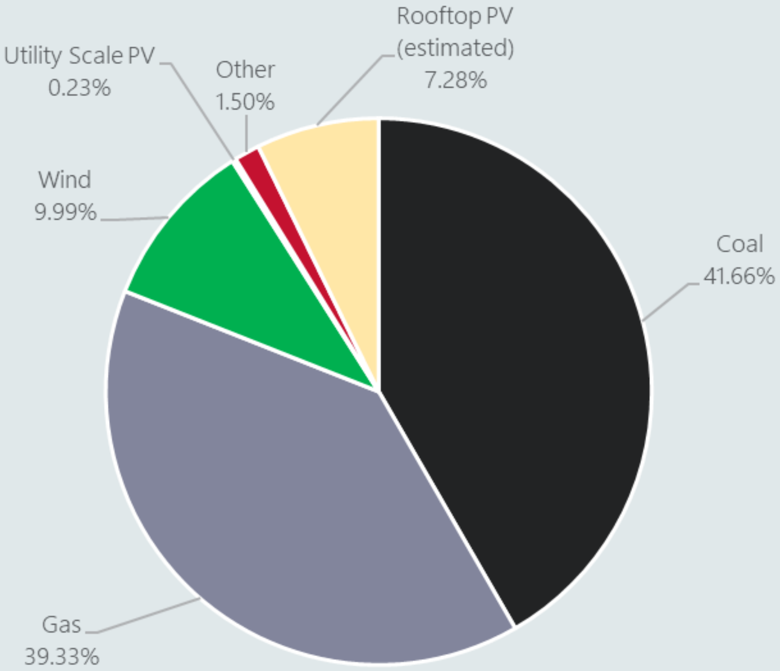


AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

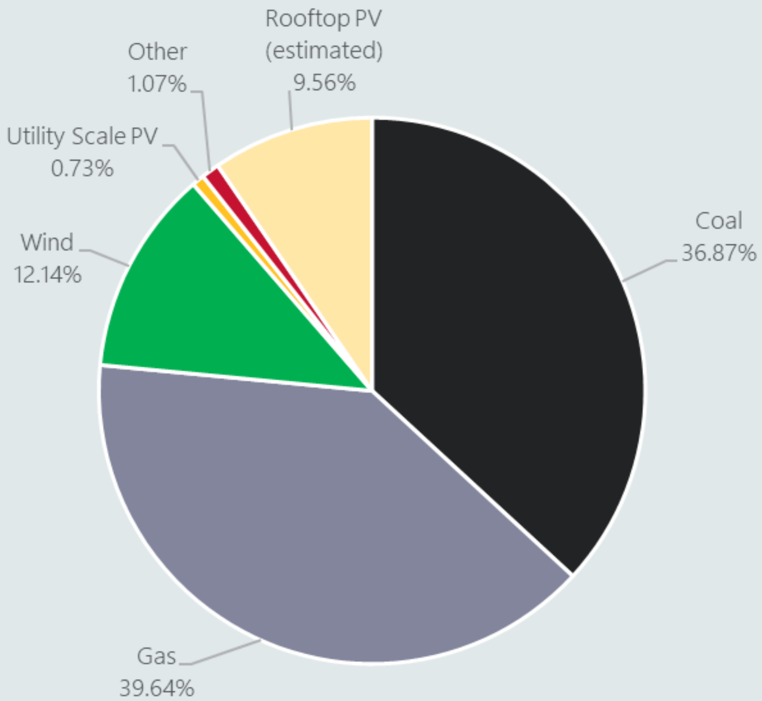
SWIS Generation Mix 2018 - 2020



2018



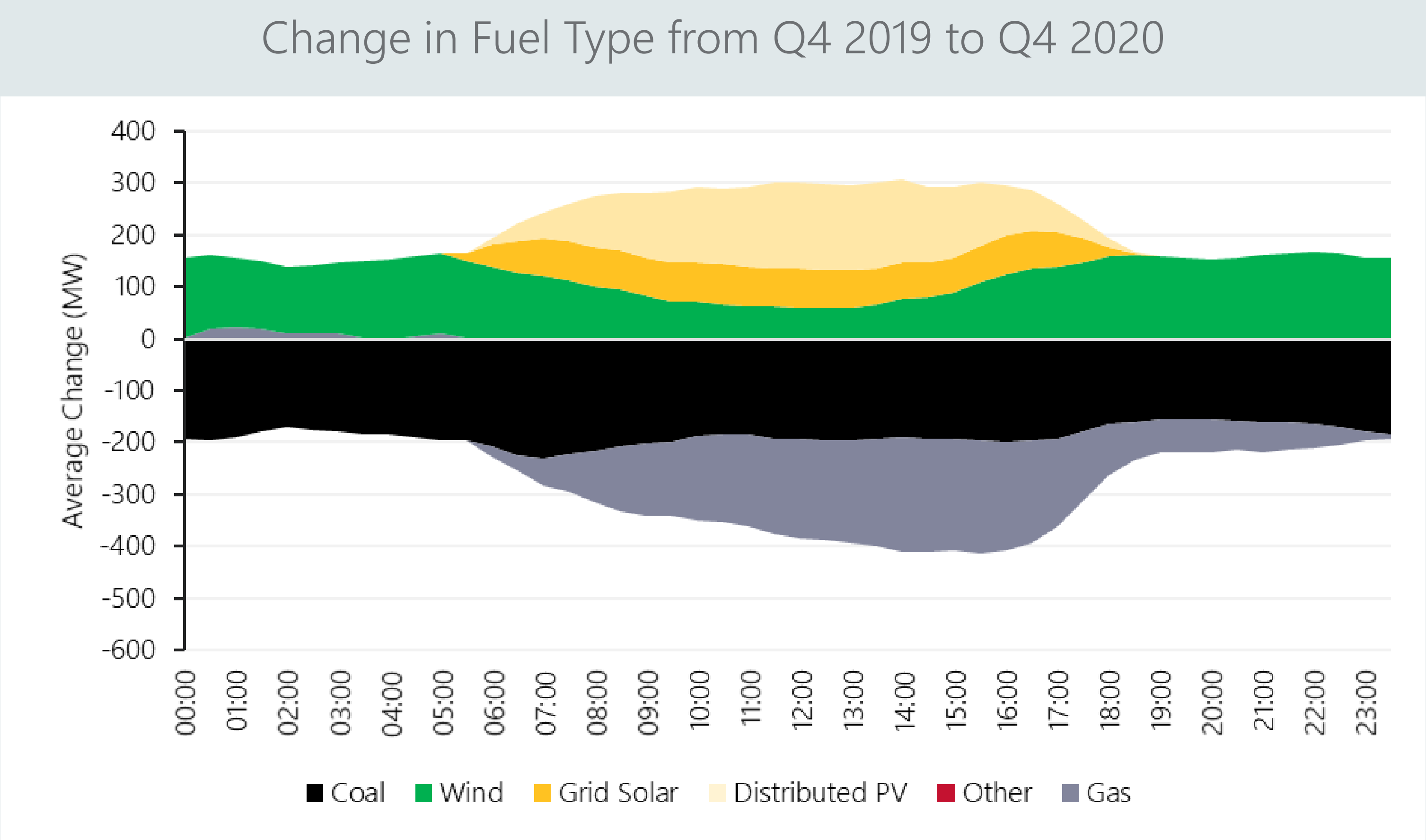
2019



2020

Calculated based on gross energy generation (MWh) over each calendar year (excluding embedded generators)

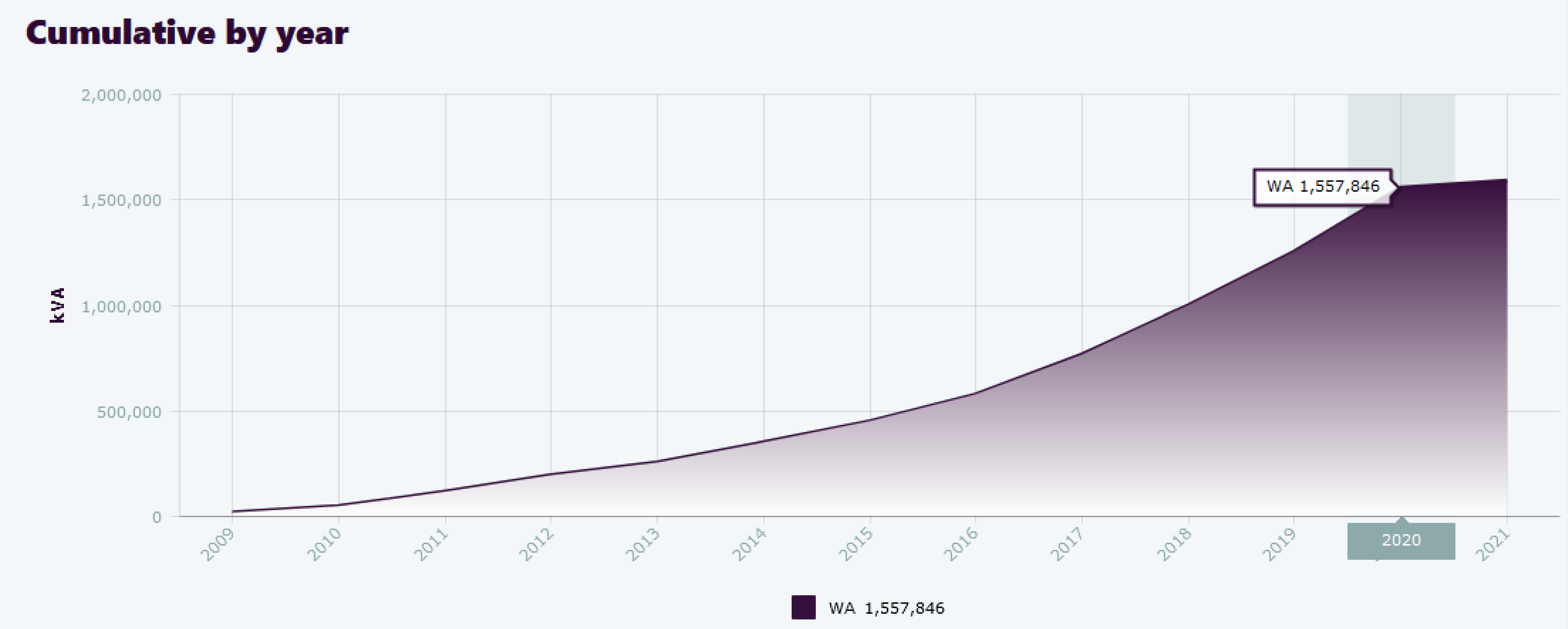
Changes to the Generation Mix



Source: Quarterly Energy Dynamics Report
https://aemo.com.au/energy-systems/major-publications/quarterly-energy-dynamics-qed

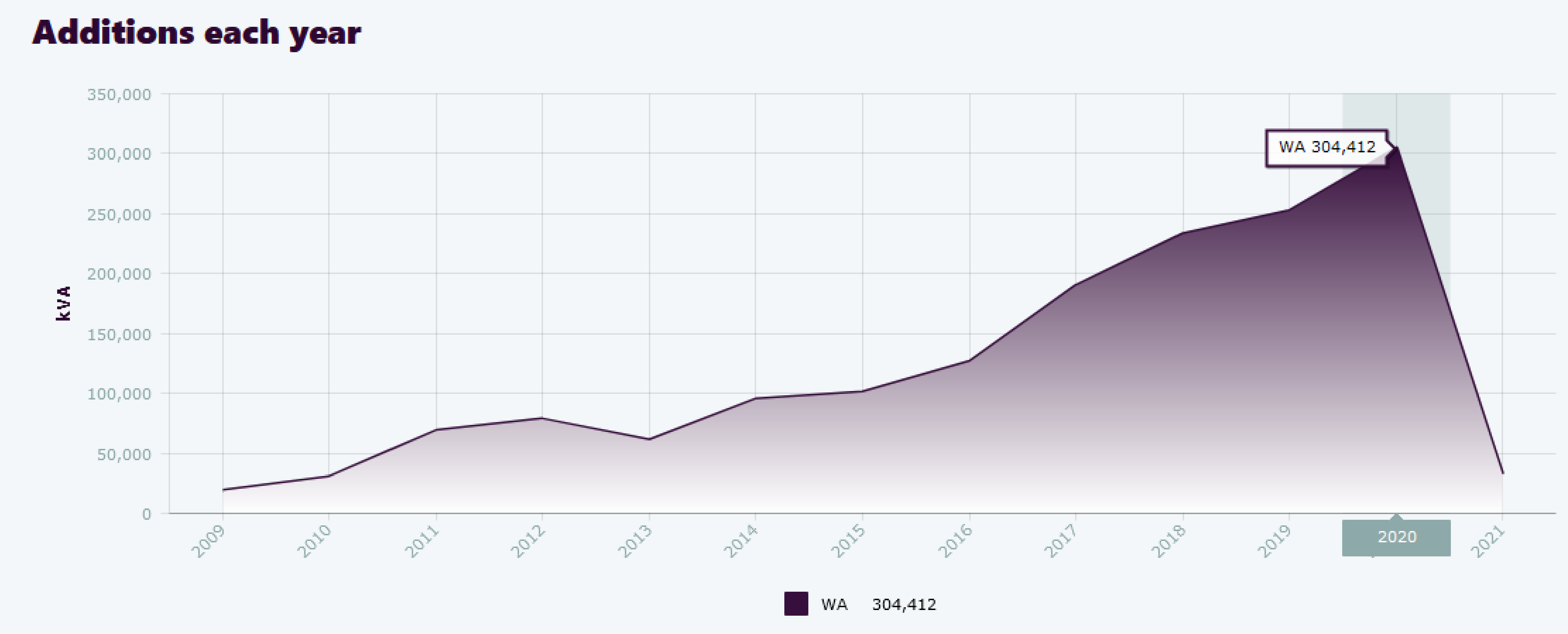
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Rooftop PV Installed Capacity



Source: https://www.aemo.com.au/energy-systems/electricity/der-register/data-dashboard-der

Growth in Rooftop PV Capacity



Source: https://www.aemo.com.au/energy-systems/electricity/der-register/data-dashboard-der

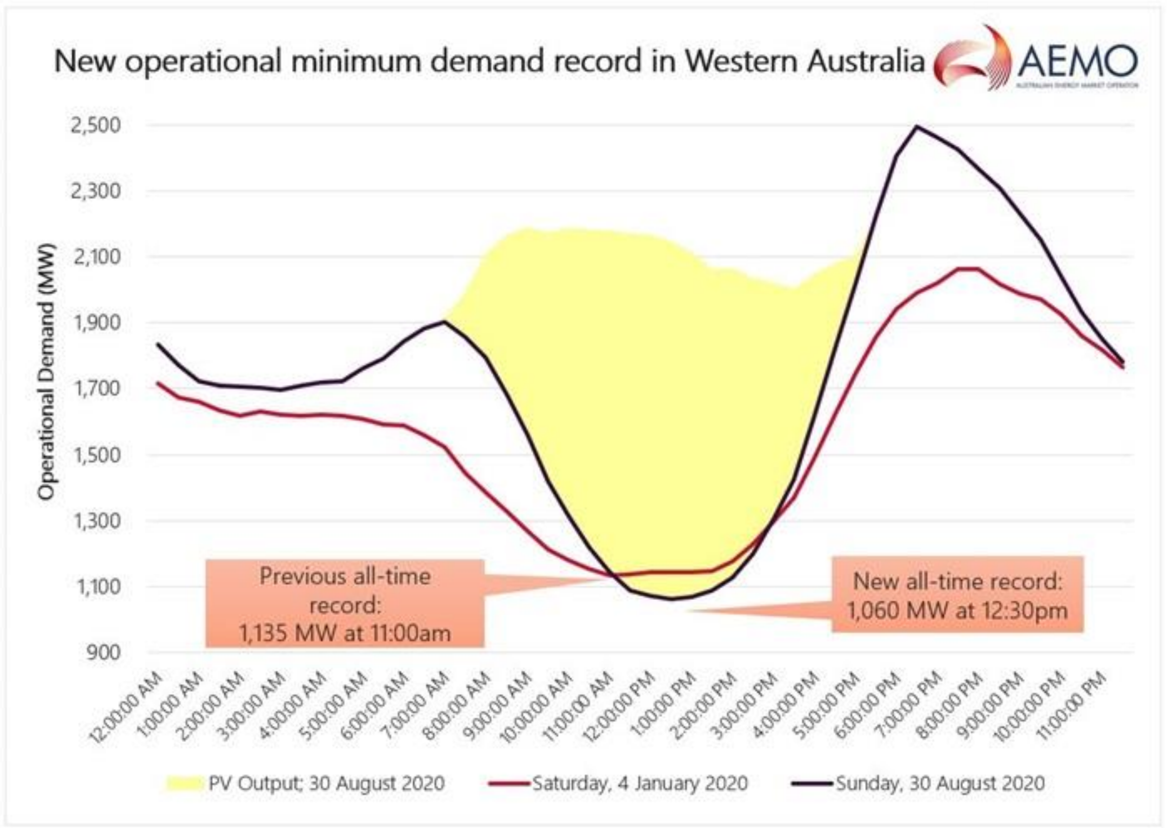
Per Capita Rooftop PV Capacity (as at December 2020)

State	Population	Rooftop PV Capacity [1] (kVA)	Rooftop PV Capacity (kVA per capita)
SA	1,769,300	1,539,629	0.870
QLD	5,174,400	3,386,758	0.655
WA	2,661,900	1,557,846	0.585
VIC	6,694,900	2,753,437	0.411
TAS	540,600	192,018	0.355
ACT	431,100	150,474	0.349
NSW	8,164,100	2,419,176	0.296

[1] Capacity connected to the NEM or SWIS only

Sources:
https://www.aemo.com.au/energy-systems/electricity/der-register/data-dashboard-der
https://www.abs.gov.au/statistics/people/population/national-state-and-territory-population/latest-release

SWIS Duck Curve

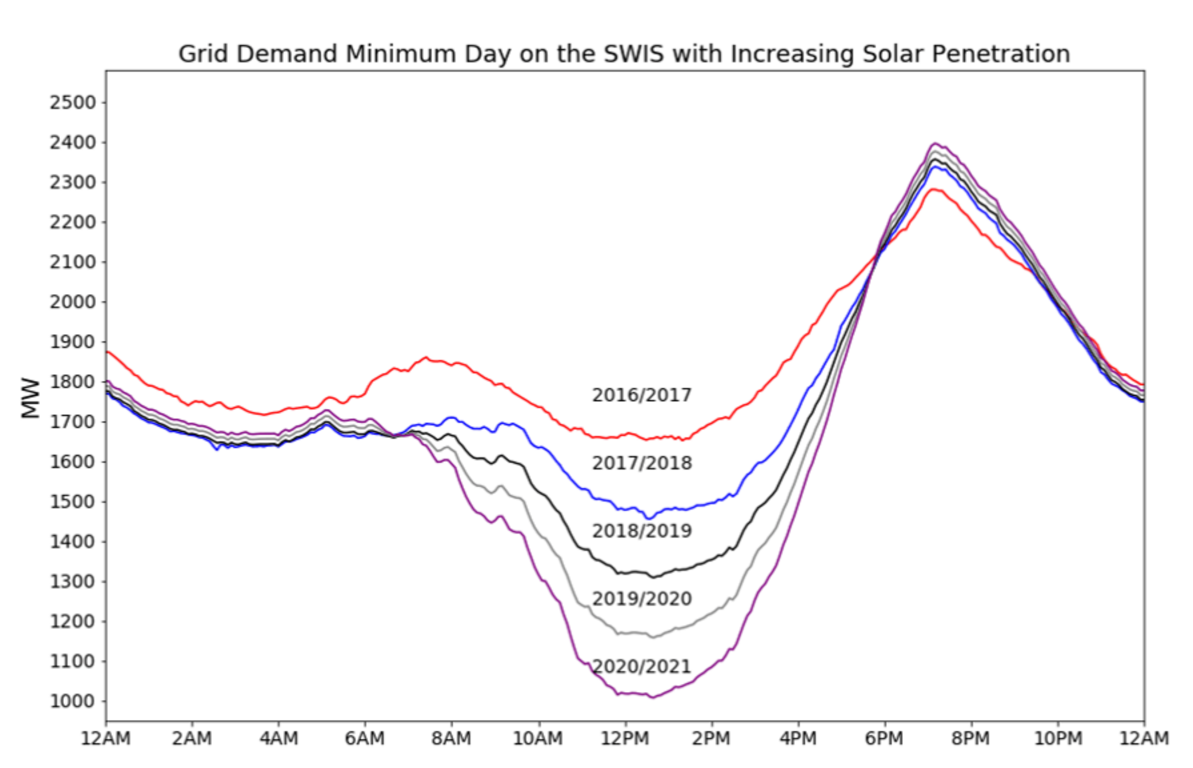


Note that this record has been broken twice since August 2020.
Source: https://aemo.com.au/newsroom/news-updates/min-op-demand-records

- Factors affecting the belly of the duck:
  - **Clear skies**
  - **Ambient temperature:** mild daytime temperatures (20-25°C) is a comfortable temperature requiring little space heating and/or cooling, while also being cool enough for efficient PV performance
  - **Position of the sun:** solar declination angle peaks at the Summer solstice (21-22 December)
  - **Day of week:** system loads are lower on weekends, particularly on Sundays
- In the SWIS, a mild sunny Sunday in the Spring shoulder season (September - November) is the sweet spot for daytime minimum demand and solar PV output.

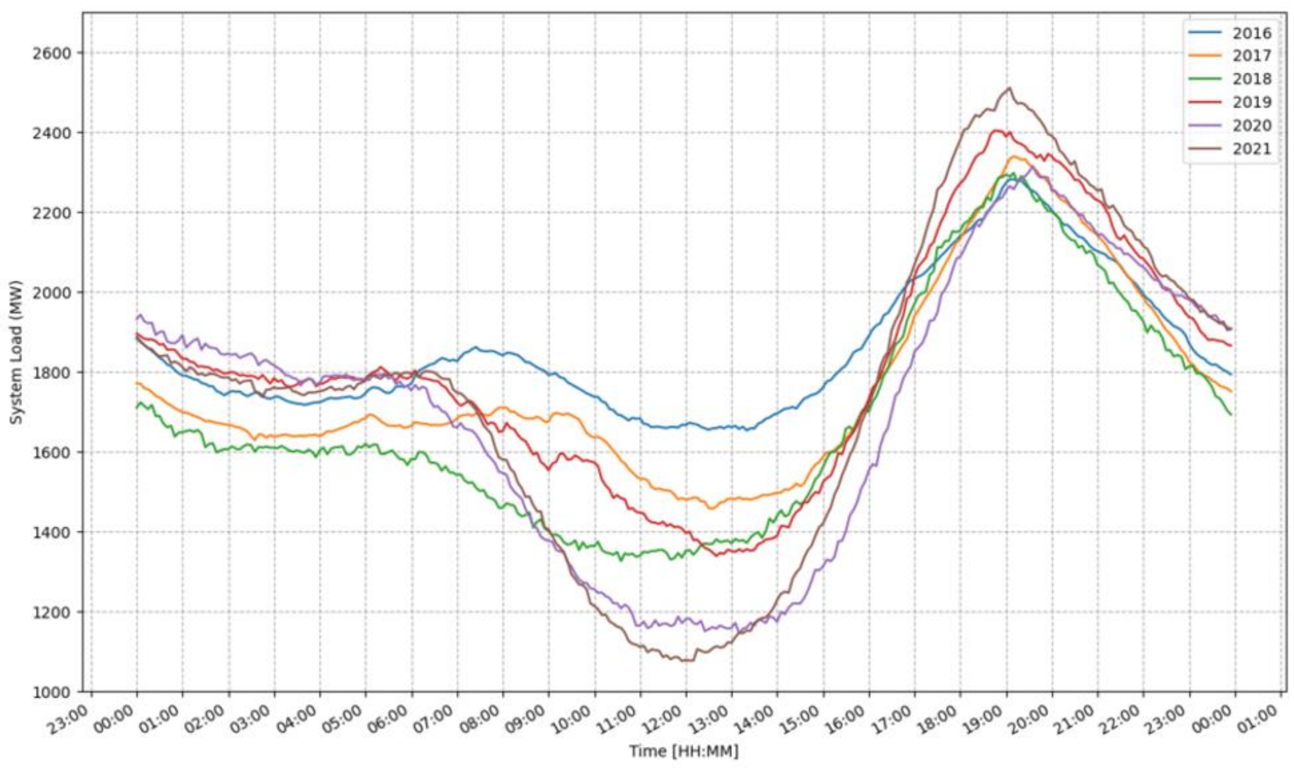
Evolution of the SWIS Duck Curve

Minimum demand day forecast from 2018:



Note that 2016/17 and 2017/18 are actual measured loads

Actual minimum demand days for each year:



The 2021 minimum demand day was on 14/03/2021

Operational Impacts of DER Integration

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Low Load Issues

How system operability issues arise from low daytime loads due to excess DER penetration

Low system load

- Excess DER triggers low daytime operational loads

Synchronous generator decommitment

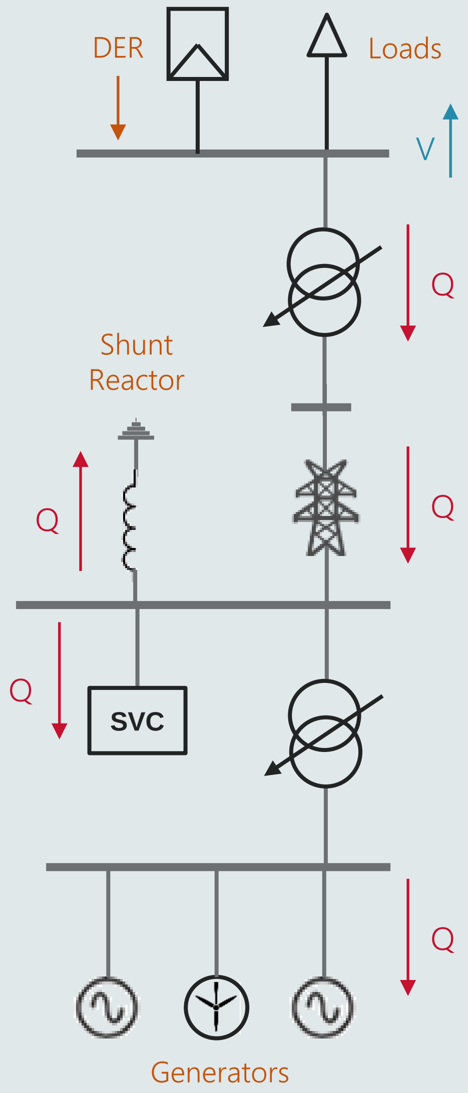
- Synchronous generators out of merit (crowded out by DER and renewables)
- Economic decommitment of base load generators

System operability impacts

- Voltage control
- Low inertia and frequency stability
- System strength

Low Load Issues: Voltage Control

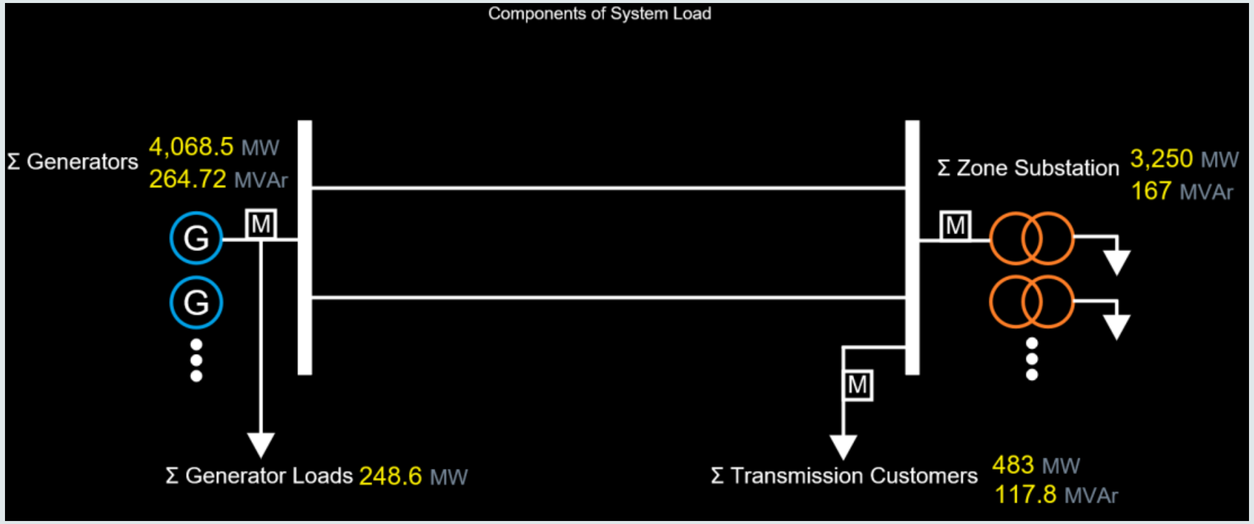
- At low daytime system loads:
  - DER (as well as underground cables) push up local distribution voltages
  - Zone substation transformers tap changers are adjusted to near minimum settings to control distribution voltages causing reactive power to flow upstream to the transmission system
  - Lightly loaded transmission lines also inject net reactive power into the system (from line capacitance)
  - Synchronous machines, shunt reactive plant and SVCs are required to absorb the excess reactive power to regulate transmission network voltages to within acceptable limits
- As synchronous generators decommit, voltage control options are diminished and there is higher risk of over-voltages developing on the transmission network.



Low Load Issues: Voltage Control

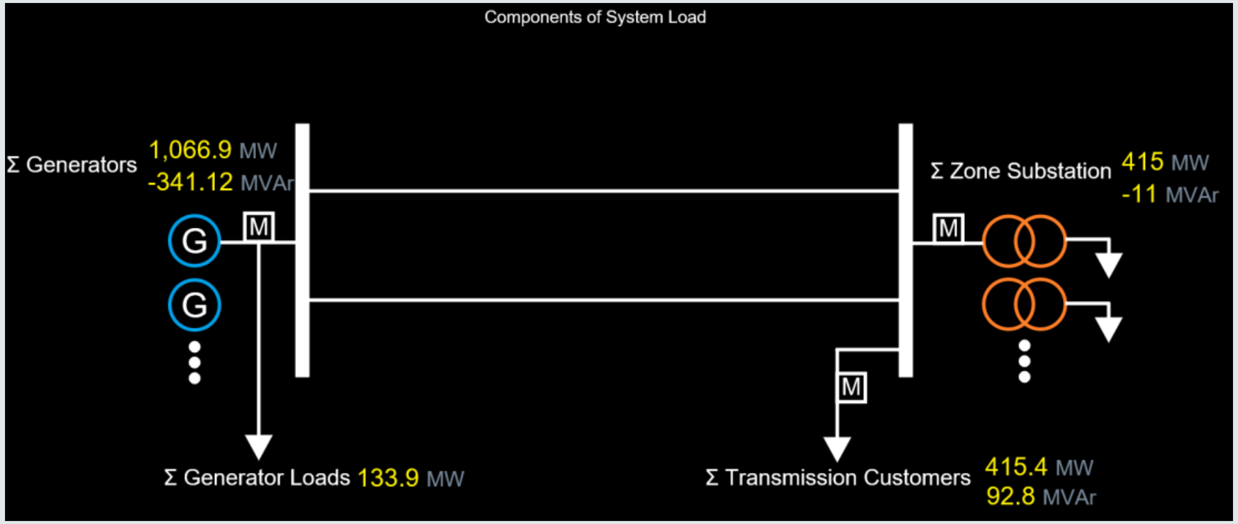
Example: how generator reactive power outputs change between peak and minimum system load

08/01/2021 at 17:50 - Near peak system load



Generator power factor 0.998 pf (lagging)

14/03/2021 at 12:03 – Record minimum system load



Generator power factor 0.953 pf (leading)

Source: Western Power, Transformation Design and Operation Working Group Meeting 34, https://www.wa.gov.au/sites/default/files/2021-03/TDOWG%20Meeting%2034%20-%20Slides%20-%20UFLS.pdf

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Low Load Issues: Voltage Control

- **Initial mitigations:** Western Power have committed to installing 490 MVAr of transmission and distribution level shunt reactors by the end of 2021 (with ~300 MVAr already installed)
- **Ongoing analysis:** Regular operational review by AEMO and Western Power and longer term requirements incorporated as part of Western Power's network planning process.

Projects	Benefits	By when
Committed works as at 30 June 2020 * see note on page 31		
Various sites in the metropolitan area: Reactive support	Address system high voltage issues during low load conditions with the installation of reactors at Yanchep, Clarkson, Henley Brook, Wanneroo, Joondalup, Southern River, Neerabup Terminal, Guildford Terminal, Southern Terminal and Northern Terminal substations	2021

Source: Western Power, Annual Planning Report 2020, https://www.westernpower.com.au/media/4768/annual-planning-report-2020-20210211v2.pdf

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

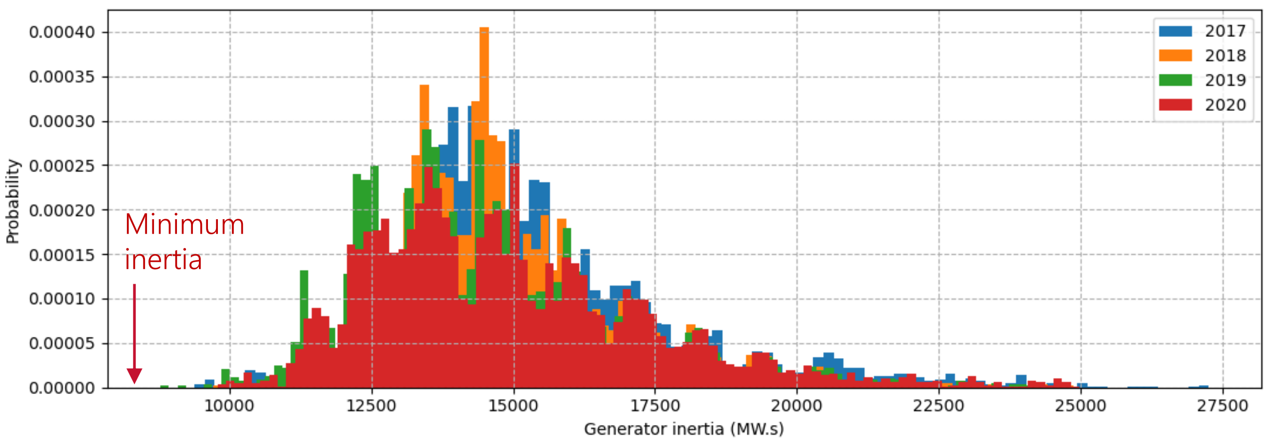
Low Load Issues:
Low Inertia and Frequency Stability

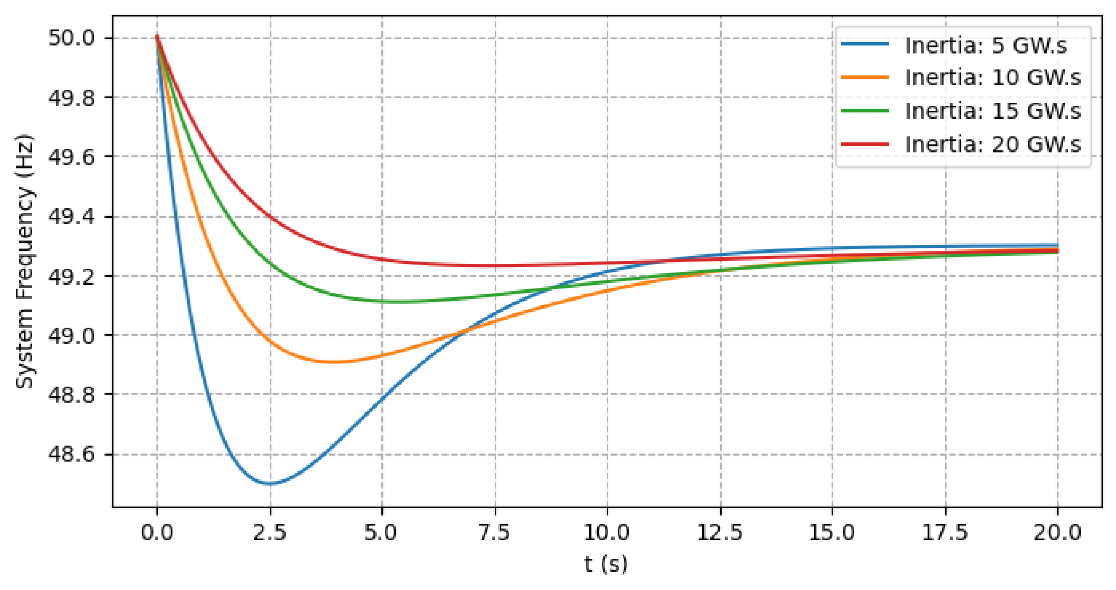
- System inertia tends to decrease at low loads as thermal plant become out-of-merit and decommit.

Typical inertia range (*)	12,000 – 17,000 MW.s
Maximum inertia (*)	27,254 MW.s (7:30pm 1 Mar 2017)
Minimum inertia (*)	7,808 MW.s (9 am to 2pm 14 Mar 2021)

(*) Excluding contribution from load inertia

- *Ceteris paribus*, low inertia systems are more sensitive to frequency disturbances, e.g. generator contingencies.

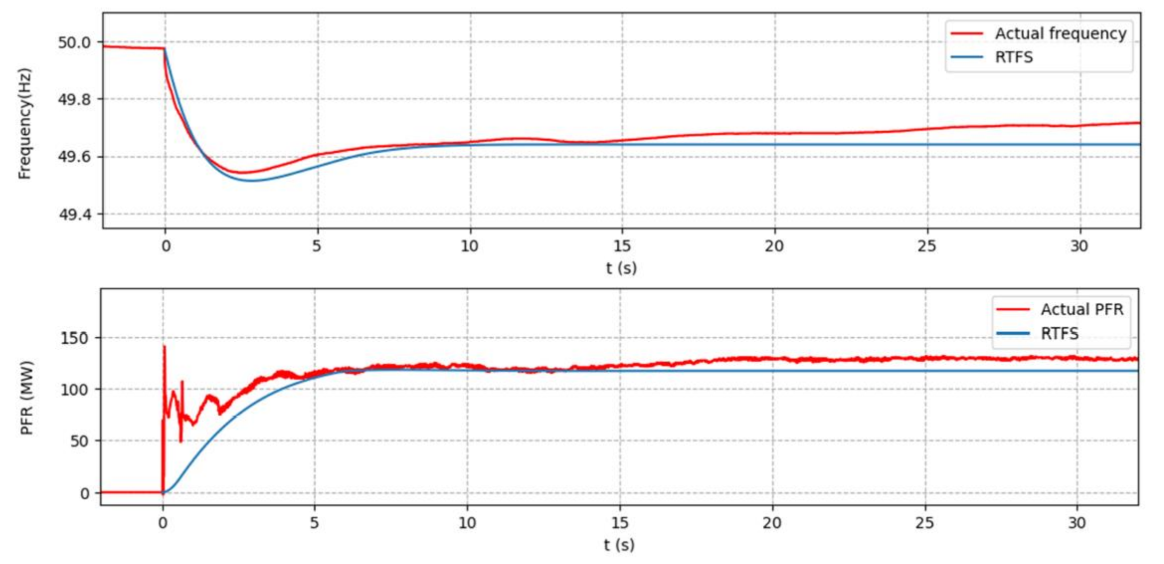


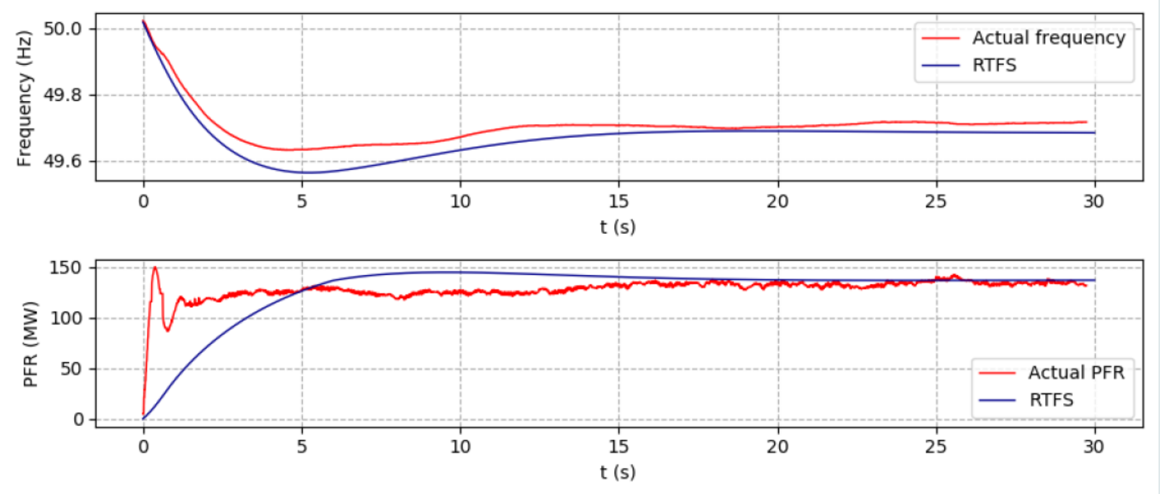


AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Low Load Issues: Low Inertia and Frequency Stability

- **Initial mitigations:** AEMO have developed and deployed a real-time frequency stability (RTFS) control room tool for the SWIS to monitor system security in real-time and allow controllers to make changes to dispatch when security risks arise.
- The validity of the tool is checked after material generator contingencies and fine-tuned (if necessary).
  - Example 1: Trip of a gas-fired generator from 244 MW
  - Example 2: Trip of a coal-fired generator from 175 MW
- **Ongoing analysis:** Determination of minimum synchronous generators which need to be online to meet system security requirements.



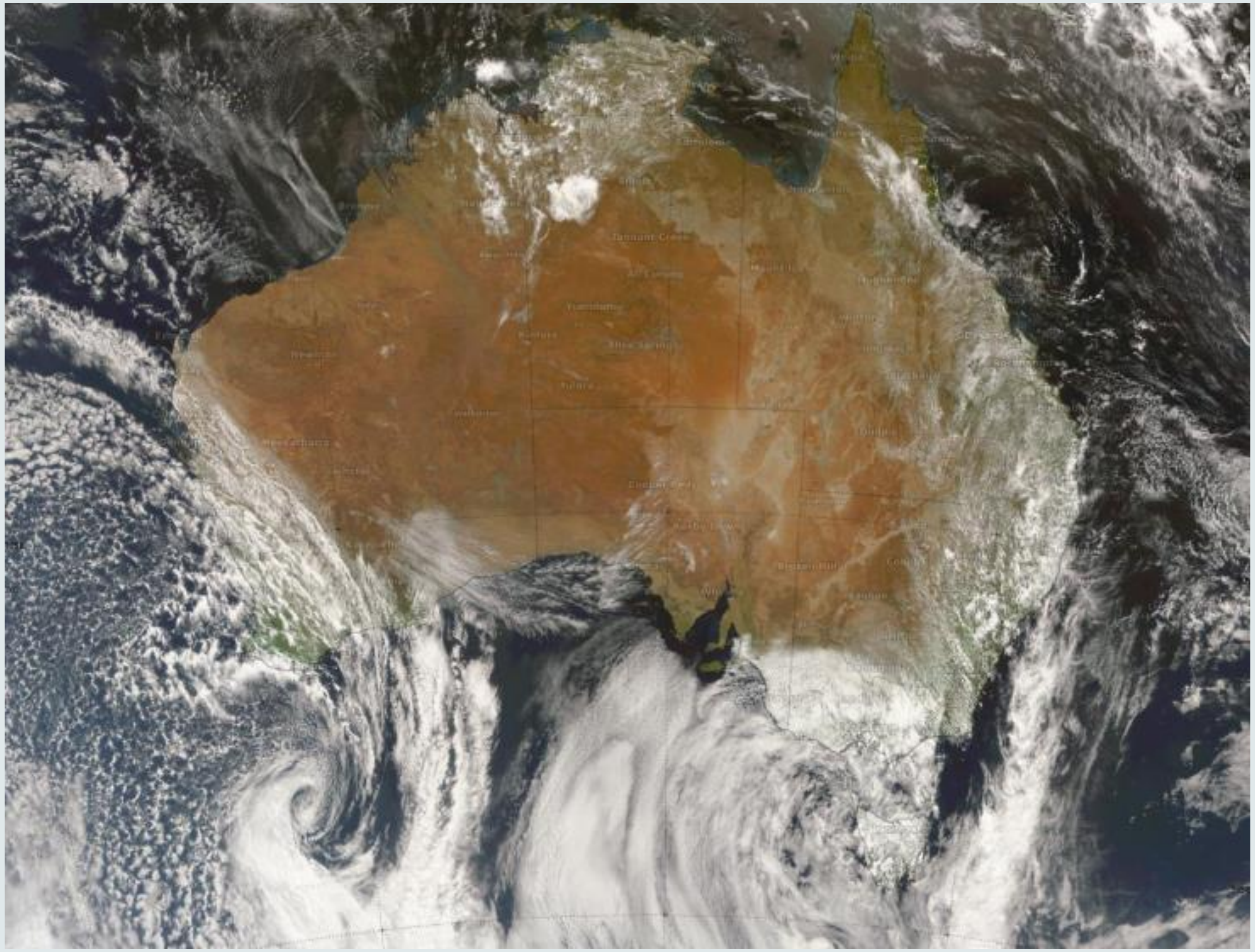


Low Load Issues: System Strength

- Similar to inertia, system strength tends to decrease as thermal plant become out-of-merit or decommit (as synchronous machines are good sources of fault current).
- System strength issues haven't yet been observed in practice, but preliminary screening studies indicate risks may be present in some rural (less meshed) parts of the SWIS, particularly when the network is not intact, e.g. due to transmission line outages.
- Studies are currently being undertaken by Western Power to assess the risks in more detail (i.e. with EMT models).

System Load Volatility

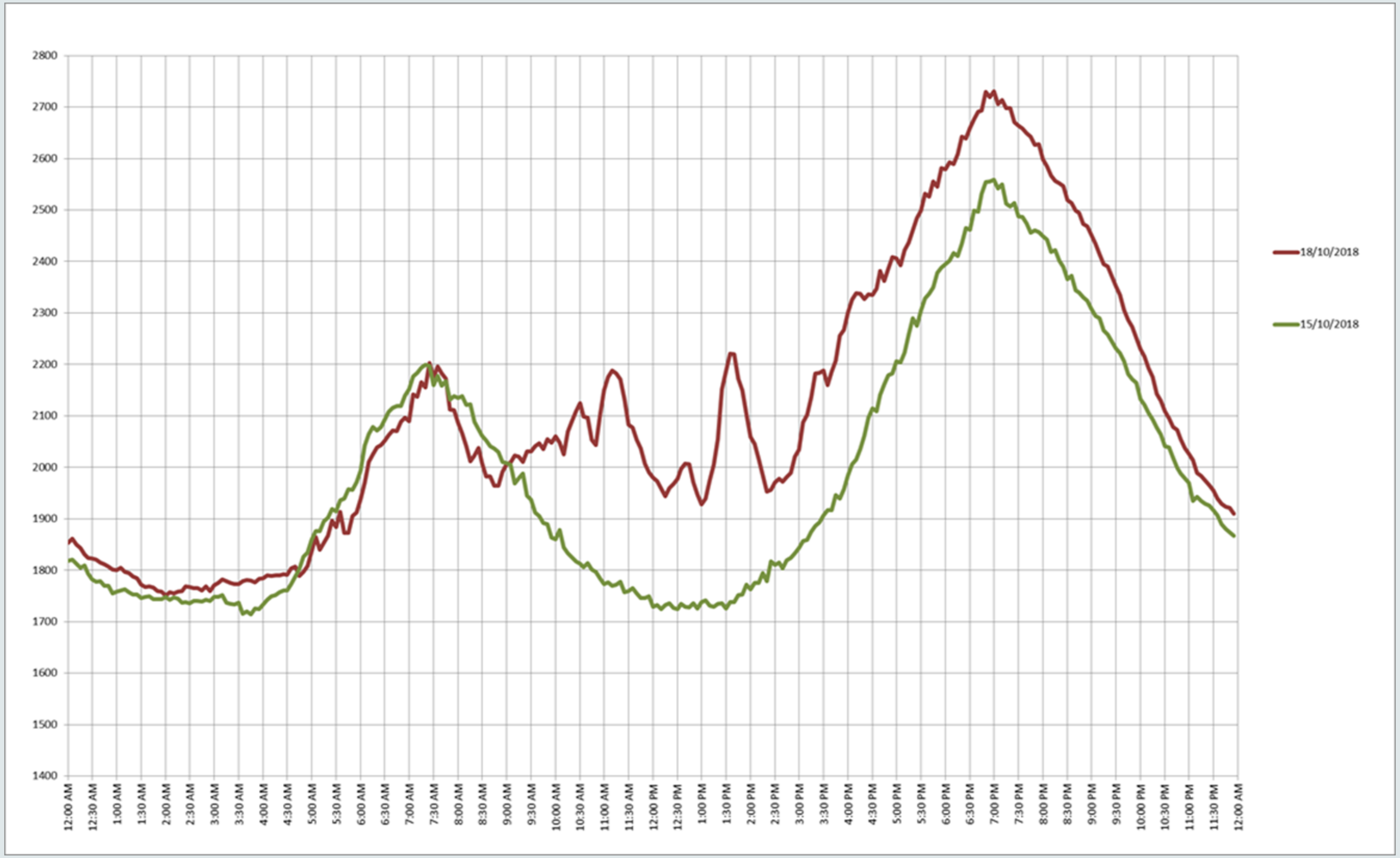
- Cloud bands over the SWIS (particularly over the Greater Perth metro area) are causing increasingly large swings in system load due to high DER penetration.
- Cloud formations can be extremely large, potentially covering the entire area of the SWIS, i.e. geographic diversity of rooftop PV does not always mitigate the issue.
- Weather forecasting tools are used to prepare the generation fleet for cloud-induced volatility. Where necessary, Backup Load Following Ancillary Service (LFAS) can be called up.
- However, rapidly forming clouds over the Perth metro can also cause large swings that are difficult to forecast.



AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

System Load Volatility
Mixed Sky Day on 18/08/2018

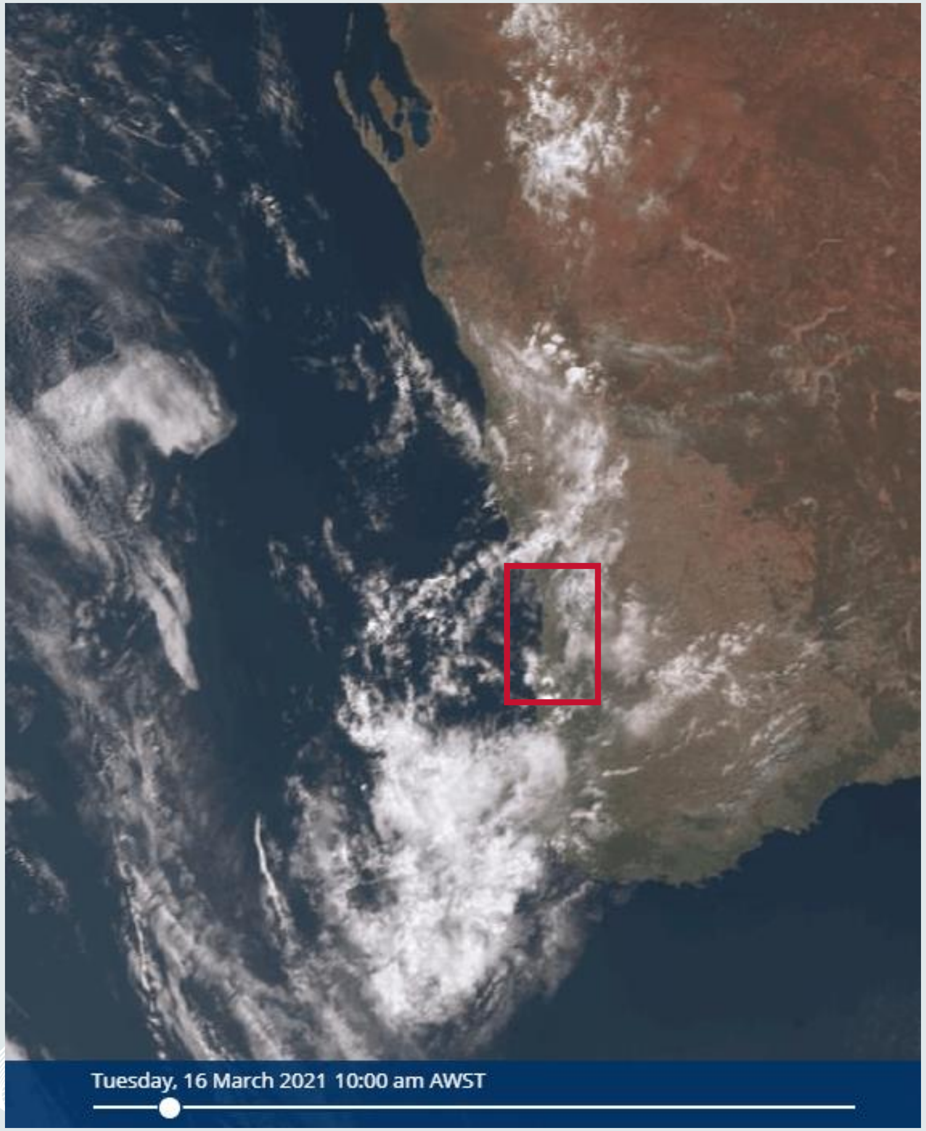
- On 18th October 2018, large cloud bands with clear skies in between were forecast to move through the SWIS from the southwest between 9am and 3pm.
- This resulted in system load swings of up to 300 MW during that period.
- Backup LFAS was called up by AEMO real-time control on the day to manage the load swings.

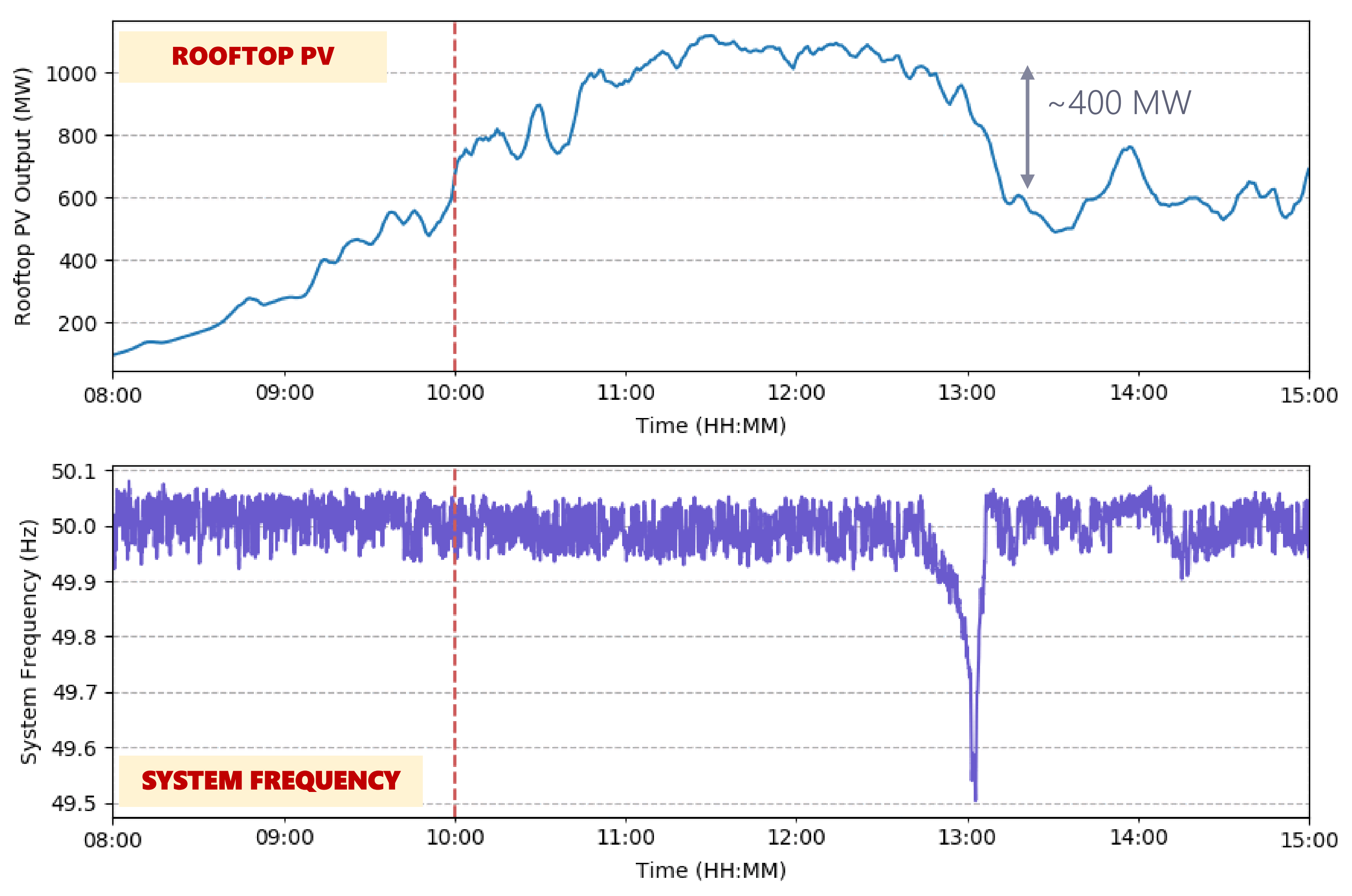


System load on 15/10/2018 and 18/10/2018

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

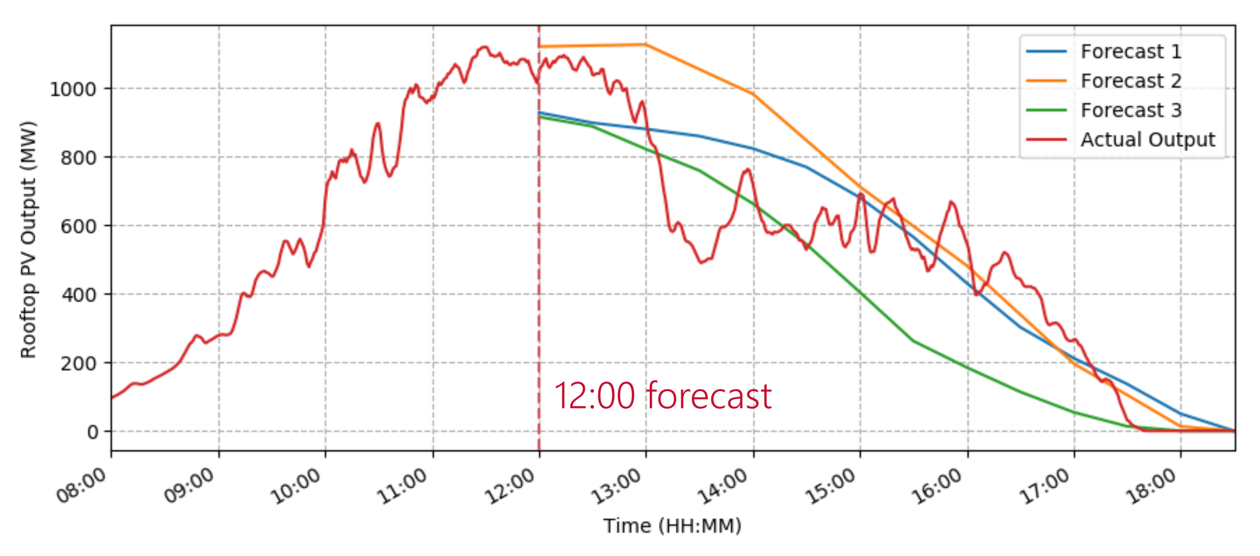
System Load Volatility: Rapid Cloud Formation on 16/03/2021

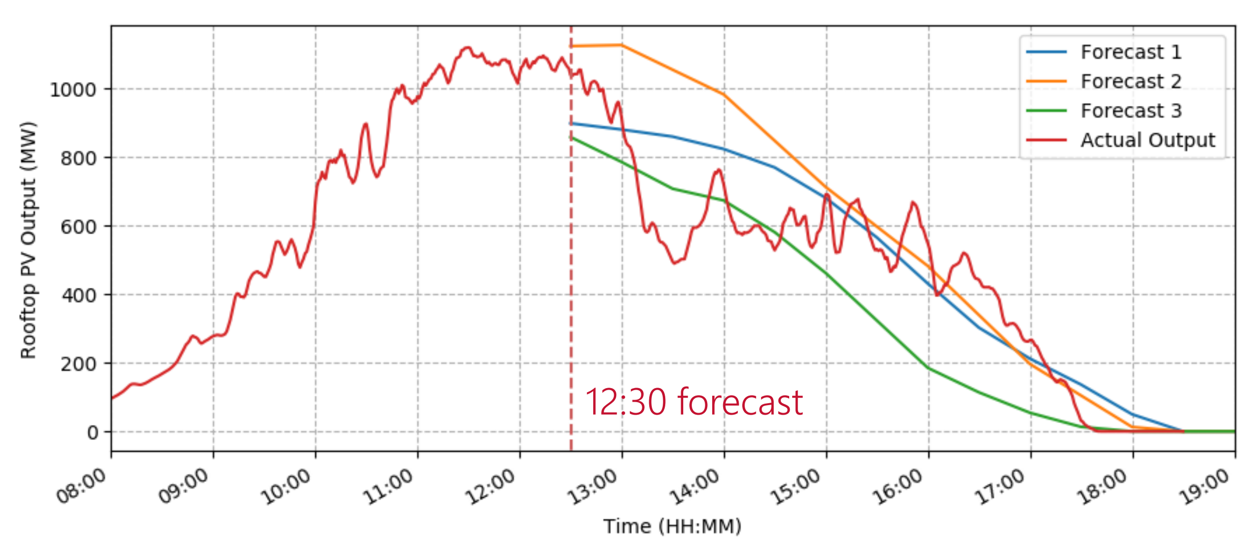




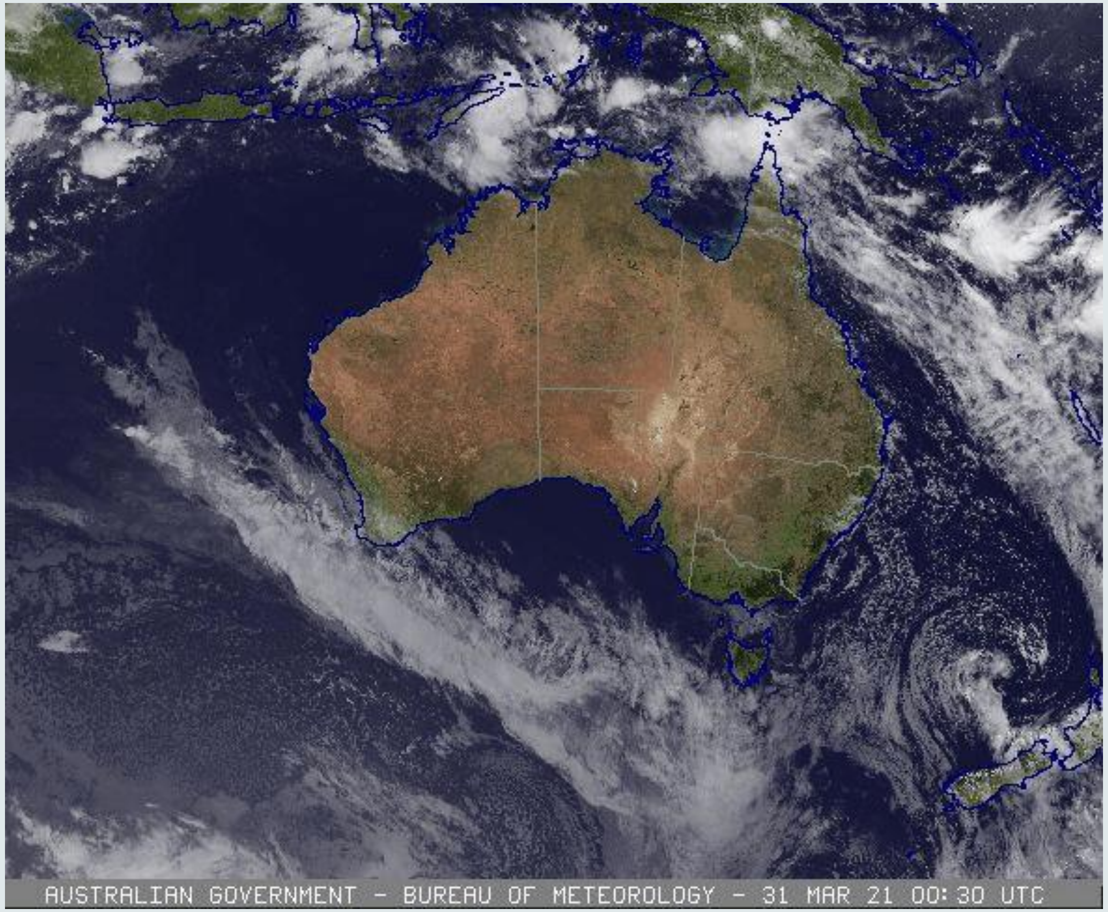
System Load Volatility: Rapid Cloud Formation on 16/03/2021

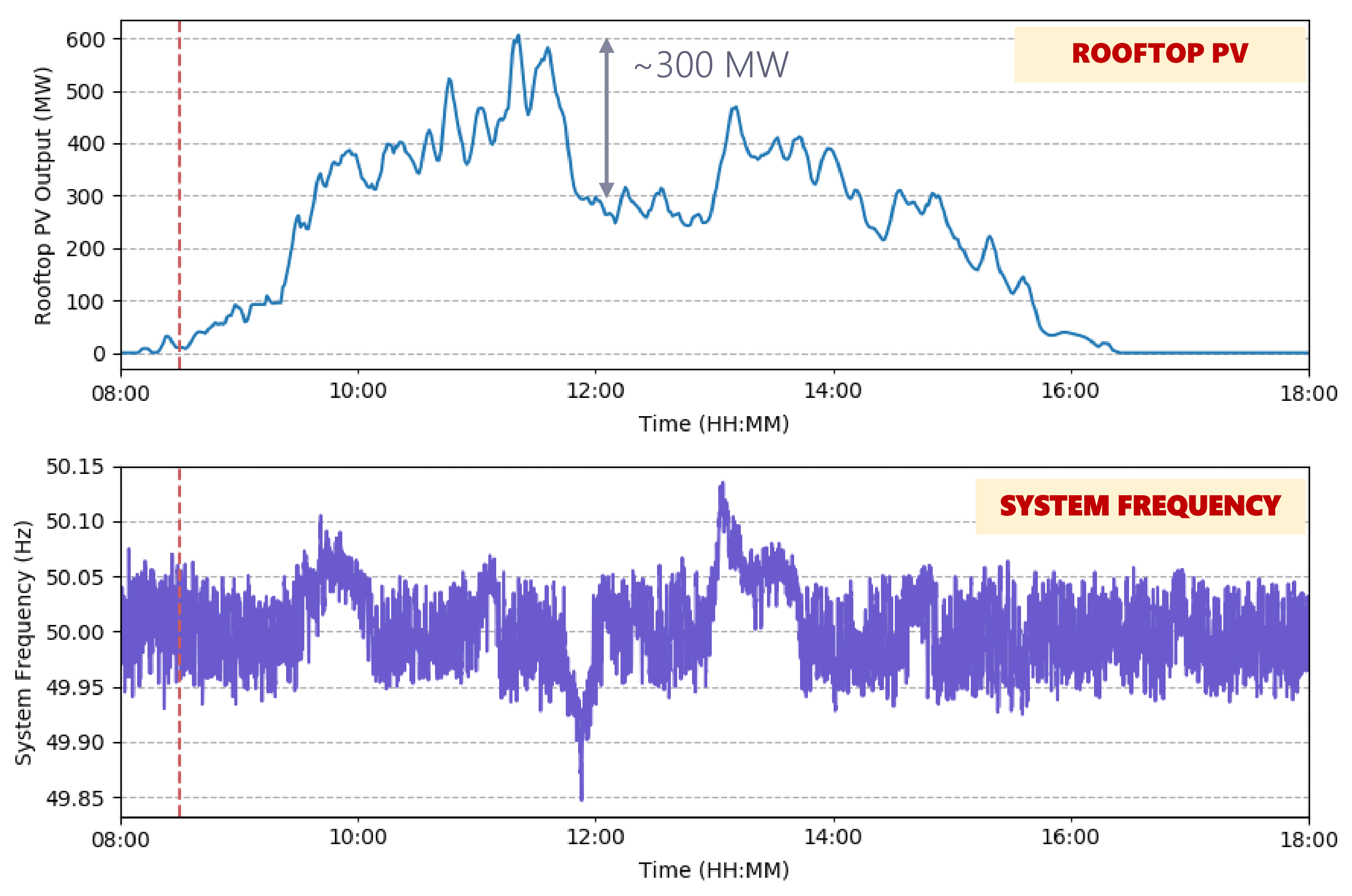
- AEMO real-time control has access to continuous data feeds from several weather forecast providers for short-term rooftop PV forecasts in the SWIS.
- During this event, the 1-hour or 30-min ahead forecasts did not provide any indication of the severity of the PV output reduction.
- Currently working with weather providers to see what improvements to short-term forecasting are possible.





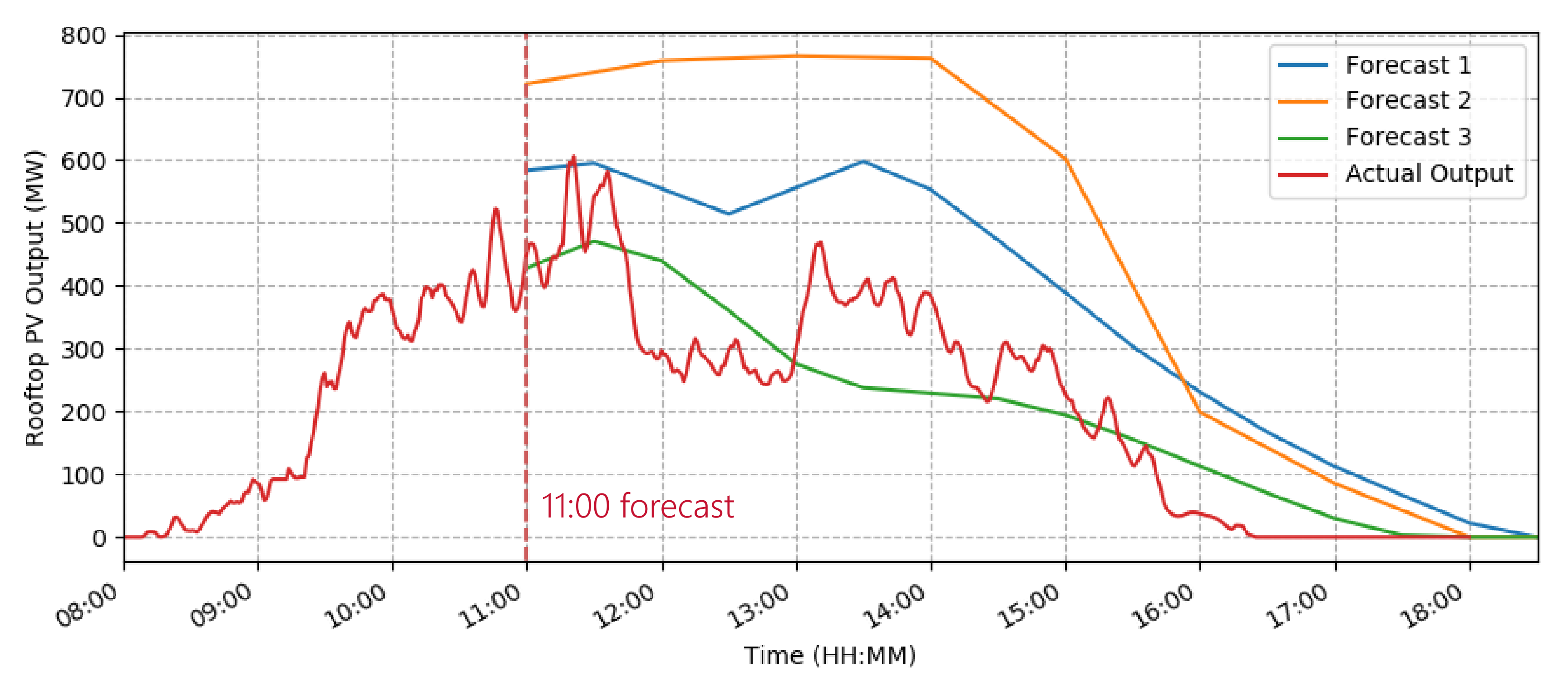
System Load Volatility: Large Cloud Band on 31/03/2021





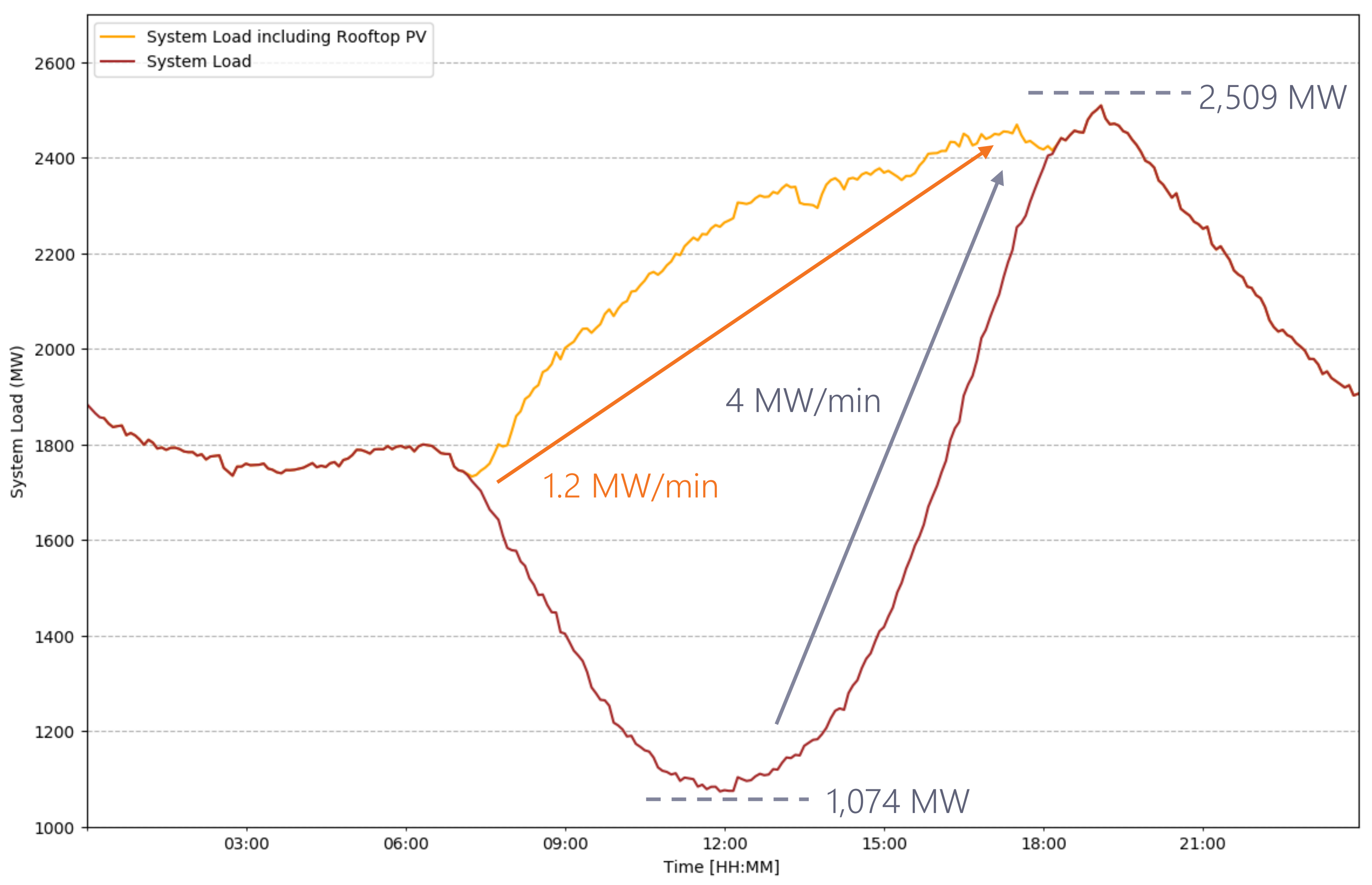
System Load Volatility: Large Cloud Band on 31/03/2021

- In this event, 1-hour ahead forecasts predicted material reduction in PV output from 12-1 pm.
- Large reduction actually occurred between 12:45 and 1 pm, but forecasts were accurate enough to allow AEMO controllers to prepare the generation fleet.



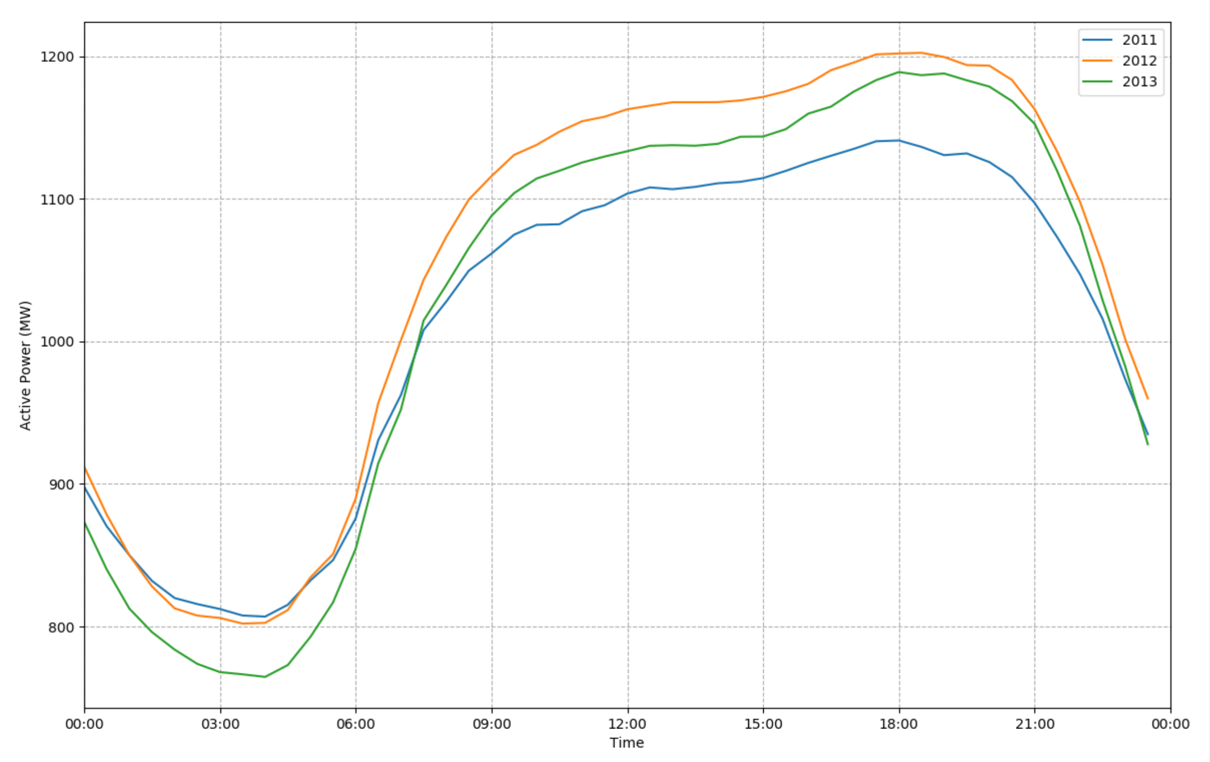
Ramping and Cycling

- As the belly of the duck gets deeper, the ramping requirements from midday trough to evening peak become more onerous.
- Example from minimum demand day (14/03/2021):
  - Trough-to-peak: 1,435 MW (or 134% of load at trough)
  - Average ramp rate: ~4 MW/min
  - Average ramp rate (without DER): 1.2 MW/min
- Require an increasingly flexible generating fleet as duck belly gets deeper.

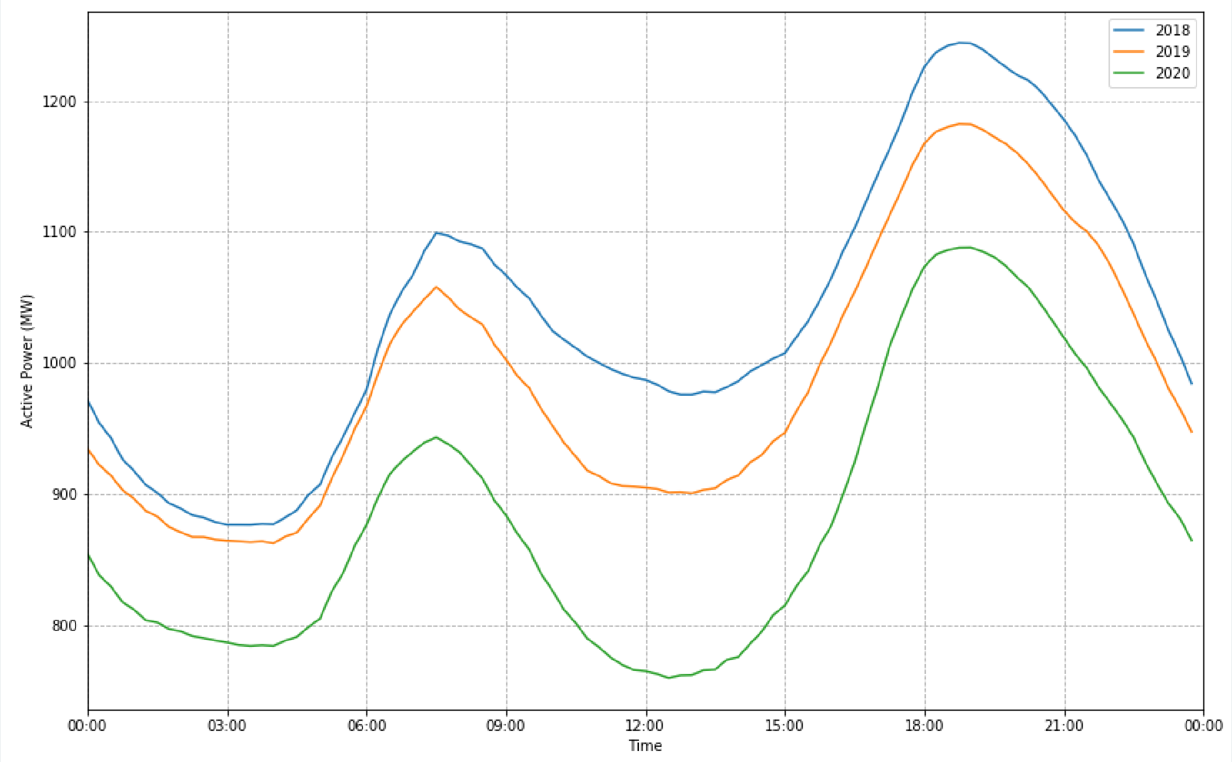


Ramping and Cycling

Deepening duck curve is also causing increased cycling of base load generation, particularly the SWIS coal-fired fleet.



Average coal fleet output 2011 - 2013



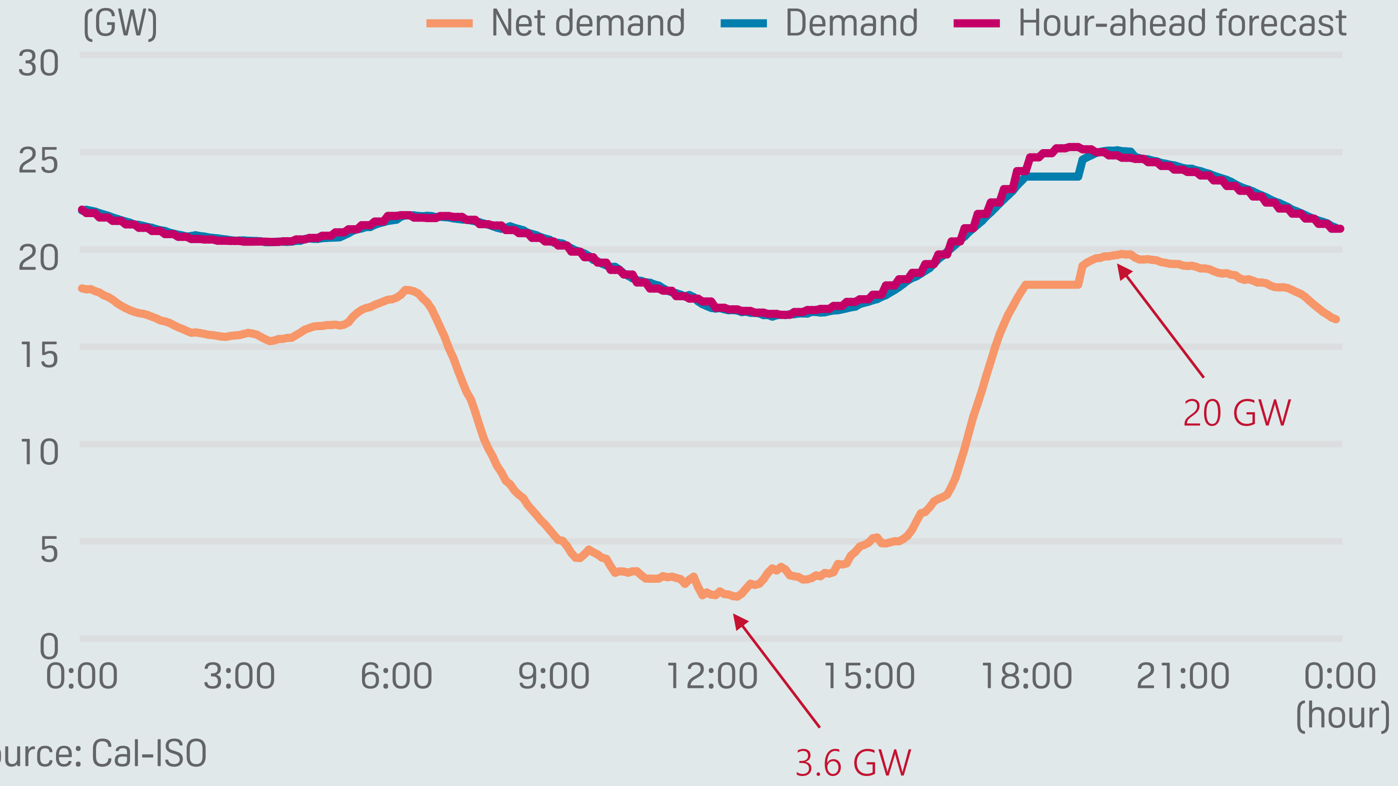
Average coal fleet output 2018 - 2020

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Ramping and Cycling

- Some perspective: SWIS ramping situation is not quite as bad as California (yet)
- **Initial mitigations:** operational planning to ensure flexible generating plant (e.g. gas turbines) are not on outage and available
- **Ongoing analysis:** studies to ensure capability of online fleet is adequate to meet expected ramps going forward.

CAL-ISO DUCK CURVE MARCH 13

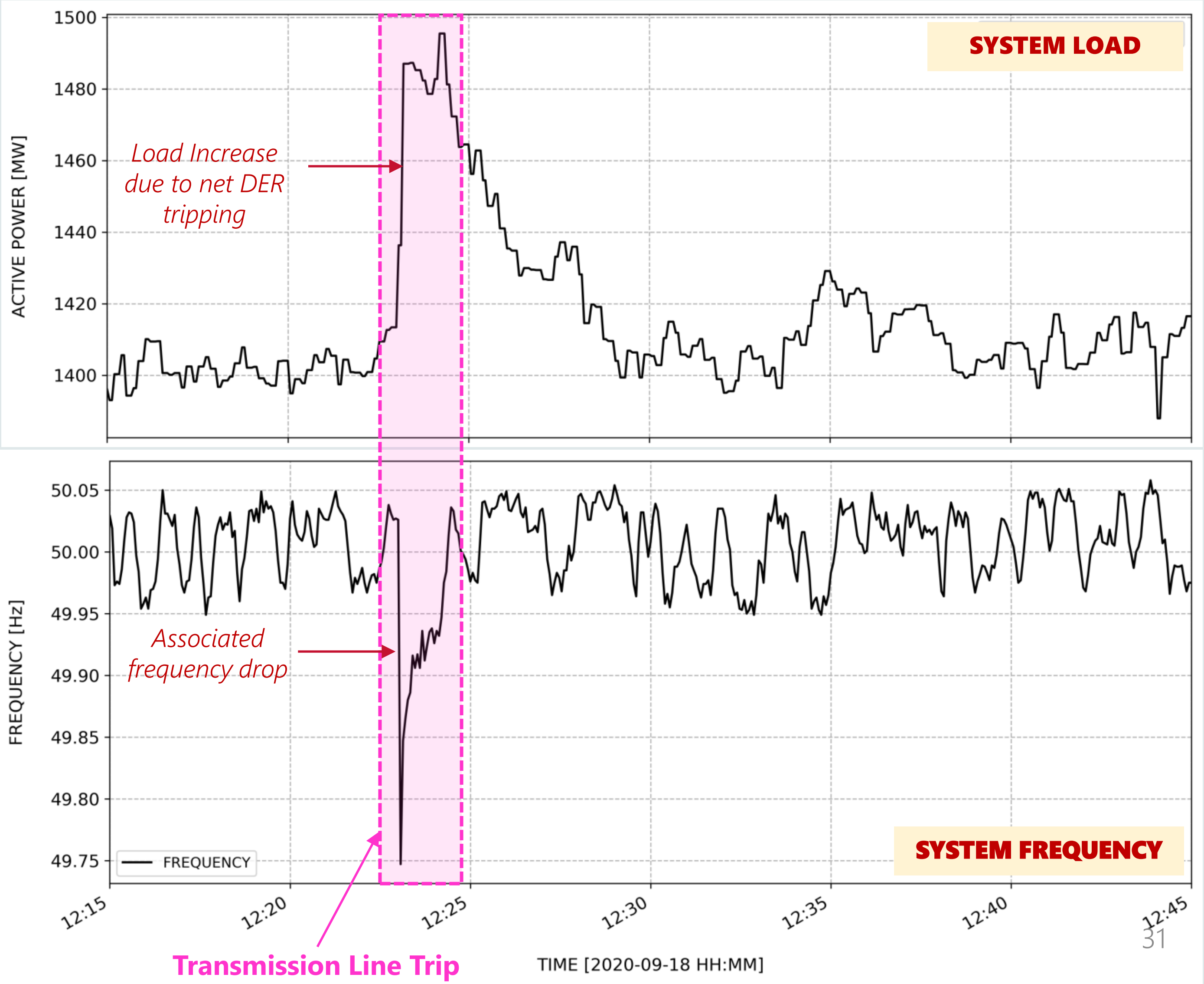


Source: Cal-ISO

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Emerging Contingency Risks: Rooftop PV Tripping

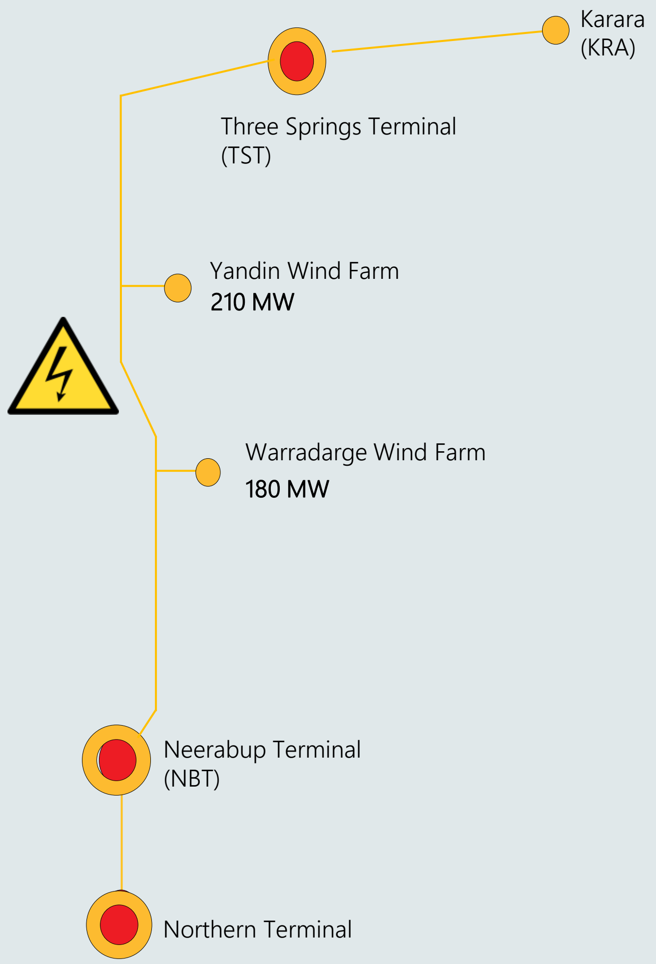
- During system disturbances (e.g. network faults), a portion of rooftop PV inverters in the system have been observed to trip unintentionally.
- This was not a problem in the past when there was lower penetration of DER in the system, but nowadays, a network fault can also cause a generation contingency, i.e. DER tripping > load tripping.
- **Case study:** on 18th September 2020, there was a transmission line trip south of Perth at around noon, which resulted in a system load increase due to DER tripping (~100 MW) and, in turn, a frequency drop in the system.



AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

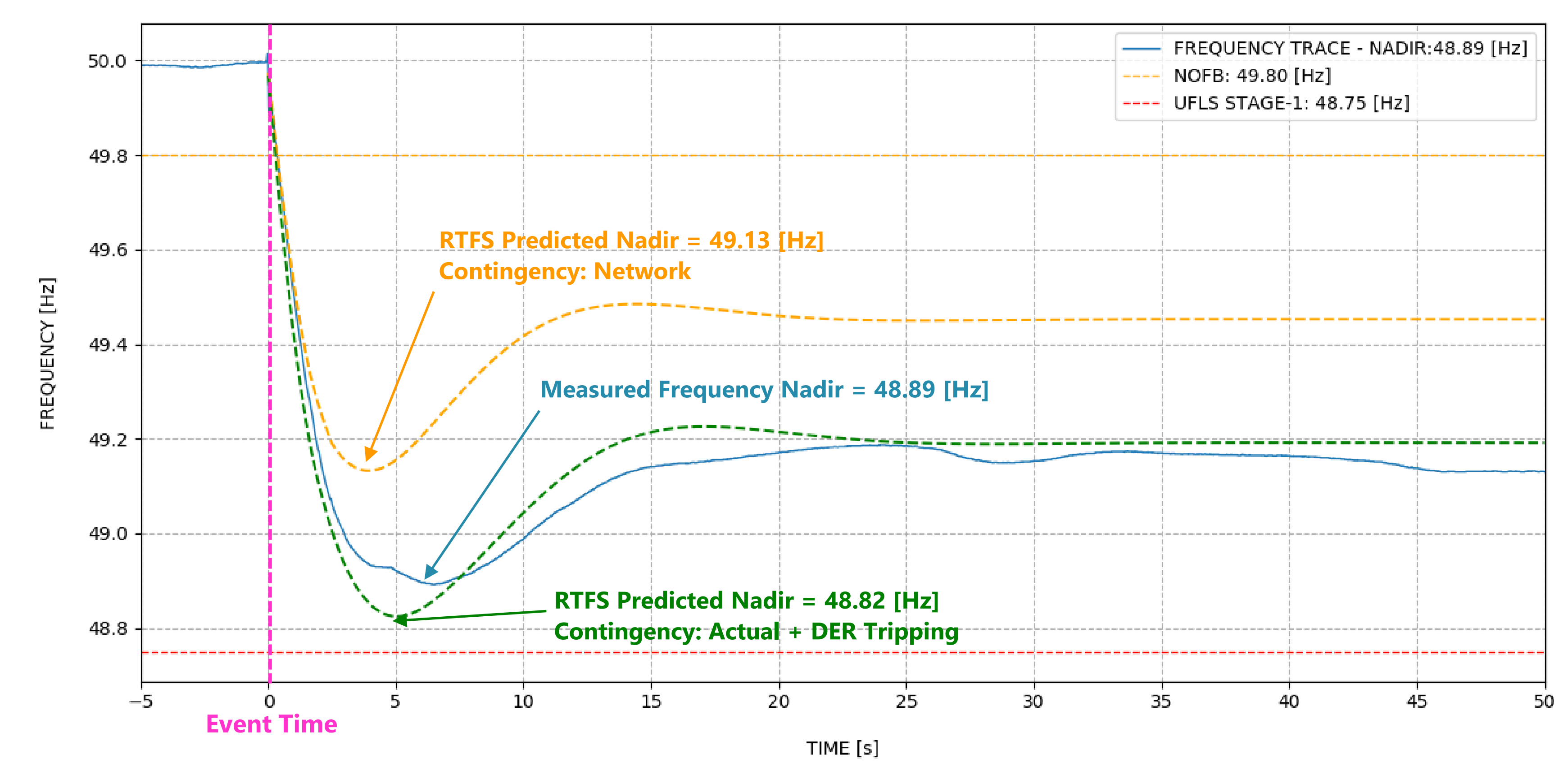
Emerging Contingency Risks: Rooftop PV Tripping

- By itself, a network fault leading to DER tripping is generally not considered a major risk as the total volume of net DER tripping typically does not exceed normal generator contingencies.
- However, the risk becomes material when a network fault leads to loss of generation *as well as* DER tripping, e.g. the 330 kV North Country transmission line.
- **Case study:** on 2nd January 2021 at 11:26am, a single-phase-to-earth short circuit on the 330 kV North Country line (and subsequent inter-trip protection scheme operation) led to the simultaneous trips of Yandin and Warradarge wind farms (combined output of ~257 MW) and Karara Mining load, followed by 124 MW – 134 MW of net DER tripping. The total contingency size was ~310 MW.



Emerging Contingency Risks: Rooftop PV Tripping

Initial mitigations: augmentation of the Real-Time Frequency Stability Tool (RTFS) to include an estimate for potential net DER tripping after credible network contingencies.



Example for the event on 02/01/2021

Emerging Contingency Risks: Rooftop PV Tripping

Ongoing analysis

- AEMO is continuing to build on work done in the NEM, with an ongoing workstream led by Jenny Riesz aimed at:
  - Refining estimates of the amount of DER and load tripping that can occur following network faults in the SWIS via detailed power system modelling
  - Determining the most appropriate solution(s) going forward
- There is also a new ARENA funded project led by UNSW (Project MATCH) to further investigate DER behaviour during power system disturbances and develop tools to assist AEMO in managing higher penetrations of DER.

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Impact on Under-Frequency Load Shedding (UFLS) Scheme

- The UFLS scheme is the last line of defence against frequency collapse from large generation contingencies when spinning reserve, mandatory droop, etc else has failed.
- The current settings for the UFLS scheme in the SWIS is laid out in Table 2.8 of the Western Power Technical Rules, specifying 5 stages of load shedding starting at 48.75 Hz and with 15% of load shed per stage.
- The loads shed in each stage are mainly sourced from distribution feeders serving non-essential commercial and residential customers.
- DER is turning a portion of these feeders from loads into net generators. Shedding these feeders would exacerbate an under-frequency issue.

Stage	Frequency (Hz)	Time Delay (sec)	*Load* Shed (%)	Cumulative *Load* Shed (%)
1	48.75	0.4	15	15
2	48.50	0.4	15	30
3	48.25	0.4	15	45
4	48.00	0.4	15	60
5	47.75	0.4	15	75

Source: Western Power Technical Rules [Table 2.8]

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Impact on Under-Frequency Load Shedding (UFLS) Scheme

Example: Backfeeding zone substations on 14/03/2021 at 12:03pm:

Substation Load MW by Region

Substation Load MW 415

Substation MVAR -11

CT

Station	MW	MVar
BEL	12	0
BTY	5	0
CK	15	0
CL	5	0
COL	3	0
F	10	1
HAY	25	4
JTE	5	0
KDL	6	2
MIL	22	0
NP	10	1
RVE	14	-1
TT	8	1
W	11	2
WE	2	-6
	152	0

EC

Station	MW	MVar
BNY	9	2
CAR	7	2
CUN	1	0
KDN	1	-5
KEL	1	1
MER	1	-2
NOR	0	-2
SVY	2	-1
SX	0	-1
WUN	1	0
YLN	4	-3
	13	-14

EGF

Station	MW	MVar
BKF	27	3
BLD	20	7
PCY	7	2
WKT	14	6
WMK	0	0
	67	17

GLT

Station	MW	MVar
D	-1	-1
FFD	5	1
HZM	1	0
K	-1	0
MDY	6	1
MJ	7	2
	16	2

KW

Station	MW	MVar
MED	-4	-4
MH	-7	-6
MSR	25	11
MSS	-7	-7
RO	8	1
WAI	-11	-6
	5	-11

MU

Station	MW	MVar
ALB	10	4
BNP	1	0
BOD	0	0
BTN	11	-2
CO	3	0
KAT	4	-3
KOJ	1	0
MBR	1	-2
MJP	4	0
NGN	2	-3
WAG	1	-1
WGP	2	0
	39	-7

NC

Station	MW	MVar
CPN	2	0
CTB	8	3
ENB	-2	-1
GTN	12	-1
MOR	3	-1
RAN	15	3
RGN	4	3
TS	3	-2
	44	3

NT

Station	MW	MVar
A	6	1
BCH	-7	-3
BCT	1	0
CKN	-5	2
H	-1	0
HBK	-12	5
JDP	3	7
LDE	-9	-3
MA	4	0
MLG	5	0
MO	6	1
MUC	1	-2
MUL	4	0
NB	-1	-1
OP	10	3
PBY	-2	-2
WGA	0	-1
WNO	3	3
Y	5	0
YP	-3	-1
	9	9

PIC

Station	MW	MVar
BSN	3	-7
BUH	8	0
CAP	1	0
CLP	1	-1
MR	2	-3
MRR	11	-2
PIC	18	-17
PNJ	5	-4
	18	-17

SF

Station	MW	MVar
AMT	8	-1
APM	4	2
BIB	-2	-3
E	8	2
MYR	5	-1
OC	1	0
	23	-2

ST

Station	MW	MVar
BYF	-10	-3
CC	0	-2
CVE	4	3
G	-5	-1
MDN	0	1
MUR	8	-2
RTN	-2	0
SNR	-18	6
WLN	-1	0
	-23	1

WT

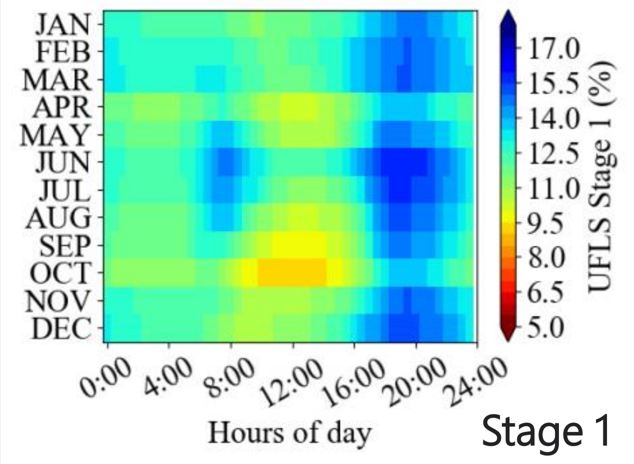
Station	MW	MVar
CTE	7	-1
MCE	19	3
SPK	11	1
WD	2	0
	39	3

Source: Western Power, Transformation Design and Operation Working Group Meeting 34, https://www.wa.gov.au/sites/default/files/2021-03/TDOWG%20Meeting%2034%20-%20Slides%20-%20UFLS.pdf

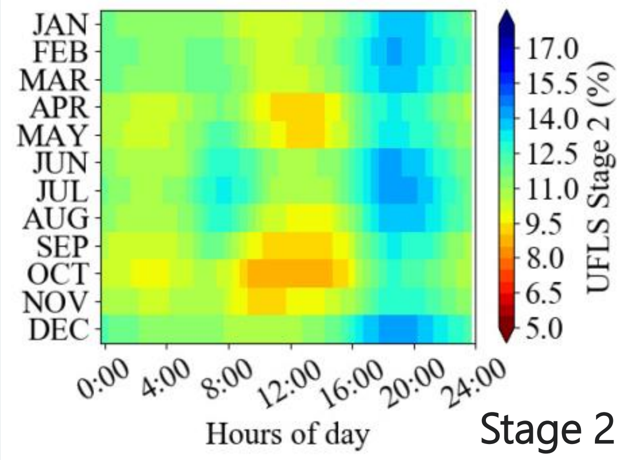
Impact on Under-Frequency Load Shedding (UFLS) Scheme

Monthly average UFLS load availability in 2019 for the SWIS UFLS scheme.

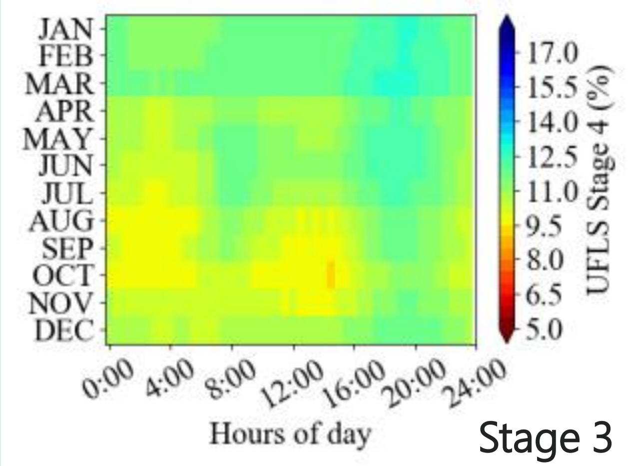
DER has eroded the load availability in the middle of the day.



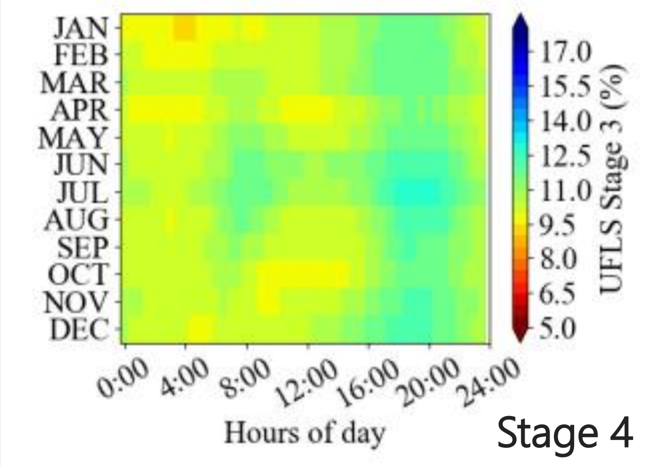
Stage 1



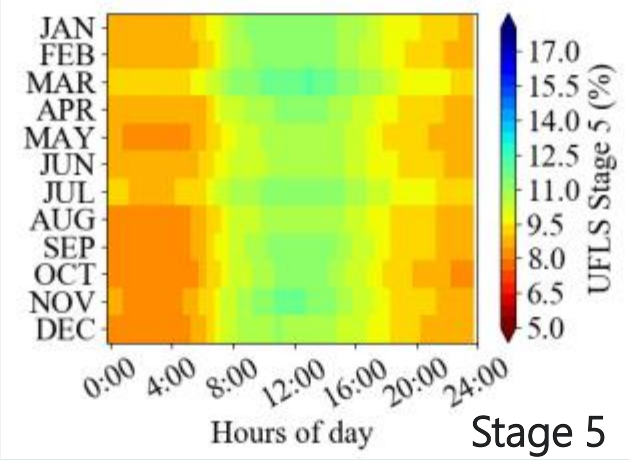
Stage 2



Stage 3



Stage 4



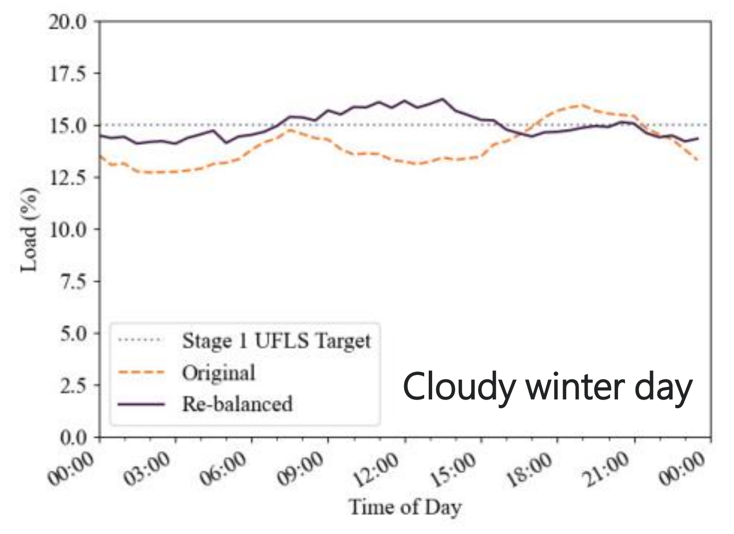
Stage 5

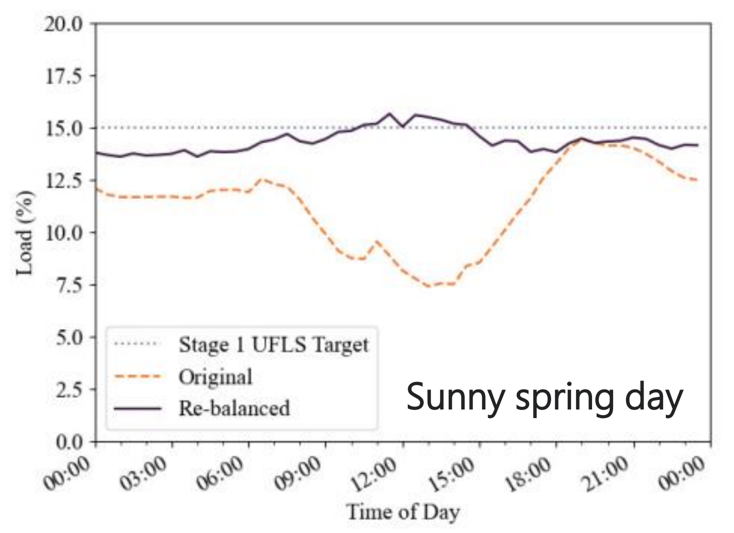
AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Source: R. Frost, L. Zieland, D. Sharafi and J. Susanto, "Impact of Reverse Power Flow in Distribution Feeders on Under-Frequency Load Shedding Schemes", *SGES 2020*, https://doi.org/10.1109/SGES51519.2020.00025

Impact on Under-Frequency Load Shedding (UFLS) Scheme

- **Initial mitigations:** AEMO worked with Western Power to remove or shift backfeeding and high DER feeders to later UFLS stages so that Stage 1 and 2 UFLS are less compromised.
- **Ongoing analysis:** Work is currently being done under DER Roadmap action 10 to review the current UFLS scheme and identify what needs to be done to ensure an appropriate outcome going forward.

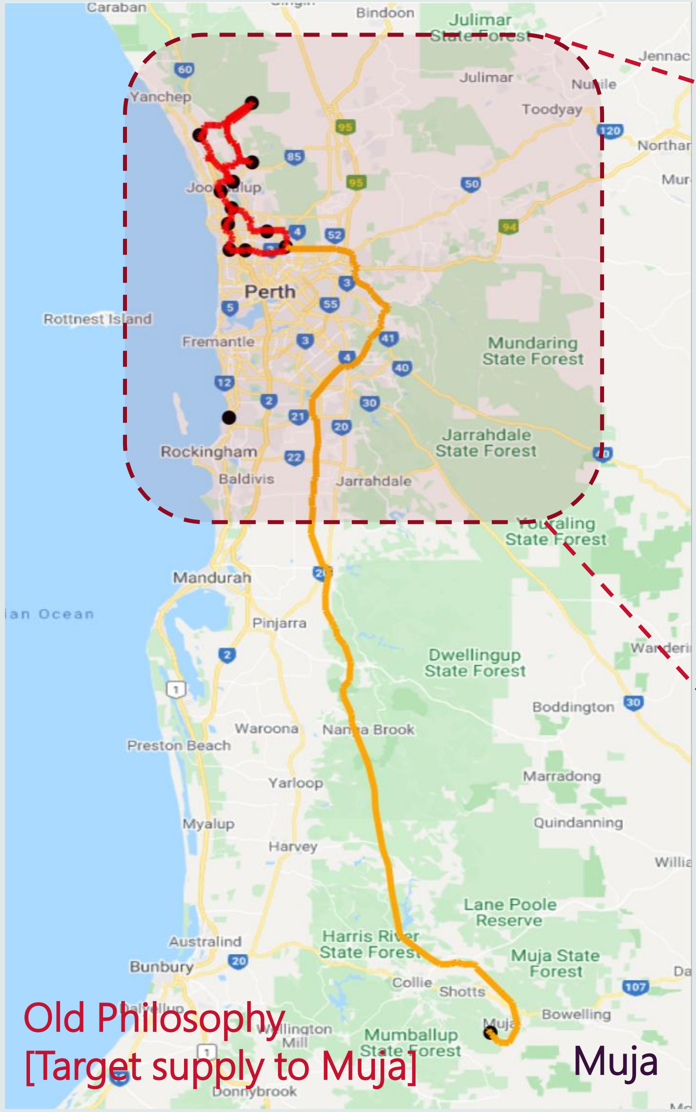




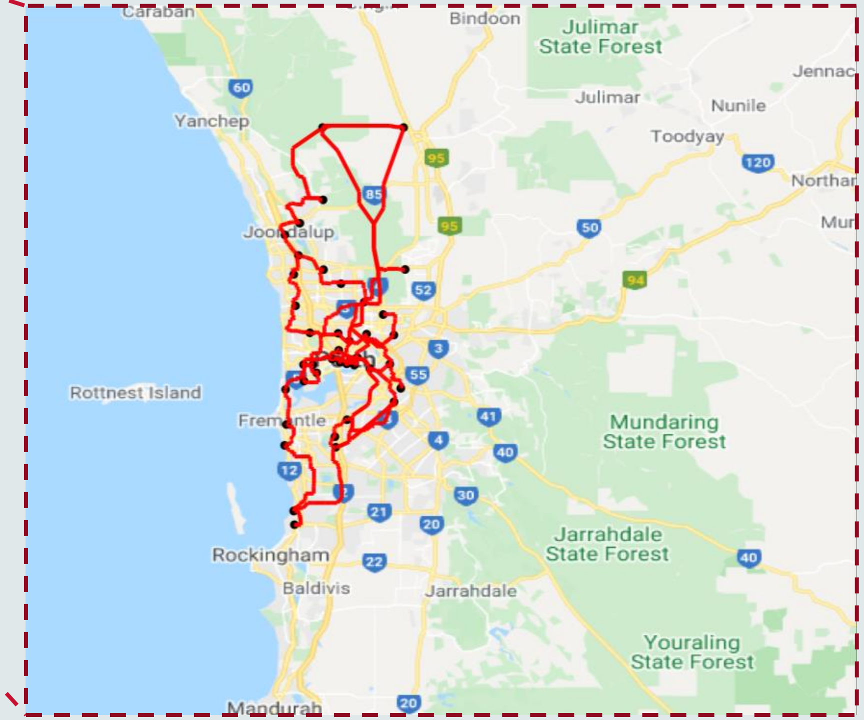
Source: R. Frost, L. Zieland, D. Sharafi and J. Susanto, "Impact of Reverse Power Flow in Distribution Feeders on Under-Frequency Load Shedding Schemes", *SGES 2020*, https://doi.org/10.1109/SGES51519.2020.00025

Impact on System Restart

- In the event of a complete System Black, the SWIS has to be restarted from specific power stations contracted by AEMO to provide system restart services.
- The old restart philosophy (dating back to 1990) prioritised the re-energisation of coal-fired generators at Muja via the 330 kV transmission corridor from Perth.
- However, increasing DER has reduced the availability of stabilising load needed to manage voltages when energising long 330 kV lines.



New Philosophy [Target supply to Perth Metro]



- The restart philosophy has been revised to target stable Perth inner metro loads (e.g. CBD) with lower exposure to DER.

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

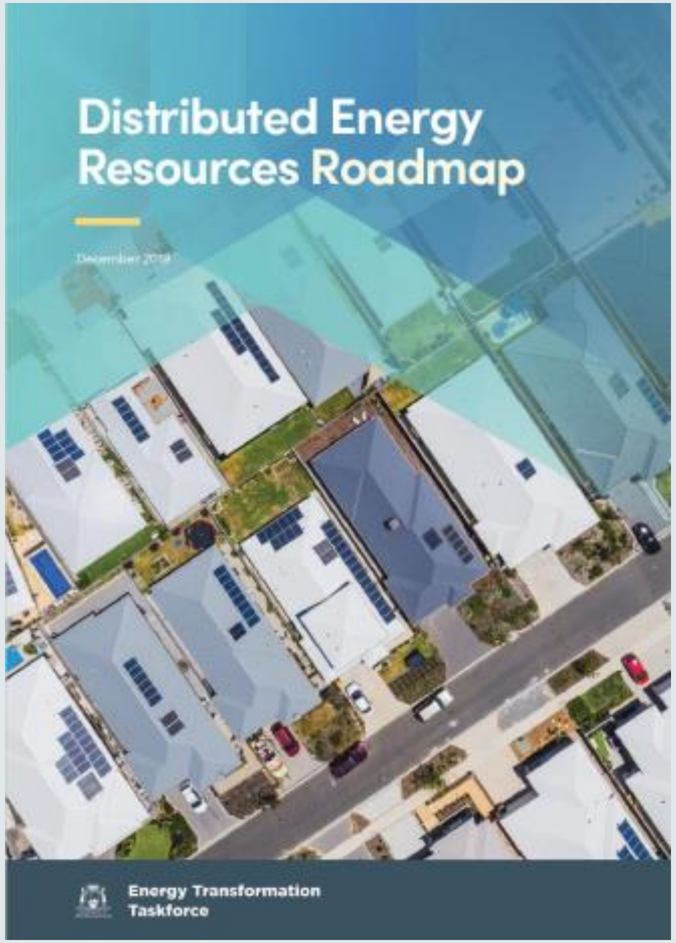
Impact on System Restart

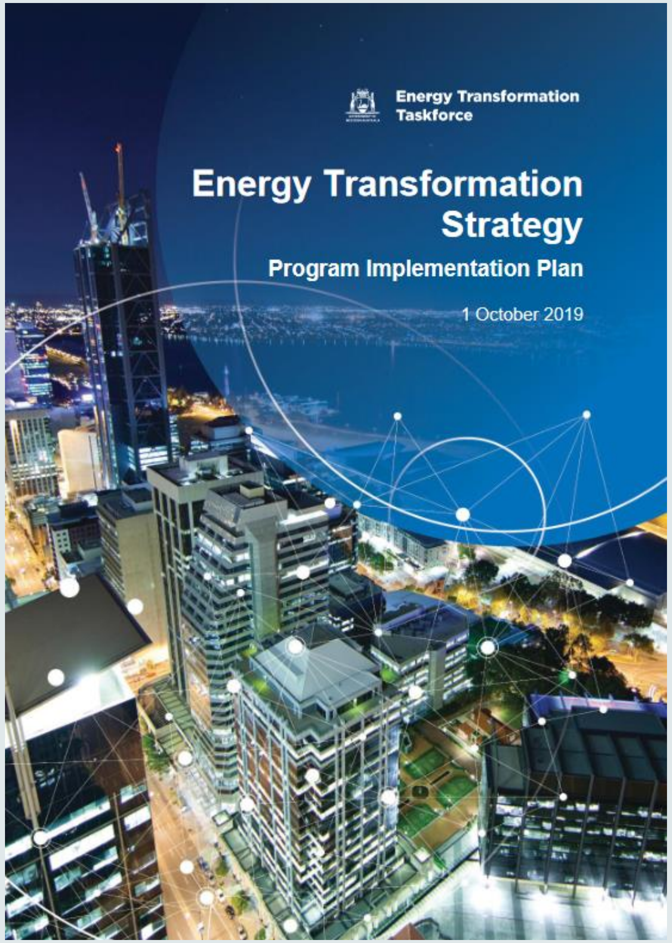
Explicit consideration of DER has been central to developing the new system restart philosophy and plan:

- Each restart strategy is validated against the minimum load day with maximum penetration of rooftop PV
- Perth CBD substations are targeted early on in the restart process as good stable load due to the lower rooftop PV penetration at these substations
- Selected zone substations (e.g. Landsdale, Southern River, Henley Brook) have been identified as "pass-through" (i.e. no load is picked up at these substations) because they have the propensity to backfeed during the day due to too much rooftop PV
- Highly flexible gas generation is prioritised for energisation to accommodate fluctuations from DER

Conclusion

- In just 5 years, increased DER penetration has become one of the key challenges in securely operating the SWIS, affecting practically every area of system operations.
- The appropriate management and incentivisation of DER has also become central to longer term policy planning by the WA government through initiatives such as:
    - DER Roadmap
    - WEM Reform
- With these initiatives in place, future DER growth will serve to support rather than destabilise the SWIS.





Questions and feedback

Julius Susanto
susanto@ieee.org