The OzEA 50% renewables modelling - results and reflections

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ABSTRACT

High levels of non-dispatchable renewable generation are shown to displace the similarly inflexible coal-base-supply. Using hour level historical demand and weather data, we modelled wind and concentrating solar thermal (CST) at 50% penetration across the National Electricity Market (NEM). These renewable sources are combined with traditional coal-base, gas-intermediate and gas-peaking supply sources, pumped storage hydro (PSH) and buffering via thermal storage within the CST plant.

This analysis has been conducted using an Open Science approach, with all data and working available online [www.oz-energy-analysis.org/TTS.html]. The use of this approach is demonstrated.

This modeling and analysis, while simplified, suggests that high levels of wind and concentrating solar thermal can be configured so that integration into the NEM does not require greatly increased gas 'backup', and can thus act as base-supply. As such, these renewable supply sources are competing with coal and nuclear for the same niche in future markets.

This paper finishes with some thoughts on demand side flexibility and the importance of load shifting capacity, including the potential for expanded use of chilled water storage in air-conditioning systems.

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Abbreviations:

OzEA	www.Oz-Energy-Analysis.org
CST	Concentrating Solar Thermal
NEM	National Electricity Market
PHS	Pumped Hydro Storage
CCGT	Combined Cycle Gas Turbine
OCGT	Open Cycle Gas Turbine
WPC	Wind Power Curve
BoM	(Australian) Bureau of Meteorology

INTRODUCTION

Others have reported on work modelling 100% renewable electricity supply for the National Electricity Market (NEM) [1, 2]. Here we present a half-way scenario for such a system evolution, with renewable supply from wind and concentrating solar thermal (CST) providing 50% on average, and with conventional coal and gas-fired electricity making up the balance.

This work was designed to critically examine the idea of "base-load" in relation to renewable supply from wind and solar. We have come to understand, and show here, that the criticism "renewables cannot do base-load" involves a conflation of concepts by mixing up "supply" with "load" (or demand). Electricity systems with high levels of renewable supply are always possible when enough storage and flexible fuelled backup is included; what matters is how much.

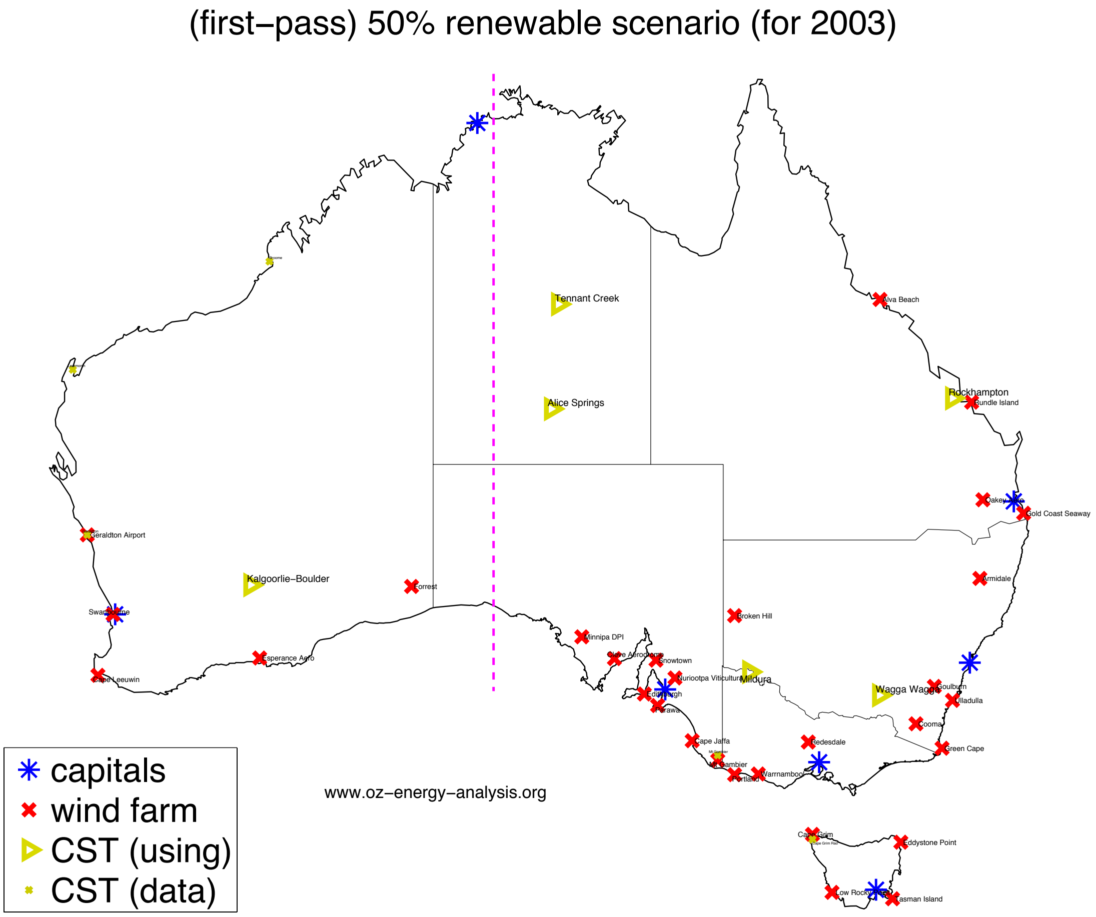


Figure One: Siting of simulated renewable plant. Of the 11 solar sites for which we have data, six (Rockhampton, Wagga Wagga, Mildura, Alice Springs, Tennant Creek and Kalgoorlie) are used in what follows. The NT sites are essentially proxies for central QLD. There are 30 wind sites "from Broome to Cooktown", although here sites north of Geraldton are not considered (and we also examine a no-WA case).

Traditional coal and gas supply can be matched conceptually to distinct load phases; that is, coal power running all the time accounts against a 'base-load', Combined Cycle Gas Turbines (CCGT) pair against an 'intermediate-load', and Open Cycle Gas Turbines (OCGT) operate as needed to provide peaking supply.

Continuing with this conceptual framework: *i*) coal base-supply is inflexible, has high capital costs, low fuel costs, and produces low cost electricity through high utilization; *ii*) OCGT are highly flexible, have only a modest capital cost, but are not efficient with gas and thus produce higher cost electricity when it is needed, and; (iii) CCGT sit in the middle being more efficient and capital intensive than open-cycle, having a medium level of flexibility, and producing electricity at an intermediate price.

In this paper wind farms and CST plant are simulated, hour-by-hour, at the locations shown in **Figure One**, and as described in the Data and Methods. This simulated power generation is subtracted from NEM demand data to give a *demand remainder*, which must be satisfied by the traditional coal and gas fuelled generators. The presented scenario relies on significant levels of storage and buffering. Storage takes the form of 30 GWh of Pumped Hydro Storage (PHS), and the ‘buffering’ exists as 6 hours of thermal storage within the simulated CST plant. By examining and exploring these dynamics carefully, a *prima facie* case is made that these variable sources of renewable electricity can take the place of coal as a source of base-supply. The presented work does not include analysis of transmission system requirements.

Importantly, this work also presents the abstraction of the demand-remainder-plot, showing in a high-level way the contributions from different supply sources. This can be a powerful tool for developing scenarios and understanding of possible evolutionary pathways to high penetrations of renewable electricity.

DATA AND METHODS

A core aspect of the Open Science approach is that data and methods are recorded in detail on the OzEA website (www.oz-energy-analysis.org). This allows a substantially abbreviated treatment to be given here. One overarching point of note is the choice of 2003 for the historical data; this was decided after considering the availability and quality (in relation to missing data) of the ground based solar irradiance data [21]. Below we first describe the three data sources, and then the four component models that were developed to simulate renewable power generation, storage and buffering.

Demand Data: Demand data for NEM states was taken from the AEMO "Aggregated Price & Demand" data files [3], and then processed and characterised at OzEA [4]. For the year 2003 there is no data for Tasmania, and the then-existing electricity region "SNOWY" was found to represent comparatively little demand and was ignored. Since 2003 the NEM demand dynamics have changed somewhat [4], including from recent growth in distributed photovoltaic systems. We accept these limitations to our analysis, and recognise in particular that managing peak demands is a challenge with or without high levels of renewable supply.

Wind Data and Site Selection: We first obtained from BoM a list of wind speed measurement sites [5], and used Google Earth to prospect for sites (and choose between nearby alternatives) from "Broome to Cooktown", including Tasmania and inland sites. Existing and proposed wind farm sites as reported by Geoscience Australia [6] provided some guidance, and we also received useful input from the OzEA open discussion for the wind data page [7]. An initial selection of 40 sites was made, and wind data for these sites obtained from BoM. Histograms showing the distribution of wind speed measurements were examined with most having a mode at around 4 m/s with a tail to around 15 m/s; nine sites were judged to be problematic (having insufficient wind). Alternatives for five of the nine were identified, with one of these again failing sanity-check once the new data was obtained. A further five sites did not have adequate coverage for 2003. Thus 30 wind measurement sites act as virtual wind farms (**Figure One**), and as detailed on the OzEA wind data page [7].

Solar Data: The Australian Bureau of Meteorology (BoM) has measured irradiance at 16 ground site locations, giving direct (also called DNI and beam), diffuse, direct horizontal and global (GHI) measurements. We put aside gridded satellite products and focused on use and analysis of the ground based measurements. Characterisation and presentation of extracted data is given on the OzEA website [8]. Individual stations have different start, and sometimes finish, dates; we found the period 2003-05 gave the best data coverage [21], and in this work we restrict scope to 2003.

Missing data complicates data processing. In many circumstances the presence of a single NaN (Not a Number) took out a whole day in a totalling or plotting task. We considered it a defensible expedient to infill singleton and doubleton NaN's, as follows: single NaN replaced with mean of adjacent values; double NaN, by example: [X, NaN, NaN, Y] to [X, X, Y, Y]. Longer runs of missing data remained.

Wind Power Curve: BoM weather stations are not generally positioned in the locations where wind farm builders might choose. That is, BoM stations are often located at somewhat protected airports or towns, while wind turbines are often located atop windy ridges. Also, BoM wind measurements are taken at 10m above ground level, whereas a wind turbine hub is usually at around 80m, and it is well understood that wind speed increases with height. The shear effects that reduce wind speed closer to the surface depend on local topology and weather conditions. Thus, we do not attempt a physical model for wind farm output from BoM wind speed data.

In developing our Wind Power Curve (WPC) methodology we compared the reported output from seven South Australian Wind Farms with simulation results from nearby BoM wind speed sites [9]. We sought to make the WPC as simple as possible at the same time as seeking to minimise the difference between simulated and actual wind farm output for reference cases. The established WPC model transforms wind speed data into simulated wind farm output, as described in detail at OzEA [10].

It is the variability information in the BoM wind speed data that is essential. After fixing the shape of the WP-Curve, there remains a single 'stretching' parameter (W_t). An imposed capacity factor of 35% acts to parameterise W_t for each site, in effect scaling the wind speed data to achieve the required average level of power generation. Also, as explained shortly, corrections were applied to address diurnal and seasonal biases associated with the wind shear dynamics.

When examining for systematic biases in the differences between the reference sites and associated simulations, it became clear that the wind shear (change in wind speed with height) changes during the day. An associated bias is seen, albeit less strongly, on a seasonal level. We suppose that air temperature is a key here. We developed heuristic corrections for application to the raw wind speed data [11], with the adjusted wind speed data then applied to the WPC to obtain simulation output. The efficacy of these corrections was examined and found to be mixed but worthwhile overall. Further work could productively target this area.

Blindly applied, the developed WPC methodology can take any (ludicrously inappropriate) wind data and produce respectable power output for a hypothetical wind farm. It was thus important that care was taken with the selection of sites (described previously). Also, it does not matter for the sake of this work if some mild exaggeration exists in the simulated wind farm generation results (i.e. the imposed capacity factor); only when an economic analysis is overlaid does this become concerning, and for that a whole gamut of construction and integration issues would also need consideration.

In summary, we established reasonable methodology for simulating the variability aspect of a virtual wind farm based on wind speed data from BoM sites. As the capacity factor is imposed, care is needed to ensure selected sites are not unrealistic for wind power generation. The more interested reader will also note the issues with diurnal and seasonal biases and corrections.

The CST power curve: In contrast to the WPC, it is relatively straightforward to set out a physical model for estimating the electricity generation from virtual Concentrating Solar Thermal (CST) plant. A tower based system is used: that is, an array of heliostats track the sun and reflect direct sunlight onto a collector at the top of the tower, whence the concentrated light is absorbed and the resultant heat used to power a conventional steam turbine (much as found within a coal power plant) that in turn runs a generator to produce electricity. The power curve established for transforming irradiance data into electrical output is described in detail at OzEA [12]. This power curve was applied to the data as described [13].

The problem breaks down into a number of component parts: (i) amount of solar radiation captured for concentration; (ii) net heat energy flux captured at the receiver; (iii) flow of heat energy through the 'engine', and that converted into mechanical work; (iv) the efficiency of the generator in producing electricity, and (iv) allowance for the engineering reality that any real implementation will be optimised for a particular flux and will not in practice operate as well as predicted by this sort of model away from this point.

The turbine efficiency is taken as being described by Curzon-Ahlborn Engine Theory [14, 15], rather than the more theoretical Carnot cycle or a more complex Rankine cycle parameterisation. The level of concentration achieved by the system was set conservatively at 600; the high and low-end temperatures were taken as 900 K and 400 K respectively. Other physical parameters are as tabulated on the referenced OzEA page.

The Pumped Hydro Storage Model: Conceptually, PHS is modelled as a single 30 GWh bucket (there is around 20 GWh of PHS in the current system [16], plus substantial run-of-river hydro resources) that can provide supply between 0-4 GW (if not exhausted), while charging occurs at (and only at) 1.5 GW for a minimum of 3 hr. These constraints roughly mirror the engineering realities of existing PHS [16], and are stringent in treating all the PHS as a single unit (consistent with this modelling work not including transmission). While the primary role of the PHS model is to shave peaks, it also acts to provide demand when the demand remainder is low (thus lifting the base).

For full details on this somewhat involved heuristic model the reader is referred to the code [17]. Roughly, the demand remainder profile is divided into sections that are processed individually. When there is not a clean division between adjacent sections these are combined. For the processing of each section a level is established above which the PHS is able to shave the peaks. The heuristic also looks ahead to see if charging can take place without pushing the demand above the shave-level.

The Thermal Storage Model: A heuristic model first establishes three time points (for each day), t_1, t_2, and t_3; with t_1 representing the start time for possible generation (i.e. solar input), t_2 being the end time for generation without storage, and $t_3 = t_2 + S_{hr}$, where S_{hr} is the parameterised storage time (6 hrs in this work). Within the $[t_1, t_3]$ time window, we seek to provide output in a way that is weighted to follow demand, while subject to two constraints: (i) the cumulative output at any time does not exceed power collected to that point on that day, and (ii) that plant output does not at any point exceed 110% of nameplate capacity. Losses are ignored at this stage.

The heuristic takes a demand trace that in practice is a demand remainder after the subtraction of the wind farm output. Weighting values for each hour, $W(t)$, are created by squaring the demand values and normalising, thus giving a sharper response to the higher demand values. With total power harvested for the day as CST_{tot}, the output at time t is taken as: $P_{cst}(t) = W(t) \, . \, CST_{tot}$, subject to the two constraints above. See the code for full details [18].

Operators of CST plant in a real market can be expected to act more intelligently than this simple heuristic, and its application is thus considered conservative.

RESULTS and DISCUSSION

As per data and methods, and as laid out on the OzEA website [19], hour level simulated output for thirty virtual wind farms and six virtual CST sites (**Figure One**) was calculated using wind speed and solar irradiance data for 2003.

The overall demand for the NEM states in 2003 (QLD, NSW, VIC, SA) averages around 20.6 GW, and peaks at 28.5 GW. We thus seek 10.3 GW average from the renewable supply. **Figure Two** shows the total demand being meet with 15% of supply from the six CST sites, 35% from the wind farms, and 50% from fuelled supply. This figure also shows a putative breakdown for the fuelled supply into ‘base’, ‘intermediate’ and ‘peaking’ components.

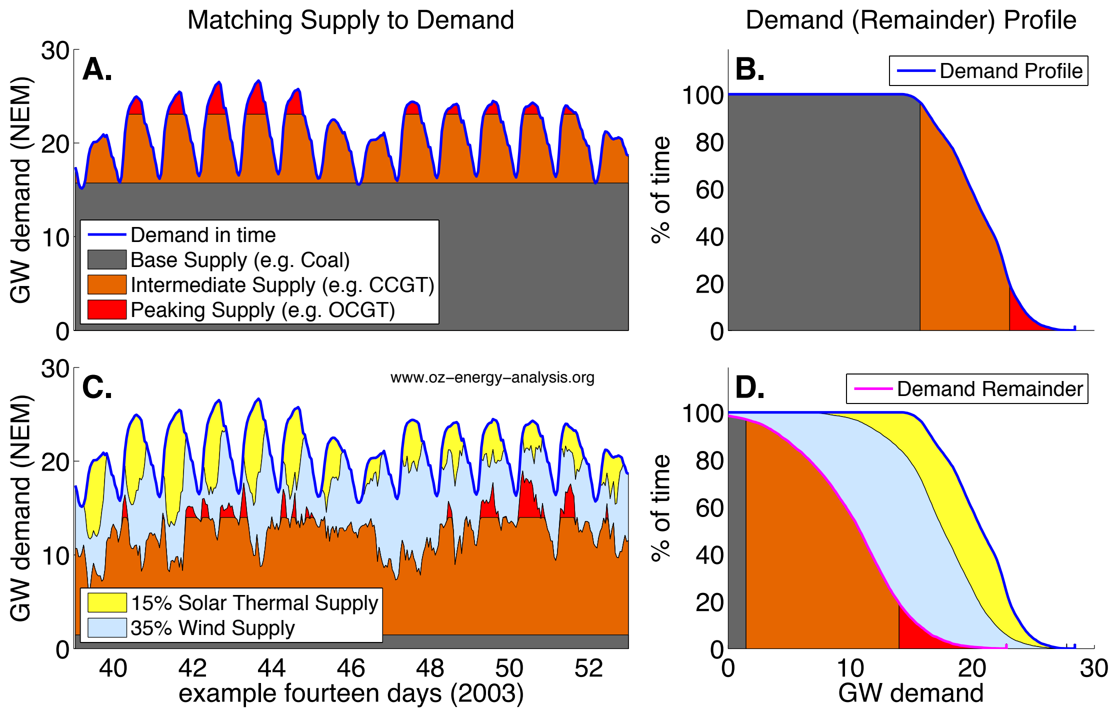


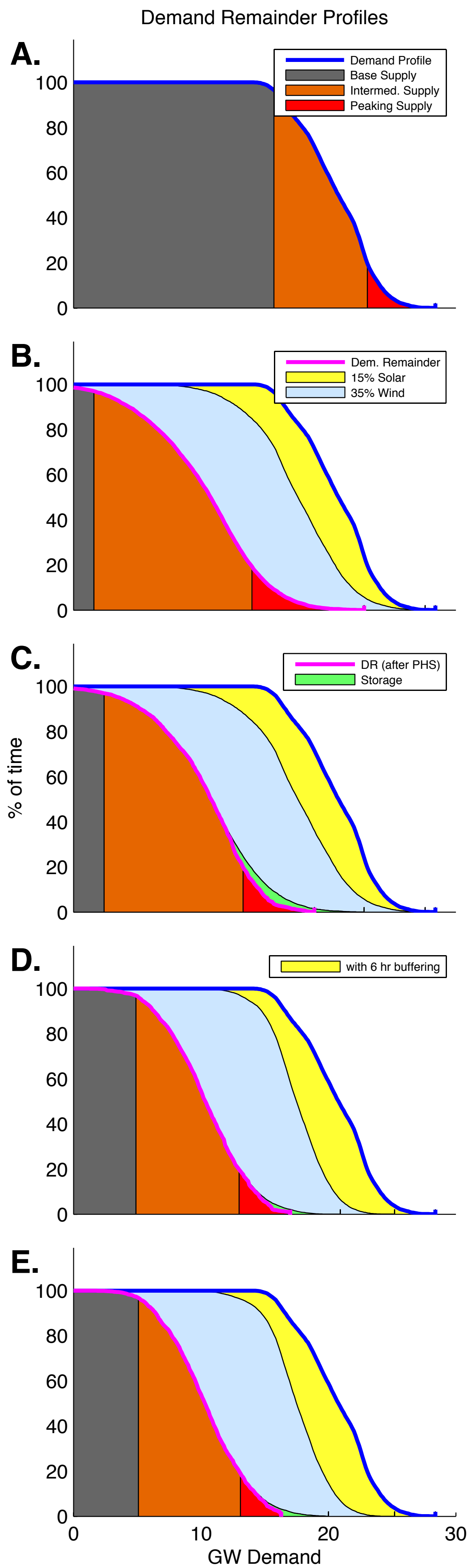
Figure Two: Supply meeting demand – naive scenario with no storage or buffering. **A.** Demand in time showing the 'base', 'intermediate' and 'peaking' phases for no-renewables; **B.** the demand profile for panel A (over the full year); **C.** Supply meeting demand for the naive 50% renewables scenario; **D.** The Demand Remainder Profile for Panel C (over the full year). For all panels the 'base' (dark grey) has been defined as 97-100% of the time and the 'peak' (red) as up to 20%. These cut-offs are simply selected for illustrative purposes.

It is striking that the neat appearance of the current matching between the demand and fuelled supply (top panels) changes into a somewhat messy or jagged mix when the renewables are included (lower panels). This is not surprising. The current system has been built and refined over some fifty years, and thus contains much internal order. Conversely, this blunt imposition of 50% renewable supply has not been accompanied by changes to the way demand is structured and supply buffered.

Panel D requires particular attention, observing especially that peak demand at ~28.5 GW has reduced in the Demand Remainder to only ~23 GW. That is, after the expense of 50% renewable infrastructure, the amount of fuelled supply infrastructure needed has been reduced by only ~20% (the so-called capacity credit). Such a low capacity credit is most unhelpful in seeking to make an economic case for renewables; however, as we will see shortly, it is not difficult to develop the scenario to achieve an improved capacity credit.

Examining the full temporal view for the naive scenario (i.e. full versions of Panels A and C on the OzEA site), the night-time lows in demand are close to identical night after night in traditional mode, thus enlarging the 'base' over the 'intermediate' phase. Mechanisms such as off-peak hot water, and the overnight 'charging' of PHS facilities, act to produce this neat situation. In contrast, the 50% renewable supply often meets much of the demand, thus enlarging the 'intermediate' supply phase over the 'base'.

Figure Three: Demand Remainder profiles summarising the development of the first OzEA 50% scenario. **A.** No renewable supply – a traditional demand profile, broken into base, intermediate and peak components; **B.** Naive 50% renewables (no storage or buffering mechanisms); **C.** Inclusion of Pumped Hydro Storage model; **D.** Additional use of 6 hr CST storage; **E.** Demand Remainder Profile for refined 50% renewables model (optimisation of relative site capacities).



Note also that while raw demand peaks in the afternoon or early evening, the demand remainder often peaks in the evening or early in the day (before the days solar energy catch provides supply). While these peaks will be managed with the storage mechanisms introduced next (**Figure Three**), it remains noteworthy that a systematic change has occurred in the timing of the peak requirement for fuelled supply.

The first refinement is to include the Pumped Hydro Storage (PHS) model (see Methods). For this work we use a total of 30 GWh. The model acts both to shave peaks from the demand remainder, and to provide demand when the demand remainder is low. **Figure Three**, panel C shows the resultant profile. The PHS has substantially drawn back the demand remainder peak, and thus improves the capacity credit. It is important to note that the 20 GWh of PHS that exists in the current system has not been included in panels A and B.

The second refinement is to introduce the thermal storage within the CST plant (see Methods). For this work we use 6 hours of thermal storage and for simplicity limit its use to six hours into the evening. This shifts solar power into the early evening peaks, and transfers the demand remainder peaks into the mornings (before the next days solar becomes significant). **Figure Three**, panel D shows the resultant profile. Again, an improvement in the capacity credit is observed, along with a reduction in the required level of fuelled intermediate and peaking supply. As the combined use of the PHS and CST buffering heuristics was problematic, with the PHS operating best with clear ups and downs that the CST buffering acted to smooth out, it can be expected that more sophisticated modelling could do better.

The third and final refinement in this work was to implement a simulated annealing procedure that sought to reduce the peak value and the variance of the demand remainder by shifting generation capacity between the wind farms, and also between the CST plant. In this way the demand remainder peak was reduced from 17.1 MW in Panel D to 15.5 GW in Panel E (**Figure Three**). Excluding the WA sites made only a small difference (15.7 MW). Naively, a peak demand at 28.5 GW with a corresponding peak in the demand remainder at 15.5 GW corresponds to a 45% capacity credit for 50% renewable penetration; however, this figure is neither fair nor robust on the basis of the work done. We simply note that this tentative observation is encouraging.

CONCLUDING REMARKS

The work presented seeks to contribute in three ways. First, the demand remainder profile approach provides a powerful abstraction for examining how different supply configurations can act to meet demand. This high-level view can be applied in developing a coherent series of scenarios at increasing levels of renewable penetration (i.e. to sketch potential evolutionary pathways).

Second, we showcase an Open Science approach whereby data and workings underpinning an analysis or modelling exercise can be easily accessed, questioned, and built upon.

Third, while the work presented does have a clear quantitative basis, the simplifications and limitations require that quantitative results be heavily qualified. Thus, we restrict our claims to a single point: the modelling suggests *prima facie* that wind and concentrating solar thermal could provide base-supply to the NEM at a 50% penetration level given realistic levels of storage and buffering. In claiming the provision of 'base-supply' we engage an important semantic distinction between 'base-load' and 'base-supply' in order to counter the claim that 'renewables can not do baseload'. In more straightforward terms, the modelling shows successful integration of wind and solar at the 50% level (i.e. without the variability of these sources requiring substantial additional gas backup).

The use of 30 GWh pumped hydro storage, compared to the existing 20 GWh [16], is counterbalanced by two factors: first, Australia has some 7.8 GW of hydro capacity [20]. While run-of-river hydro resources can be precarious, it remains that existing use of hydro for routine generation (e.g. in Tasmania) can be significantly displaced by renewable electricity when it is abundant (e.g. S.A. wind), thus preserving more hydro for when it is really needed. Also, the work here does not include any demand side flexibility, an area anticipated to develop strongly in coming decades.

Buffering with thermal storage in the CST plant was the critical element in achieving a comparatively balanced contribution from the renewables, avoiding the need for a large expansion in gas peaking infrastructure. While a high penetration of renewables can require substantial backup supply from gas turbines to 'fill the gaps' – this being the real essence of the 'renewables can't do base-load' criticism – we observed in this simplified modelling work (e.g. no transmission) that it can be possible to configure the system to meet demand without greatly expanded 'backup'.

It is seen clearly in **Figure Three** that renewables fit into the 'base' component of supply; one inflexible source of supply (coal) being displaced by others (wind and solar – note, however, that wind can be considered semi-dispatchable as it can be rapidly scaled down); also, the CST as implemented here does include a degree of dispatchability via the buffering with hot-thermal-storage). The supply components that provide flexibility and control are maintained (panel E), with their time-of-use dynamics reconfigured around the demand remainder. In meeting demand with a range of supply technologies, the division between the flexible and inflexible is a crucial one. It is thus the case that coal, wind and solar, and nuclear are competing to occupy the same niche.

This work was initially scoped around the large and more centralised technologies, whereas it appears likely that solar photovoltaic will drive electricity systems to become more distributed. It also appears probable that the need to handle peak loads in particular, combined with growing renewable generation and the costs of transmission and distribution, will drive system evolution to include significant buffering and storage within the distribution networks. Smart grid control of some devices is foreseeable, especially in relation to refrigeration and air conditioning.

We speculate on purely physical grounds that cold thermal storage associated with air conditioning systems, especially large commercial systems, has the potential to provide significant load shifting capabilities. In isolation such a development can be expected to contribute to managing peak demands; in generality this mechanism represents an enabling technology for buffering renewable supply. The collocation of such cold-thermal-storage systems with PV acts to further reduce the demands on transmission and distribution networks. Such a development is especially needed for networks outside the NEM, such as in the Northern Territory where there is no significant hydro and limited interconnection.

Thus, centralised generation and storage, as modelled in this work, can be expected to continue giving ground to more distributed approaches. None-the-less, the core issue of integrating and buffering a range of generation sources to meet demand remains a rich topic for ongoing scenario building and analysis. The Open Science approach at OzEA can assist the Australian renewables research community to progress these works.

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Note: “~” has been used below to represent “http://www.oz-energy-analysis.org”

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