Renewables and the NEM:

What are the limits and what else is needed to go zero?

Gamma Energy Technology
EXPERIENCE THINKING INNOVATION

REDVector

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About Red Vector:

Red Vector is a UK Limited Company that provides an energy consulting service based on Andy Boston's 30 years experience in the energy industry starting with the nationalised CEGB, through privatisation firstly with PowerGen and thence E.ON, and finally with the Energy Research Partnership.

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Gamma Energy Technology P/L is an independent energy consulting service, offering a range of technical and support services, including but not limited to power generation technology.

Gamma Energy Technology P/L is proud to contribute to the on-going discussions on energy in Australia as we seek to solve the trilemma of energy supply - to assure energy system security and affordability so that emissions reduction targets are delivered.

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Executive Summary

Most Australian states and territories have relied on coal fired power generation for over 80% of their electricity supplies. More recently, Queensland, Victoria, South Australia and ACT have adopted policies to substantively increase sourcing their electricity from renewable energy and, along with NSW, targeting net zero emissions aspirations for the future. The state and territory policy positions are broadly consistent, with a minimum renewable energy target specified and aspire to net zero emissions by 2050 at the latest.

How this impacts on the physical operation of the National Energy Market (NEM) has been examined in this work, an extension of the 2017 study, Managing Flexibility Whilst Decarbonising Electricity: the Australian NEM is changing.[1] In a recent report, the impact of the Queensland and Victorian renewable energy targets (QRET and VRET) has been modelled using MEGS which takes account of the enduring need for grid strength and reliability services.[2] The modelling presented in this report seeks to examine a "very high renewables world" that minimises fossil fuel consumption whilst aiming for 90% decarbonisation.

Note: This assessment is for demonstrative purposes only to highlight the effect of forcing renewable energy onto the NEM system. It extrapolates an outcome of the RET approach to market failure. The authors are confident that there will exist a lower cost diverse and optimised energy technology asset portfolio that can deliver to net zero ambitions

The broad conclusions of this work are summarised as follows:

Deep Decarbonisation requires a diverse portfolio of plant

- It is not possible to go beyond 65% decarbonisation with renewables alone without incurring huge uplift costs to the system. In some capex scenarios it makes sense to avoid going beyond even 40% with renewables alone.

- CCS makes a perfect complementary technology for renewables in deep decarbonisation scenarios. Without nuclear, CCS is essential to achieving +90% emission reductions, requiring at least 10GW in a highly favourable scenario for renewables.

- In addition, there will need to be an element of flexible, low load factor fossil for meeting peaks, providing grid services and supporting the grid in weeks of low renewable production.

- Retaining the option for deep decarbonisation requires immediate and continuing investment in the development of CCS, with a strong emphasis on upgrading existing fossil to improve its flexibility to operate in emerging electricity markets

[1] Boston, A. Bongers, G, Byrom, S and Staffell, I. (2017). *Managing Flexibility Whilst Decarbonising Electricity – the Australian NEM is changing.* Gamma Energy Technology P/L, Brisbane, Australia.

[2] Boston, A., Bongers, G., and Byrom, S. (2018), *The Effect of Renewable Energy Targets and Meeting Climate Targets,* Gamma Energy Technology P/L, Brisbane Australia.

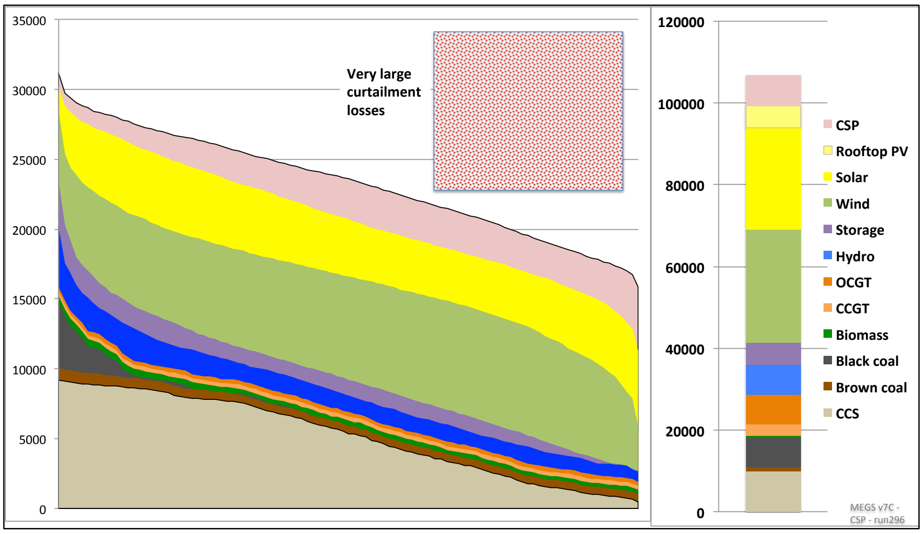
Performance Metrics for Decarbonisation of a Grid

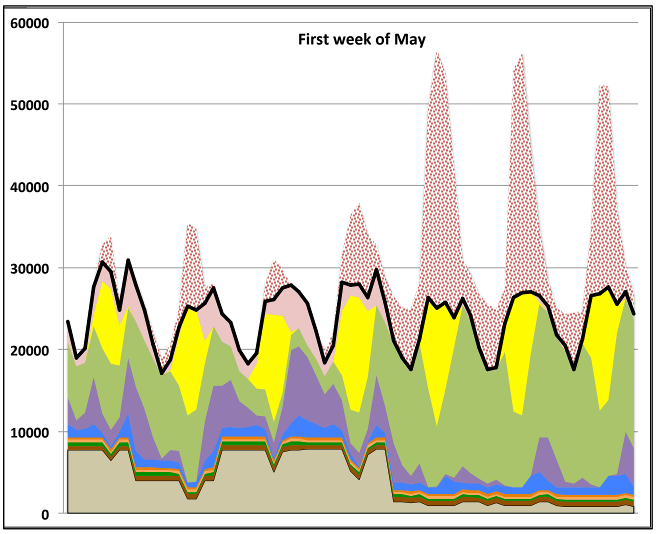
- It is increasingly clear from this study that the "Total System Cost" is the better metric by which to assess the affordability of emissions reduction pathways. Although familiar to many, the Levelised Cost of Electricity (LCOE) would be completely out of the context it was designed for and therefore very misleading when comparing generation options.

- National electricity pricing and energy competitiveness will be a strong function of Total System Cost. The most effective path to a low emissions grid will be to track the "least cost" pathway for transforming the constituent asset portfolio.

- Current Federal and State policy settings drive renewable generation investment. However, in Australia, there are no structural or market mechanisms in place to minimise the Total System Cost and ensure affordability of power. It is recommended that accountability for total system cost is transparently assigned within Australian market and regulatory systems.

Load duration, capacities and weekly schedule for 90% decarbonisation high renewables scenario





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Background

Previous Modelling

The current Australian grid has delivered reliable and secure energy for decades. The majority of electricity in the NEM is provided by coal-fired power generation, a technology that has also delivered the services required for grid stability such as inertia and frequency control. Coal and gas-based technologies have underpinned the energy competitiveness of the Australian economy. However, with increasing penetration of weather dependant, intermittent renewable generation, it is becoming more important to plan for and manage generation asset investment to track close to the least cost and highest reliability path to a low emissions future.

A previous study, sponsored by ANLEC R&D[1], used an innovative modelling approach, MEGS, to examine the Australian NEM. MEGS considered the grid system cost by recognising the importance of firm generation, the cost of balancing the system, and the required flexibility, while on the "pathway" to a lower emissions grid.

Key Points from this study included:

- As well as energy supply, each power generation technology brings with it a different set of grid services such as low emissions, inertia, frequency control, flexibility etc
- The NEM is unique when compared other international grid systems; it consists of 5 State-based grids that are only weakly interconnected
- The characteristics of the NEM plays a significant role in determining the value of an additional asset placed on the system. Each State grid will have unique asset requirements and a material impact on the overall NEM system
- It shows that decisions based on technologies with the lowest LCOE can result in a high cost grid system at deep decarbonisation levels due to misleading nature of this metric

The results highlight that approaches to meet short-term emissions targets (e.g: Paris 2030) can be suboptimal if they ignore the long term. The lowest cost energy supply technologies change as NEM decarbonisation proceeds. For example, at high penetration, renewables become increasingly expensive to the grid.

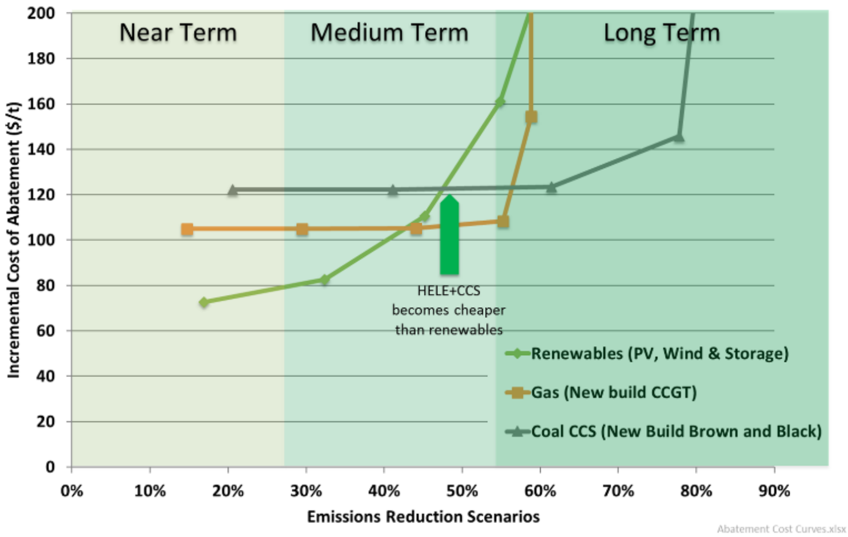

Figure 1: Cost of abatement pathways with increasing emissions reductions from 2017

In Figure 1, renewables costs increase due to intermittency and curtailment. Inflexions for other technologies occur when their emissions limits are reached. At high decarbonisation levels, dispatchable power like coal or gas with carbon capture and storage (CCS) will be required to deliver the required resilience for grid stability**. It can also deliver the deepest decarbonisation ambitions at the lowest cost.**

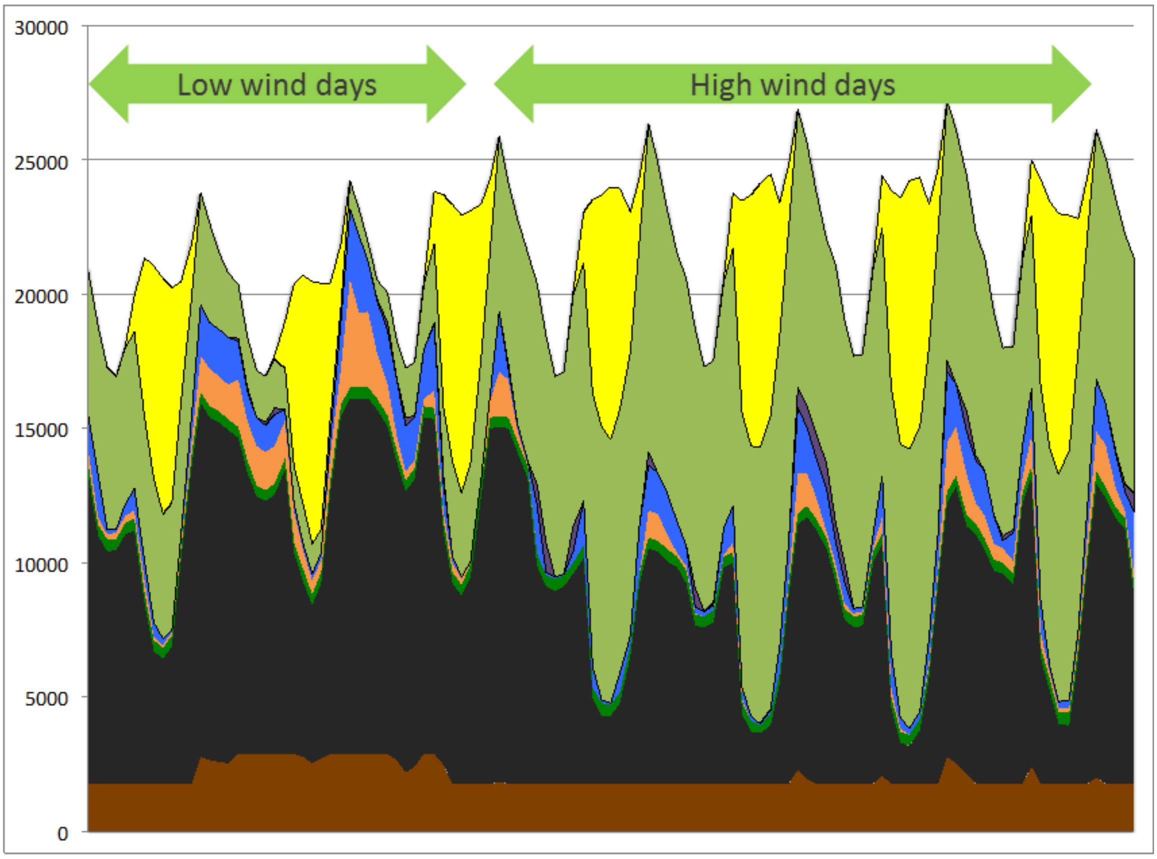

Figure 2: Modelled 7-day generation (high renewables scenario)

High penetrations of wind and solar PV will require companion low carbon technologies if they are to provide firm capacity that is available "on-demand" (refer to Figure 2). In high renewables scenarios, the existing fossil-fuelled power plant (especially black coal) will have to become increasingly flexible and cycle on a daily basis.

This is a new operating paradigm for coal assets on the NEM. It requires either new build or investment to upgrade existing plant to ensure they have such flexibility.

Key Terminology / Concepts

The following terms and concepts are defined here for a common understanding of their use within this report

- **Cycling**:
  Range of operations in which a plant's output changes, including starting up and shutting down, ramping up and down, and operating at part-load (less than full output).[3]
- **Forced Outage**:
  An unplanned component failure or other condition that requires the unit be removed from service immediately, within six hours, or before the end of the next weekend.[3]
- **Ramping**:
  Output that varies between full and minimum levels in order to follow changes in demand.[3]
- **Start**:
  Starting of a unit that is offline. Starts are described as hot, warm, or cold, depending on the temperatures of the metal in the turbine.[3]
- **Two Shifting**:
  Operational sequence whereby a generating unit is started and shutdown within a 24-hour period. Typically, the shutdown is overnight. Also used as a general term describing more than one shutdown within a 24-hour period.[3]
- **Wear and Tear**:
  Wear means the component reaches the end of its natural life through ordinary causes, though wear can be accelerated by cycling. Tear refers to an abnormal event that accelerates the life, such as occurs during poor control of operating conditions. While tear may occur during baseload operations, they are more likely during some cycling modes.[3]
- **Frequency control ancillary services (FCAS):**
  Frequency control is critical to power system security, and in the NEM, AEMO is responsible for procuring sufficient frequency control ancillary services (FCAS) to maintain frequency within prescribed operating standards. This task currently relies heavily on the services provided by synchronous generation, although newer technologies (especially storage) are in theory able to provide these services. However, this comes at significant cost if renewable output is curtailed to provide headroom for reserve.[4]
- **Inertia:**
  Inertia is provided by the large rotating masses of all thermal and some hydro generators and turbines. These synchronous machines rotate with the system frequency and their mass resists changes to frequency instantaneously. Inertia could therefore be seen as a store of kinetic energy within the grid itself which is drawn on during a system disturbance. In the past inertia has been abundant in the NEM and it is not directly valued at present, so scarcity is not transparent. However, as conventional plant continues to be displaced by low inertia technologies (intermittent), there are signs of inertia becoming scarce in some parts of the network. Low inertia systems require more FCAS services to be procured and these need to respond on a shorter timescale.[4]

[3] Cochran, J., Lew, D., Nikhil Kumar, N. (2013). *Flexible Coal Evolution from Baseload to Peaking Plant.* National Renewable Energy Laboratory, Colorado, USA. NREL/BR-6A20-60575.
[4] Finkel, A., et al. (2017) *Independent Review into the Future Security of the National Electricity Market: Blueprint for the Future*, Commonwealth of Australia.

The life of a steam turbine and other temperature sensitive components is related to thermal transients experienced over time. Most temperature components have well defined thermal limits and constraints. For a ‘sample’ steam turbine, Figure 3[5] requires slow temperature changes to manage the thermal stress in their heavy metal components.

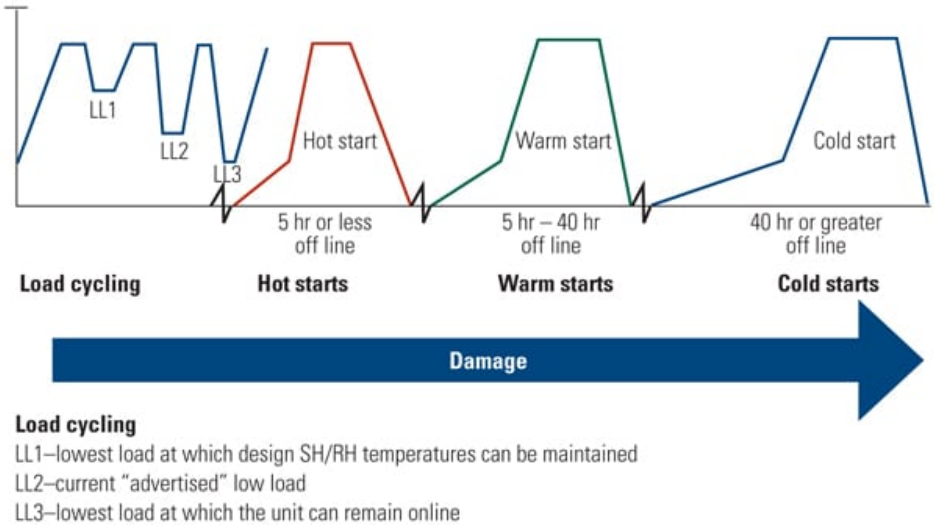

Figure 3: Relative damage caused by cycling steam plants

MEGS: Overview and Capabilities

The model at the heart of this work is **MEGS** – **M**odelling **E**nergy and **G**rid **S**ervices. Like many models, it balances energy for each calculated point in time for a grid of interconnected regions, but what makes it unique is its attention to the engineering constraints and ancillary services that ensure a grid is operable. In MEGS, these boil down to ensuring:

- Sufficient fast acting reserve is available to each region,
- A minimum level of inertia is connected in each region, and
- The grid is reliable and operable.

Figure 4 shows how MEGS compares to other modelling techniques.

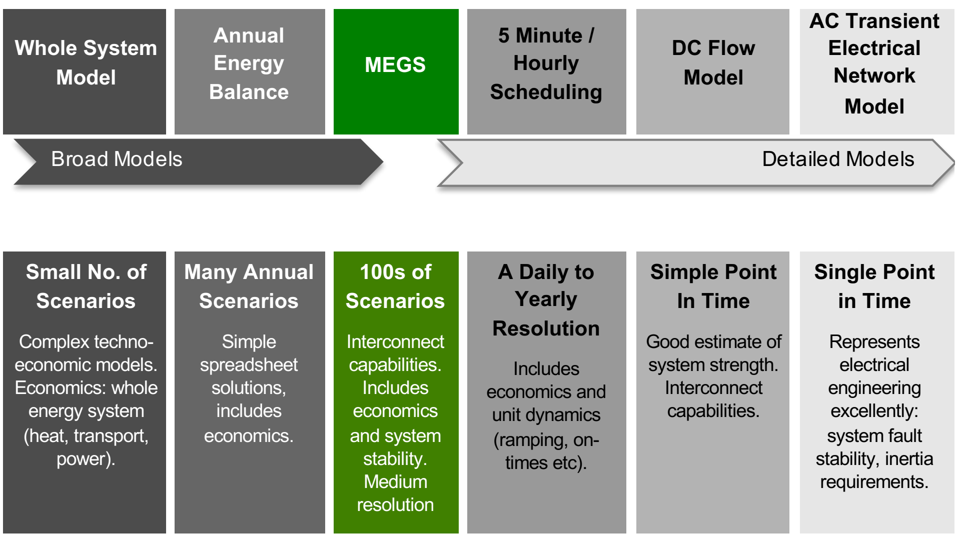

Figure 4: MEGS model in comparison to other methodologies

While MEGS is typically configured to model power plants as aggregated tranches of similar units, it may be configured as an individual plant configuration. For each modelled point in time

[5] Lefton, S.A. and Hilleman, D. (2011) *Make Your Plant Ready for Cycling Operations*, available at http://www.powermag.com/make-your-plant-ready-for-cycling-operations

(typically 2-3 hours apart), the solver determines generation and reserve provision from plant whilst minimising system short run costs which are given by fuel, carbon and non-fuel variable costs.

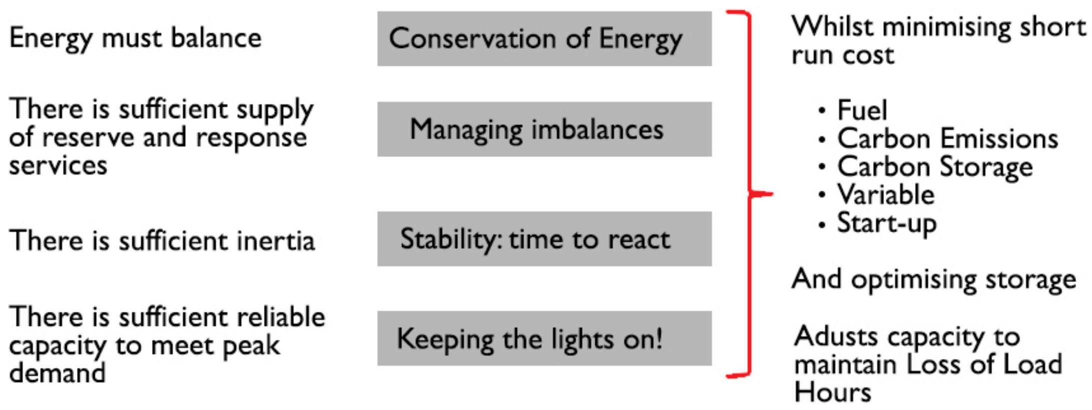

Figure 5: MEGS balances several services essential to grid operation

Forecasting into long term futures is inherently speculative. The ability to explore large uncertainties in future scenarios is an additional MEGS capability. When configured in this format, the model is denoted as **S-MEGS**. S-MEGS can model up to five key uncertainties via a Monte Carlo analysis:

- Weather: chosen from historic data affecting renewables and demand,
- Fuel Prices: chosen annually from a lognormal distribution,
- Capex: chosen annually from a lognormal distribution,
- New Build Projects: large projects are all or nothing, chosen randomly, and
- Clean Tech Build: capacity of renewables or CCS constructed is chosen from a uniform distribution.

For each simulation, a value is chosen for the uncertain parameters from a given distribution. This sets a portfolio of plant with a defined set of costs and historic weather data. A typical S-MEGS run results in 100’s of simulations with high-level outputs reported for each one. Viewing a distribution of probabilistic endpoints can be instructive to both recognize patterns that may emerge and highlight the boundaries of an outcome envelope. Although S-MEGS offers a wide range of input parameters which can vary, it is best to limit input variation to the minimum needed to explore the issue in question.

A Very High Renewables Scenario

Claims that Australian electricity could be 100% renewable are popular, with the latest claim in a paper from the Australian National University.[6] However, many of these simply add up annual energy production from various renewable technologies (often just the intermittent ones) and neglect to check whether the resulting system is actually operable or affordable. To test this thesis, MEGS was used to build as high a renewable backed system as technically feasible and examined how this would impact Total System Cost (TSC) and abatement cost, the key metrics for understanding what consumers will have to pay and to allow comparison with other abatement options.

Previous work had determined an optimum mix of wind, PV and batteries that added renewable energy at minimum cost to the system. A small amount of hydro additions were also considered. The actual mix was bespoke for each state, some being better for wind (SA), some for hydro (TAS) and others for PV (QLD). It was assumed that Snowy 2.0 was completed. Additionally, MEGS was upgraded to allow for modelling of Concentrating Solar Power (CSP) using Direct Normal Irradiance (DNI) data. Figure 6 illustrates the difference between PV and CSP. It can be seen that the latter is much more volatile than expected, as this technology is dependent on direct sunshine and shuts down on cloudy days. This in part explains why CSP uptake is not high in the modelling. More detail on the adaptions to MEGS to model CSP are detailed in the appendix.

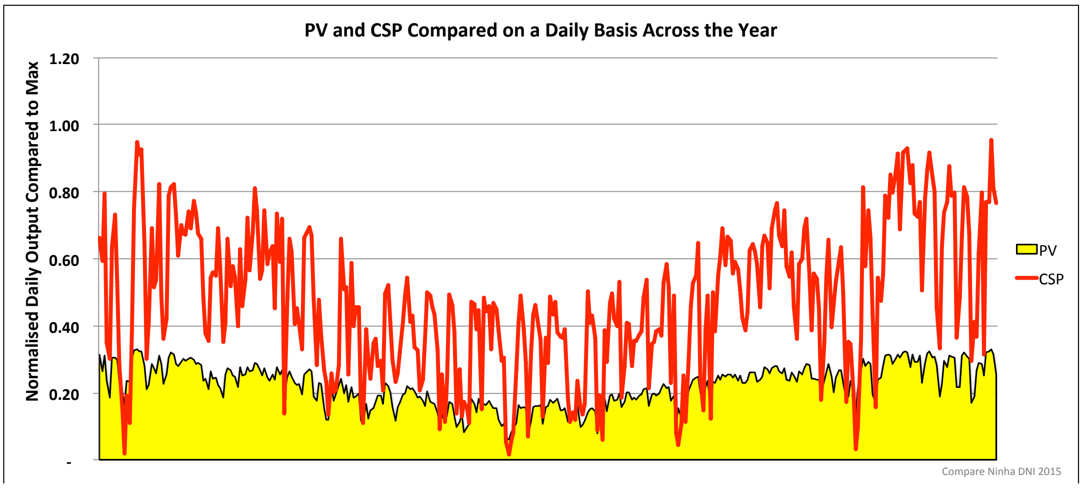

Figure 6: Comparison of PV and CSP performance day by day

CSP was modelled in MEGS as an option to be built directly connected to the grid in AEMO's Renewable Energy Zones (REZs)[7], or in a new region located in the sunniest parts of the states which require substantial new grid development (details on page 13).

Results

Figure 7 below compares three basic pathways. The right-hand chart shows the same pathways, but using CSIRO as the source for capex data[8]. These have much more aggressive cost reductions for PV (down to $650/kW by 2050) and CSP ($2,200/kW), as well as lower costs for coal CCS ($5,600/kW), which are used to represent the lower end of expectations. With such low capex for

[6] Baldwin, K., Blakers A., and Stocks M. (2018) *Australia's renewable energy industry is delivering rapid and deep emissions cuts,* Australian National University, Canberra, Australia

[7] AEMO (2018) *Integrated System Plan,* available at https://www.aemo.com.au/Electricity/National-Electricity-Market-NEM/Planning-and-forecasting/Integrated-System-Plan

[8] Hayward, J. and Graham, P. (2017) *Electricity generation technology cost projections 2017-2050,* CSIRO, Australia

CSP it finds itself as part of the renewables mix solution, with 10% of the renewable capacity delivering 15% of renewable energy. However, although the renewables curve is much lower, it still crosses over the CCS pathway (albeit later at 65% decarbonisation) and becomes very expensive. Gas at $12/GJ is no longer an option for bulk fuel switching, so the solution for 80% decarbonisation is Coal-CCS, a broad renewables mix and a small amount of existing fossil.

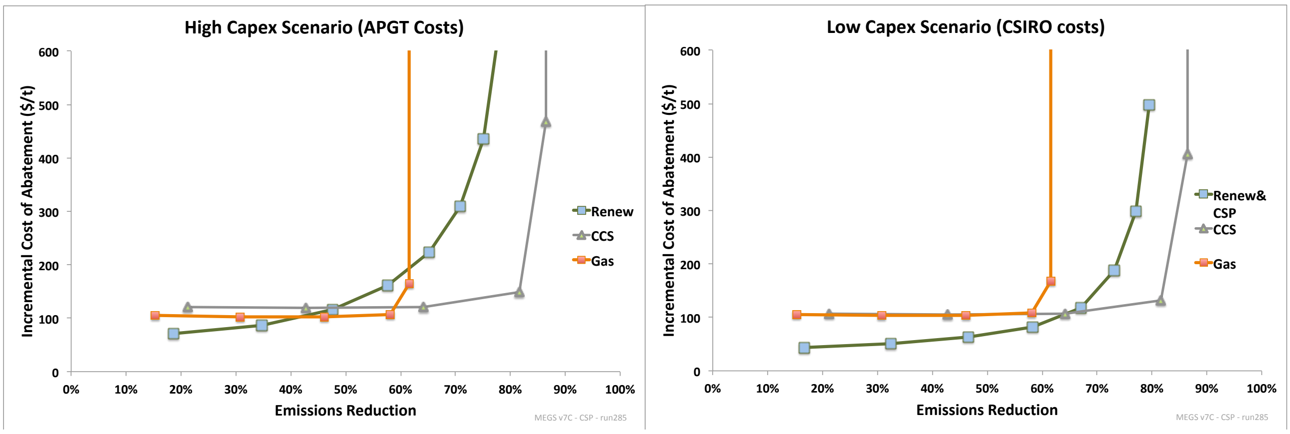

Figure 7: Incremental abatment cost of 3 options for high and low capex

Figure 8 shows how a combination of renewables and CCS can achieve 80% decarbonisation of the NEM at a cost of abatement (around $100/t), however it must be remembered this is with a very low capex scenario for renewables, especially CSP. At this level of cost resolution, there is not much difference in the cost of abatement irrespective of whether it is by a combination of renewables and CCS or by CCS alone. What is clear though is that renewables alone cannot approach this level of decarbonisation without exponentially rising costs. To minimise the risk of deteriorating energy competitiveness, it is essential that the CCS option is developed pro-actively so it is ready to be deployed when the cost of deploying renewables becomes prohibitive (probably in the early 2030's).

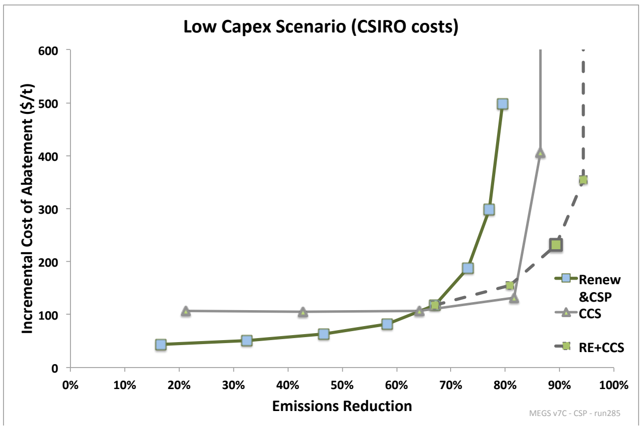

Figure 8: Incremental abatement cost of combining 2 options for low capex

Figure 9 shows the details for the 90% decarbonisation solution shown as a large square in Figure 8. It is clear that this optimal lowest cost system is underpinned by CCS. This delivers a significant proportion of the energy required (21%) for the low renewables-high demand periods. It is required to be flexible in this scenario though, dropping back load for most of the year to very low levels when renewable input is high. Its load following behaviour can be seen on the right, running at high load factors when wind is absent in the first half of the week but dropping right back in windy periods.

Secondly, it can be seen that a small amount of gas plant runs throughout the year in support of grid services (reserve, system strength and inertia) that renewables cannot supply. Finally, there is a small amount of unabated coal plant left on the system that undertakes peaking duties. In reality, if unabated coal cannot be converted to peaking, this may be supplied by open cycle gas, which will not change the results substantially.

Of particular note in this scenario is the large amount of curtailment representing about 15% total demand, or 25% of renewable production. This is typical of high renewables scenarios where there is a balance between spilling the energy or spending on additional storage facilities. To achieve this scenario requires a doubling of current generation capacity to 106GW and the construction of about 5GW of high voltage transmission to CSP facilities deep in the Outback.

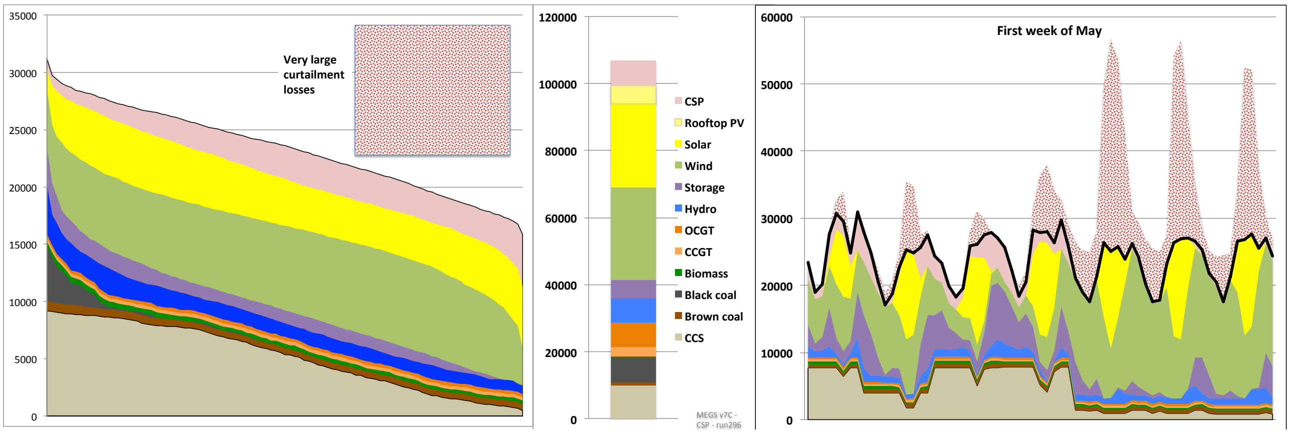

Figure 9: Load duration, capacities and weekly schedule for 90% decarbonisation high renewables scenario

Conclusions

- Deep decarbonisation envisaged by Paris 2 degrees and the States' own zero emission targets is not possible with renewables alone.
- In the most favourable conditions for renewables where +90% decarbonisation is required, they are unlikely to exceed 65% penetration.
- Significant support is required from CCS to cover peak demand and low renewable production periods. In +90% decarbonisation scenarios, there must be at least 10GW of CCS, even in the most renewables friendly environment.
- Flexible fossil, running at low load factors, is needed to provide peak power and grid services. Investment will be required to make existing fossil flexible and to develop peaking plant options.
- CSP could part of a renewables scenario, but would need to be at the low end of the capex estimates and gas price would need to be $12/GJ or more. Unless built with a day or more of storage, CSP suffers from a high degree of intermittency, compared with PV, caused by clouds and clustering of locations.

Appendix: Concentrating Solar Power

Concentrating Solar Power (CSP) is considered by some to be an important contributor to the renewables mix. It can easily accommodate storage within the cycle, and uses a conventional steam turbine that delivers inertia and other grid services to the system operator. How MEGS treats CSP is detailed here to highlight how this uncommonly modelled, and in the Australian context, developing technology, is treated.

Irradiation

Insolation data used for solar PV (from Renewables Ninja)[9] is unsuitable for CSP. In bright but cloudy conditions, solar PV still has significant output, however CSP needs direct line of sight to the sun to generate power. The appropriate measure of energy that can be captured by a CSP is the Direct Normal Irradiance (DNI). These data were obtained from the Bureau of Meteorology for 2005-2017.[10] Derived from satellite data, calibrated against ground level readings, the DNI data is gridded at a resolution of 0.05 degrees across all of Australia.

DNI is related to be very different from PV data. As shown in Figure 10, which shows generation with no storage for the two technologies, a cloudy day (January 11th 2015) can eliminate CSP output but only halves PV production, which can still generate with diffuse light. Furthermore, CSP has been configured within MEGS to only be installed within the Renewable Energy Zones (REZs) as expected, resulting in fewer sites in each state compared with ubiquitous rooftop solar PV, so there is significantly less diversity and greater volatility.

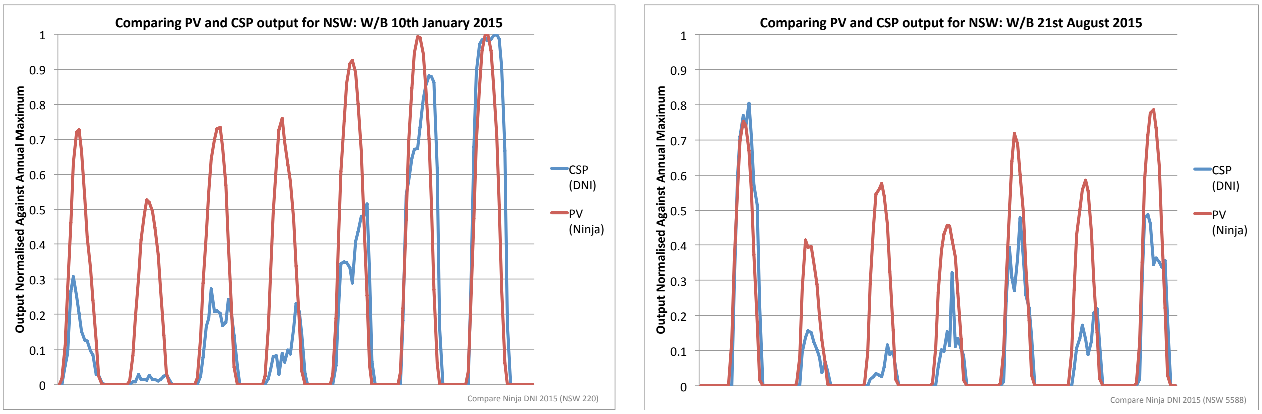

Figure 10: Comparing solar PV and CSP Output

CSP plant locations

It was assumed that all Concentrating Solar Power (CSP) plants will be built within the Renewable Energy Zones (REZs) identified by AEMO in their Integrated System Plan (ISP) of 2018[7] as suitable for solar (refer to Figure 11). In addition, a new zone was created in the region with the highest DNI (marked SOL on the map). This was in the 'Outback' centred on the point where NSW, SA and QLD boundaries meet. It was assumed that transmission lines would be built back to the grid in these three states, a significant undertaking which was added to the capex of CSP plant built in the region.

The CSP plant locations were chosen to be close to transmission lines in the sunniest parts of the REZs (generally the zones furthest inland). A small number (3-5) were chosen for each REZ, being a realistic build for CSP, which is much less dispersed than solar PV.

For each location a stream of hourly DNI data was extracted from the database. Locations within each region (State) were combined to give CSP input energy profile for that state.

[9] Staffell, I. and Pfenninger, S. (2016). *Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output*. Energy 114, pp. 1224-1239. doi: 10.1016/j.energy.2016.08.068.
[10] Acknowledgement: "Solar radiation data derived from satellite imagery processed by the Bureau of Meteorology from the Geostationary Meteorological Satellite, MTSAT and Himawari-8 series operated by Japan Meteorological Agency and from GOES-9 operated by the National Oceanographic & Atmospheric Administration (NOAA) for the Japan Meteorological Agency."

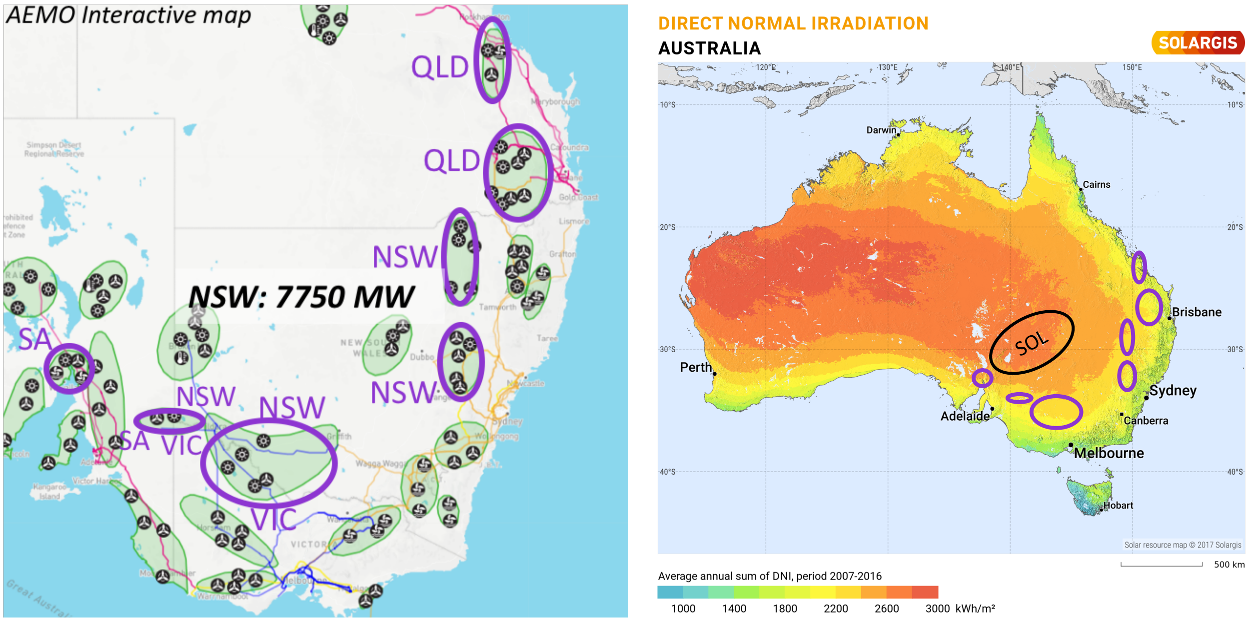

Figure 11: AEMO REZs Suitable for CSP, and their location (with new SOL region) in relation to DNI

CSP Storage

CSP plant can easily increase storage with the addition of tanks to hold the hot fluid until required for steam raising in the generation island. For this modelling, it was assumed that the storage would be sufficient for 6 hours running at full capacity.

To model this fully in MEGS, a new virtual region was created within each state to contain just the CSP generation. These special regions each contained a generator (representing the collector) and a storage facility (representing the hot fluid tank), and were linked to the main region via a single export only link (limiting output to the nominal capacity of the CSP).

The use of the storage was optimised within each day so that the CSP exports minimised system operational costs. It can be seen from Figure 12 that MEGS does what would be expected with a large amount of PV on the system: it saves much of the incoming solar energy (shown in yellow) for overnight generation (shown in red) with only a small amount of direct generation (orange). This is the same summer week as in Figure 10, and a comparison suggests that generation is "missing" towards the end of the week. However, renewable inflows exceed demand towards this period so even though DNI is high, MEGS curtails excess generation and effectively defocusses the CSP mirrors.

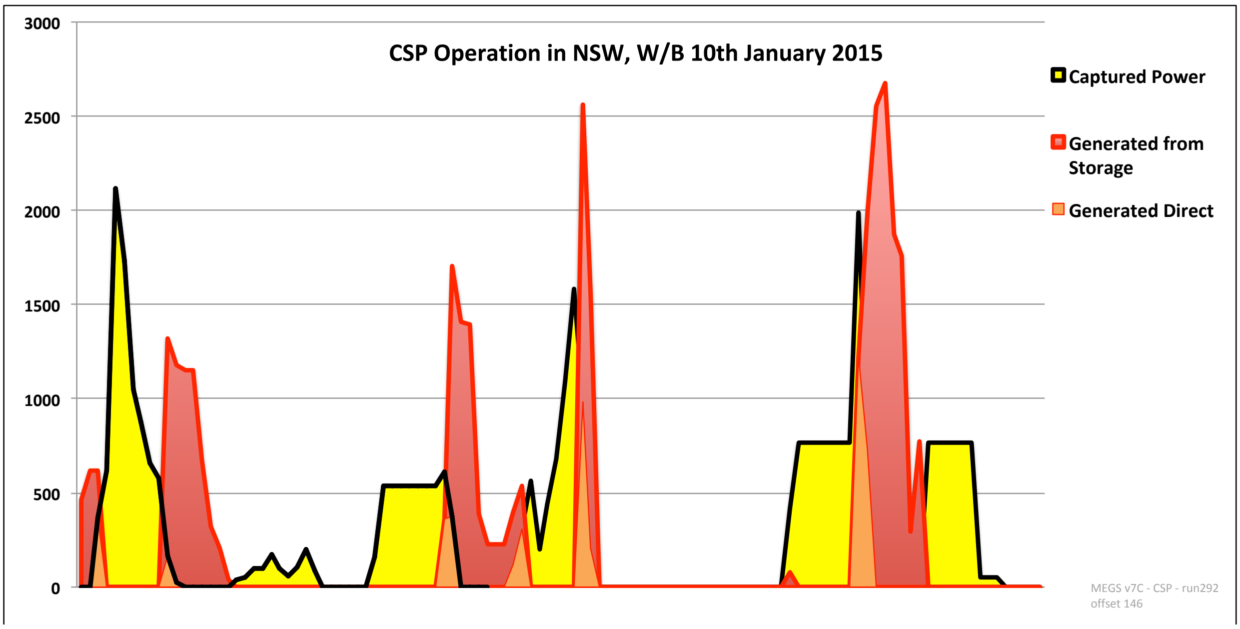

Figure 12: Example of CSP Management of Energy within MEGS.

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