Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market

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Abstract

As part of a program to explore technological options for the transition to a renewable energy future, we present simulations for 100% renewable energy systems to meet actual hourly electricity demand in the five states and one territory spanned by the Australian National Electricity Market (NEM) in 2010. The system is based on commercially available technologies: concentrating solar thermal (CST) power with thermal storage, wind, photovoltaics (PV), existing hydro and biofuelled gas turbines. Hourly solar and wind generation data are derived from satellite observations, weather stations, and actual wind farm outputs. Together CST and PV contribute about half of total annual electrical energy supply.

A range of 100% renewable energy systems for the NEM are found to be technically feasible and meet the NEM reliability standard. The principal challenge is meeting peak demand on winter evenings following overcast days when CST storage is partially charged and sometimes wind speeds are low. The model handles these circumstances by combinations of an increased number of gas turbines and reductions in winter peak demand. There is no need for conventional baseload power plants. The important parameter is the reliability of the whole supply-demand system, not the reliability of particular types of power plants.

Keywords: 100 per cent scenarios, baseload, renewable electricity

1. Introduction

This paper reports on the on-going development of energy system simulations to identify and quantify the challenges of reliably supplying 100% renew-

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able electricity to the five states and one territory spanned by the Australian National Electricity Market (NEM). The current climate science suggests that developed countries must aggressively reduce greenhouse gas emissions over the next several decades to a point of near-zero emissions by 2050 in order to avoid global warming of more than $2°C$ (IPCC, 2007). The International Energy Agency (2011) notes that 80% of the total energy related emissions permissible by 2035 in its 450 parts per million scenario are already 'locked in' by our existing capital stock of energy infrastructure. Continuing development patterns for the next five years would then require that all subsequent energy supply be zero carbon.

Today, the NEM produces around one third of total Australian greenhouse gas emissions, as the system derives around 90% of supply from lignite, bituminous coal and natural gas. If Australia, currently one of the world's highest per capita greenhouse emitters, is to make its fair contribution to such emission reductions then its highly emissions intensive electricity industry must rapidly transition to zero carbon sources (Garnaut, 2011). Given the long life of electricity industry assets, Australian energy and climate policy must therefore now consider the potential for future low emission electricity systems based on rapid deployment of commercially available zero carbon technologies. The only zero carbon 'sources' that are commercially available and seem likely to be able to make large contributions before 2020 in the Australian context are certain renewable energy sources (Department of Resources, Energy and Tourism, 2011) and demand reduction (eg, through efficient energy use).

Numerous scenario studies have been published that model the potential for countries, regions, and the entire world, to meet 80–100% of end-use energy demand from renewable energy by some future date, typically mid-century. National scenarios exist for Australia (Wright and Hearps, 2010), Ireland (Connolly et al., 2011), New Zealand (Mason et al., 2010), Portugal (Krajačić et al., 2011), Japan (Lehmann, 2003), the United Kingdom (Kemp and Wexler, 2010), Germany (German Advisory Council on the Environment, 2011) and Denmark (Lund and Mathiesen, 2009). More broadly, a regional study has been produced for northern Europe (Sørensen, 2008) and several studies of the global situation have been produced including by Sørensen and Meibom (2000), Jacobson and Delucchi (2011), Delucchi and Jacobson (2011) and WWF (2011). These scenario studies do not typically specify a transition path nor do they share a common methodology for analysis (Nielsen and Karlsson, 2007). However, they are valuable in showing that aggressive reduction in fossil fuel use is possible, and provide a vision of how the future energy system might look.

Most of the existing studies make assumptions about future energy demand, the potential for energy efficiency to reduce demand, and the future costs, performance, and rate of deployment for emerging energy technologies. A difficulty with setting a scenario reference date decades into the future is predicting demand factors such as population growth, geopolitical factors (eg, the dramatic collapse of the Soviet Union), income growth, and unexpected technological shifts. Over the past 50 years, making reliable forecasts of the most basic energy industry variables such as primary energy consumption and the price of oil

has been shown to be extremely difficult (Bezdek and Wendling, 2002). This brings substantial uncertainty into the picture.

These high penetration renewable energy scenarios remain controversial (Trainer, 2010, 2012; Delucchi and Jacobson, 2012). Beyond the potential costs of a transition from the current fossil fuel dominated energy systems, a range of technical concerns have been raised, particularly in the context of the electricity industry. Electrical power systems must instantaneously match supply with demand at all times and all locations across the network, and there are currently limited energy storage options. Balancing supply and demand across the full range of timescales is a high priority for the electricity industry, given that most energy use is variable and somewhat uncertain. The variability of weather-driven electricity generation raises additional challenges (MacGill, 2010; Outhred and Thorncraft, 2010). It has been argued that it is not technically feasible to reliably operate an electricity industry with 100% renewable generation without major technical breakthroughs in these technologies, or complementary storage technologies (Sharman et al., 2011).

In the present research, we simulate a 100% renewable electricity system in the region spanned by the NEM for the year 2010, using actual demand data and weather observations for that year. This provides a more straightforward basis for exploring the question of reliably matching variable renewable energy sources to demand. In the simulations, electricity demand is met by electricity generation mixes based on current commercially available technology: wind power, parabolic trough concentrating solar thermal (CST) with thermal storage, photovoltaics (PV), existing hydroelectric power stations, and gas turbines fired with biofuels. There is no fossil fuel generation in this mix, a marked contrast from the present NEM generation portfolio. This approach closely corresponds to the approaches taken by Mason et al. (2010) for New Zealand, Delucchi and Jacobson (2011) for California in the years 2005 and 2006, and described by Mills (2010) for the United States in the year 2006. By minimising the number of working assumptions, we aim to provide some insights into the potential contribution from different renewable sources and the reliability implications of 100% renewable electricity for the NEM.

This paper is structured as follows. In the next section and Section 3, an overview is given of the computer simulation and the data sets used by the simulation. In Section 4, a baseline 100% renewable scenario is described. The results of the baseline simulation are presented in Section 5. A series of sensitivity analyses are performed from the baseline scenario and the results of these analyses are provided in Section 6. The results are discussed in Section 7, and conclusions are made in Section 8.

2. Simulation overview

The simulations described in this paper are carried out using a computer program developed by the lead author. The program has three components: a framework that supervises the simulation and is independent of the energy system of interest, a large integrated database of historical meteorology and

electricity industry data, and a library of simulated power generators. The library only contains the generator types of interest for this study, but new types can be easily added or extended from existing types. A verification suite is included.

The program is written in the Python programming language, with a design that is easy to extend or modify. An advantage of using an interpreted language such as Python, as opposed to a traditional compiled language, is that the program can be modified by users while the program is running. Users can write their own extensions, with access to all the features of a fully-fledged programming language, to operate the program in ways unanticipated by the original software developer. As a simple example, a user can perform a sensitivity analysis by iteratively varying the capacity of a single generator and inspecting the impact of this change on the results.

For the simulations reported in this paper the entire NEM region is treated as a 'copper-plate': that is, power can flow unconstrained from any generation site to any load site. Hence, demand across all NEM regions is aggregated, as is supply[1]. For each hour of the year, the simulation calls on each generator, in a given merit order, to dispatch the most appropriate of the available generation to meet the average power demand for that hour. In general, dispatch proceeds from the lowest operating cost plants without energy storage (eg, wind and PV) before the dispatch of plant with energy storage (eg, hydro and gas turbines). If supply cannot meet the demand, the shortfall is recorded and the hour is marked *unmet*. Conversely, if available supply exceeds demand, which can occur with high levels of lower capacity factor and zero fuel cost generation such as PV and wind, the simulation attempts to find another generator in the system that can store the excess power (eg, by pumping at a pumped storage hydro station). Any remaining surplus power is then regarded as having *spilled*.

The simulation currently includes the following classes of generators: wind, PV, CST, hydro with and without pumped storage, and gas turbines. One or more generator objects may be created from each generator class. For example, all PV generation may be represented in the system by a single object, or by multiple objects grouping sites or regions. The program maintains a list of the generator classes, with the list order explicitly specifying the merit order. The model does not consider minimum operating levels, minimum start-up/shutdown times and ramping rates – a reasonable assumption given the absence of large thermal plant such as coal, combined cycle gas turbines (CCGTs) and nuclear units, which all suffer from such operational limitations to differing extents.

At the end of a run, the simulation produces a summary report and an hourly plot for the year showing the demand and the sources of supply (see Figure 1 for a sample). Any hours of unmet demand are indicated on the plot. The summary report includes total energy spilled, number of unmet hours and

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[1]In reality, the NEM has somewhat limited transmission capacity between some regions. The implication of this is one area of proposed further work

unserved energy.

The NEM reliability standard is currently set at 0.002% of unserved energy per year (Australian Energy Regulator, 2011). This standard recognises that ensuring sufficient generating capacity to meet any plausible demand in the system would impose a significant economic cost. Hence the NEM is not operated on the basis that all demand must be met every hour of the year. Instead, system balancing can be achieved through shedding controllable loads such as aluminium smelters or some location-specific brownouts for a limited period over a year. The total power demand of the six aluminium smelters situated within the NEM has been estimated at over 3 GW (Turton, 2002). A number of these smelters actively participate in the NEM as potential demand-side response.

3. Data sources

The simulation draws from a range of data sources that have been assembled into a large integrated database. Each data source is briefly described in turn.

3.1. Electricity demand

Electricity demand data for the NEM in 2010 was obtained from the Australian Energy Market Operator (AEMO). Demand in the NEM is reported on a regional basis at 30 minute intervals. As the simulation is performed on a 'copper-plate' basis with hourly time steps, demand is aggregated across all regions and averaged into hourly values.

3.2. Wind generation

Electricity generation data reported by wind farms over 30 MW and operating in the NEM in 2010 were supplied by AEMO. These data supply average wind power at each wind farm over the five-minute dispatch interval and were averaged into hourly values.

3.3. Solar irradiance

Satellite-derived estimates of global horizontal irradiance and direct normal irradiance in 2010 for the Australian continent were provided by the Australian Bureau of Meteorology (BoM) at 5km by 5km spatial resolution and hourly intervals. The data for the year 2010 are largely complete, however 22 hourly grids are missing and have been interpolated.

3.4. Other weather data

Hourly weather records for every automatic weather station in the NEM region were obtained from the BoM. These records include pertinent weather variables such as dry bulb temperature, wet bulb temperature, relative humidity, wind direction, wind speed and atmospheric pressure. These data, combined with the solar irradiance estimates, were used to automatically generate weather data files for selected sites around the NEM in 2010 (Elliston, 2011). The files are produced in a format compatible with System Advisor Model (SAM),

a performance and financial model of various renewable energy technologies. SAM was used to model the hourly power generation of PV and CST systems in selected locations in 2010, allowing realistic generation data to be included in the simulation.

4. Baseline generation mix

The following section presents a baseline generation mix for the scenario. In Section 6, the mix will be varied to analyse the effect on the system.

4.1. Hydroelectricity

Hydroelectric generation in the simulation corresponds to hydroelectric stations present in the NEM in 2010. This is limited to 4.9 GW of hydro without pumped storage and 2.2 GW of pumped storage hydro. Although the potential for significant further expansion of hydroelectric energy generation is limited by a lack of water and environmental concerns (Geoscience Australia and ABARE, 2010), there may be potential for substantially increasing pumped hydro generating capacity and hence peak load generation, even with low levels of energy storage (Blakers et al., 2010). This requires further investigation. Pumped hydro energy storage is initially set at 20 GWh based on prior estimates (Lang, 2010). Water availability for hydro without pumped storage is not limited initially.

In normal practice, a pumped storage hydro system is charged using off-peak power and dispatched during peak periods. In these simulations, pumped storage hydro plants are opportunistically charged using surplus renewable power with a round-trip efficiency of 0.8. It is dispatched conventionally to meet critical peak loads.

4.2. PV

PV serves about 10% of total energy demand at an assumed average capacity factor of 16%. The PV is distributed within the built environment of the major mainland cities of the NEM: Adelaide, the greater Brisbane region, Canberra, Melbourne and Sydney. In future scenarios, this could extend to larger, centralised plants sited in regional areas. The capacity installed in each city is chosen in proportion to the population of the city (Australian Bureau of Statistics, 2010). The hourly power generation was modelled for a 1 MW PV system sited in each city, facing due north and tilted at the latitude angle. The generation of the 1 MW plant was then scaled to the desired capacity for each city. Note that this will underestimate the potential diversity value of large PV plants located in regional areas of the NEM to the west of the major load centres.

4.3. Wind

Wind energy serves about 30% of total energy demand at an assumed average capacity factor of 30%, a mid-range value for Australian wind farms. The wind farms are sited in the same locations as existing NEM wind farms, but the hourly generation is scaled up from the installed capacity of 1.55 GW in 2010. This will underestimate the diversity value of having future wind generation sited in other wind regimes within the NEM.

4.4. Concentrating solar thermal

CST serves about 40% of total energy at an assumed average capacity factor of 60%. The CST plants are air-cooled parabolic trough designs with 15 full load hours of thermal energy storage. The solar multiple is initially chosen to be 2.5. This means that the mirror field and receiver at peak output produce 2.5 times more energy than is required by the turbine at full output. The excess energy is fed into the storage for use when there is insufficient sunlight. The hourly power generation of a 100 MW$_e$ plant was modelled in six high insolation, inland locations around the NEM (listed in Section 4.6). The hourly values are then scaled to the desired capacity for each location.

4.5. Gas turbines

Gas turbines are placed last in the merit order to meet supply shortfalls. In the scenario, the turbines are powered with biofuels derived from crop residues. Commercial gas turbines that can be flexibly powered with a variety of fuels are available with capacities up to around 200 MW. The amount of fuel consumed by the gas turbines is not limited in the simulation, so that we can observe the effect of changes to the generation mix on biofuel consumption. However, one objective is to minimise the use of biofuel.

In countries where fossil fuel is not as abundant as Australia, bioenergy has a significant share of electricity generation: Germany 4%, Sweden 7%, and Finland 12% (Geoscience Australia and ABARE, 2010). Although a small share of total electricity generation, the United States produces 70 TWh of electricity from bioenergy per year (Geoscience Australia and ABARE, 2010). Previous studies have estimated that about 30% of Australia's current electricity demand could be met from biomass residues alone in a year that is not subject to drought (Diesendorf, 2007, 138–41). Aiming for biofuel consumption below around 15% of total NEM demand is therefore considered realistic.

4.6. Generation mix summary

The generators in the baseline scenario, including their location and capacity, are summarised in the list below. The generators are dispatched in this order.

(1) Wind: existing wind farm output scaled to 23.2 GW
(2) PV (14.6 GW total):
- Adelaide (1.3 GW)
- Canberra (0.4 GW)

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- Melbourne (4.5 GW)
- Brisbane and greater area (3.3 GW)
- Sydney (5.1 GW)

(3) CST (2.6 GW per site, 15.6 GW total):
- Tibooburra, New South Wales
- White Cliffs, New South Wales
- Longreach, Queensland
- Roma, Queensland
- Nullarbor, South Australia
- Woomera, South Australia

(4) Pumped storage hydro (2.2 GW)
(5) Hydro without pumped storage (4.9 GW)
(6) Gas turbines, biofuelled (24.0 GW)

5. Baseline simulation results

In 2010, energy demand in the NEM was 204.4 TWh and peak power demand was 33.6 GW. Figures 1 and 2 show more detailed sections of the plot for a typical week in January and a challenging week in late June/early July, respectively. The simulation summary report is shown in Table 1.

The baseline scenario meets 2010 demand within NEM reliability standards, with six hours on winter evenings when demand was unmet: 15 June 6–7pm, 1 July 6–7pm, 2 July 6pm, 7 July 7pm. Comparing Figures 1 and 2, it is apparent how the seasonal variation of solar radiation influences the ability of CST plants to dispatch power. In Figure 1 (summer), the plants can be dispatched around the clock. In Figure 2 (winter), the low level of winter insolation is insufficient to fully heat the thermal stores and so the CST plant cannot generate through the night. In summer, 15 hours of storage and a solar multiple of 2.5 are more than adequate for CST to supply continuous energy day and night. Analysis of CST modelling results within SAM shows that such a large thermal store is of limited value during the winter months, as storage larger than 5 full load hours is rarely fully charged.

Spilled energy (TWh)	10.2
Spilled hours	1606
Unserved energy	0.002%
Unmet hours	6
Electrical energy from gas turbines (TWh)	28.0
Largest supply shortfall (GW)	1.33

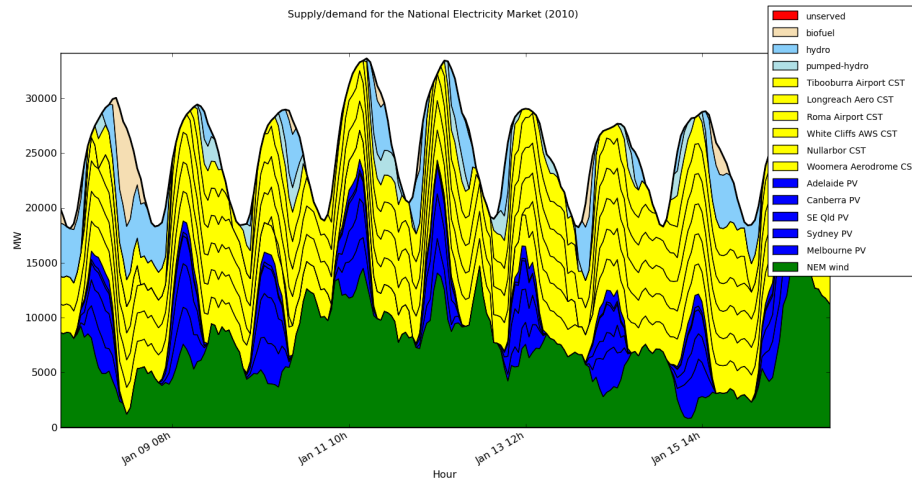Table 1: NEM simulation 2010 summary report

Figure 1: Supply and demand plot for the simulated NEM for a typical week in January 2010
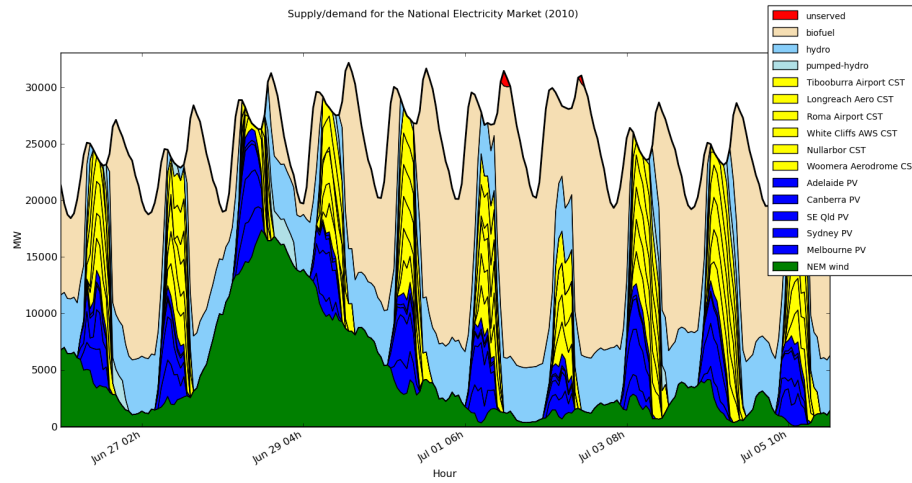

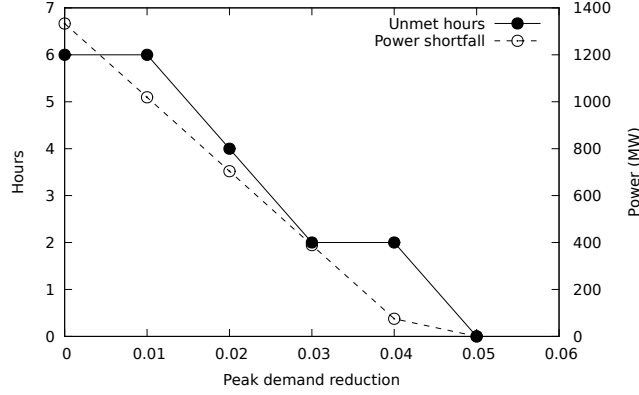Figure 2: Supply and demand plot for the simulated NEM for a challenging week in June/July 2010

Figure 3: Effect of peak demand reduction on unmet hours with 24 GW peaking capacity

6. Sensitivity analyses

In this section, six sensitivity analyses examine various options for improving the reliability of the system or reducing the biofuel consumption through lower utilisation of gas turbines.

6.1. Eliminating unmet hours through demand reduction

The main challenge for a 100% renewable electricity system is peak periods when generation from variable sources may contribute little. We consider how reliability is improved by actively managing load during these hours of otherwise unmet demand. Figure 3 shows that a 5% reduction in the six demand peaks is sufficient to bring demand and supply into balance for every hour of the year. As these peaks occur on winter evenings, this reduction could be readily achieved through energy efficiency measures, particularly to reduce residential heating demand, or by temporarily interrupting controllable loads.

6.2. Increasing solar thermal plant capacity

In the baseline simulation, CST plants have a total generating capacity of 15.6 GW. To overcome the decline in CST generation during winter and consequent increase in bioenergy consumption, we consider the effect of oversizing the total capacity of CST plants, while keeping the solar multiple constant and the storage at 15 full load hours for the expanded CST generating capacity (Figure 4). This change reduces the number of unmet hours from six to two, reduces the gas turbine generation modestly, but increases total spilled energy significantly. This, and current high costs of CST technologies, suggest that increasing CST capacity could be a very expensive means of meeting peak demand in winter. However, it was the principal measure chosen in the single simulation reported by Wright and Hearps (2010).
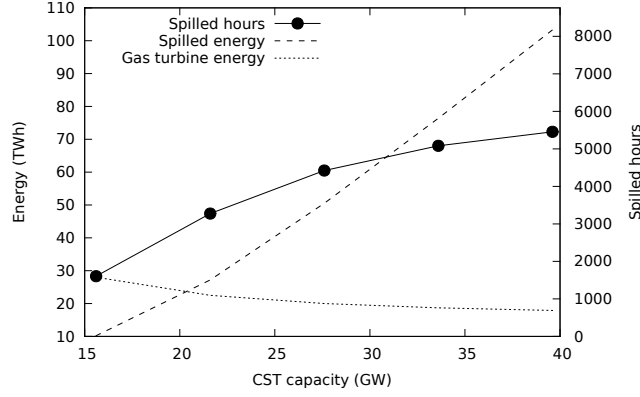
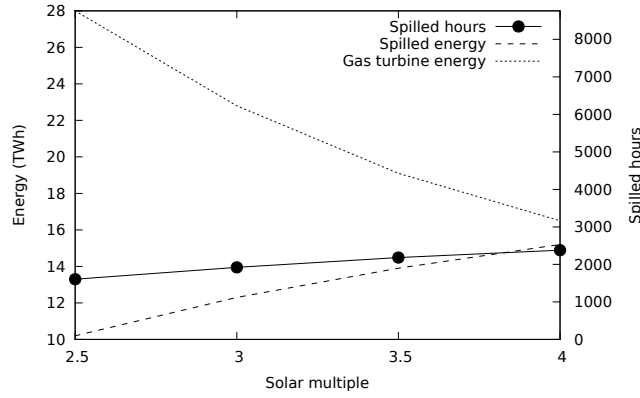Figure 4: Effect of increasing CST capacity

Figure 5: Effect of increasing CST solar multiple

6.3. Increasing CST solar multiple

Another strategy to reduce biofuel consumption was tested by increasing the solar multiple of the CST plants from 2.5 to 4.0, while keeping the CST generating capacity and storage capacity constant. In other words, the size of the solar field is increased. As Figure 5 shows, this change is much more effective than increasing the overall CST generating capacity in reducing gas turbine generation.

6.4. Delaying solar thermal dispatch

As Figure 2 shows, the dispatchable CST plants are not used to full advantage in meeting winter evening peak demand, increasing the capacity requirement for gas turbines. An alternative winter operating strategy for the CST plants is to delay the dispatch until the evening, so that peak generation coincides with evening peak demand.
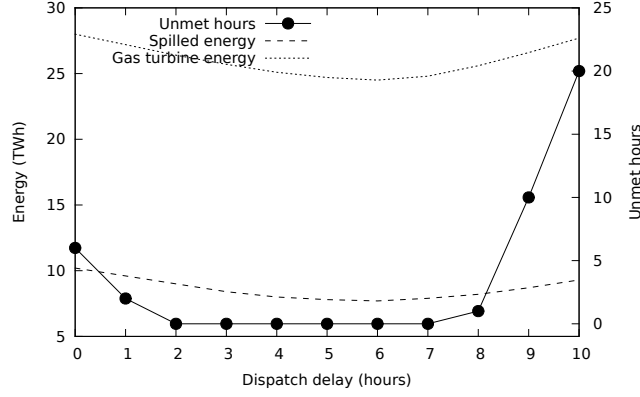
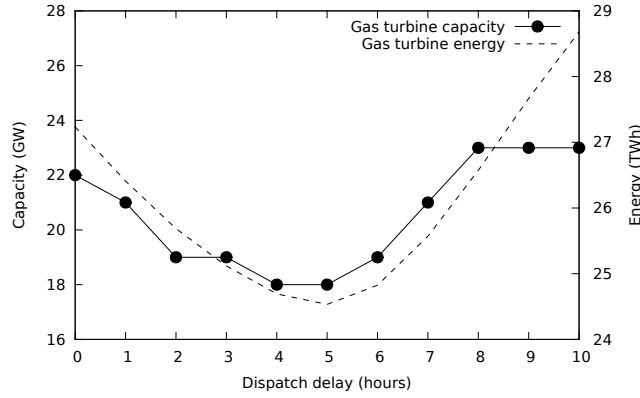Figure 6: Effect of delaying CST dispatch on unmet hours and spilled hours

Figure 7: Effect of delaying CST dispatch on minimum gas turbine generating capacity and energy to maintain NEM system reliability standard

Figure 6 shows the effect of delaying the dispatch of CST plants on the number of hours of unmet demand and the number of spilled hours in the year. The minimum for both of these variables occurs at a delay of six hours, which corresponds to dispatching the CST plants such that peak generation occurs at 6pm (Australian Eastern Standard Time). This change has only a minor effect on the requirement for gas turbine generation. This is expected, as delaying dispatch is primarily intended to reduce gas turbine generating capacity rather than energy. Figure 7 illustrates how delaying CST dispatch influences the minimum gas turbine generating capacity and energy required to maintain the NEM reliability standard. Hence, the two curves in Figure 7 maintain constant reliability. The figure shows that delaying CST dispatch permits the gas turbine generating capacity to be reduced, with the minimum capacity occurring with a five hour delay.
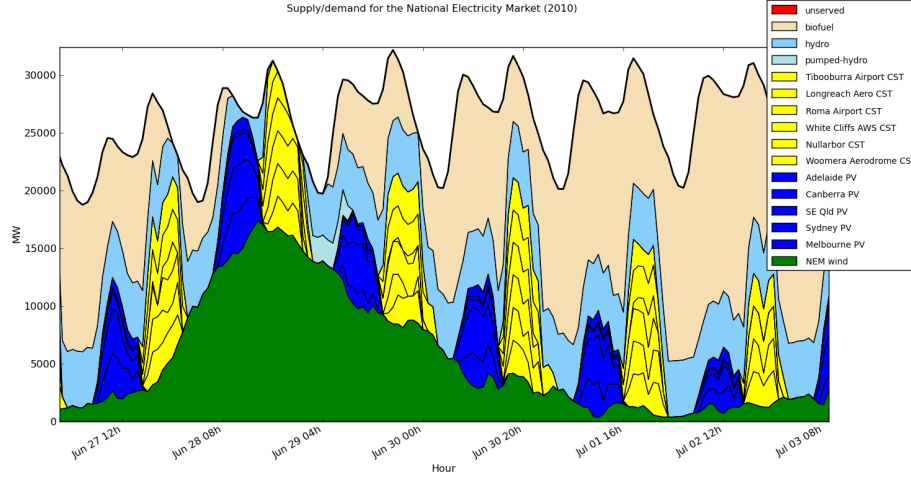
Figure 8: Supply and demand plot for the simulated NEM for a week with 7 hour dispatch delay

Figure 8 highlights how delaying CST dispatch creates different, complementary roles for CST with thermal storage and flat plate PV without storage. CST contributes more to the evening peak while PV contributes to supplying daytime demand. This is consistent with conclusions reported by Denholm and Mehos (2011).

6.5. Greater PV contribution

In Sections 6.2 and 6.3, we presented two options for decreasing the energy requirement from biofuelled gas turbines: increasing the CST generating capacity and increasing the solar multiple of the baseline CST capacity respectively. These options are expensive because they both involve building more solar collectors, currently the most expensive component of CST costs.

In the baseline scenario, the total energy provided by the two solar technologies is 50% of total demand (40% CST, 10% PV). The significant reduction in the price of PV modules in recent years raises the question of whether some of the CST generating capacity could be substituted with PV without affecting system reliability. In the simulation, when the energy contribution from PV is increased to 20% and CST reduced to 30%, we find that system reliability is maintained. The large generating capacity of PV (29.2 GW), in combination with the baseline wind generating capacity, is frequently sufficient to meet demand around noon on summer days. This suggests that the idea of delaying the dispatch of CST plants in winter could also be applied in the summer months using CST plants with fewer hours of thermal storage.

6.6. Reducing peaking capacity through demand reduction

The initial capacity of the gas turbines was chosen somewhat arbitrarily for the baseline scenario, as these generators are the last to be dispatched – a
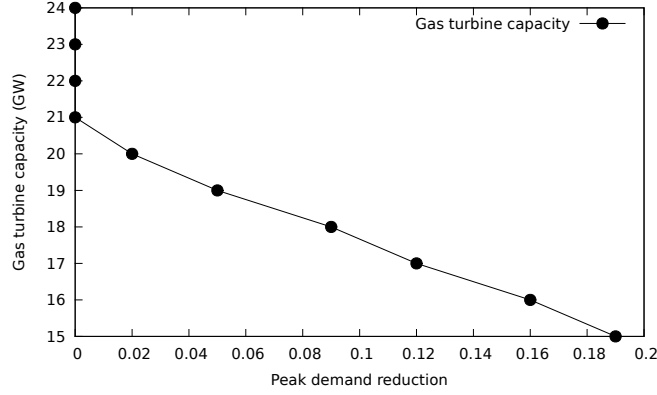
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Figure 9: Impact of reducing peak demand on gas turbine generating capacity required to maintain NEM reliability standard

consequence of the inherent energy storage of biofuels and the ability to readily dispatch this technology due to high ramp rates and fast start-up/shutdown times. A series of simulation runs were used to evaluate the effect of targeted demand response on reducing the required gas turbine capacity. For all of the unmet hours that arise with a given gas turbine generating capacity, demand was lowered until the NEM reliability standard was achieved (Figure 9). By reducing gas turbine generating capacity from 24 GW to 15 GW, the NEM reliability standard can be met if demand during the unmet hours is reduced by 19%. This result shows that a significant reduction in peaking capacity can be achieved with carefully designed demand-side policies. Energy from gas turbine generation is reduced by around 4%.

7. Discussion

These simulations provide a number of insights into the challenges of constructing a 100% renewable electricity system in Australia and possibly other regions with a high solar resource. An electricity supply system based primarily on generation that is not fully controllable leads to a supply that can be highly variable, producing excess power in times of low demand and occasional power shortfalls in times of high demand. As this work shows, the availability of renewable energy sources is not always correlated with demand in ways that are helpful for such a system. A particular challenge in the context of the NEM is, for example, calm winter evenings where both wind and solar resources are not available. It is reasonable to question whether a supply system based on a radically different mix of generation technologies should be expected to meet demand unmodified, or whether demand can be expected to accommodate to some degree the operating characteristics of the new system. The simulations show that small percentage reductions in peak-load demand in winter produce larger reductions in the required gas turbine generating capacity.

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The simulated wind generation is based on actual generation data from the NEM in 2010 and the wind farm outputs at the various sites are quite strongly correlated. Currently, NEM wind farms are predominantly sited in South Australia and Victoria in the same wind regime. This situation could be improved by choosing a wider set of sites around the NEM for wind generation that reduces the correlation between individual wind farms. Such data are being collected for future simulations.

With the exception of pumped hydro storage with its small capacity (2.2 GW, relative to peaks over 33 GW) and the biofuelled gas turbines, none of the generators in the mix could be described as being fully controllable. None provides firm capacity for 24 hours per day for every day of the year, although the CST plants can provide around the clock power during summer. In aggregate, however, the generation mix simulated here is able to meet power demand in almost all hours of the year (six shortfalls), with 10 TWh of spilled energy, and 28 TWh of electricity sourced from biofuels. This further demonstrates that generators with near-constant power output may not be required to meet demand even in a system with currently a very large base-load demand component. Instead, it is having sufficient capacity of dispatchable generators that is vital. This result is consistent with those of the studies on the integration of 20–30% wind energy into the eastern and western grids of the United States (National Renewable Energy Laboratory, 2010, 2011).

In the present scenario, the limitations of existing NEM hydroelectric plants in supporting variable generation become apparent. First, the generating capacity (2.2 GW) and energy storage (20 GWh) of pumped storage hydro plants is very much less than the peak power demand and annual energy demand respectively of the whole NEM system. Likewise, the hydro plants without pumped storage have a limited generating capacity (4.9 GW). In reality, these hydro plants are placed low in the merit order to meet peak demands, but the benefit is limited when the supply shortfalls are large. In the simulation, rather than functioning as true peaking plants, the hydro plants serve to reduce the amount of biofuel consumed to operate the gas turbines. As mentioned in Section 4.1, it may be worthwhile to investigate whether there are suitable sites for expanding pumped hydro generating capacity, within the constraint of limited water availability for storage (Blakers et al., 2010).

While it is possible to meet more winter energy demand using greater levels of CST generating capacity, or increases in solar multiple, that is, the increased solar collector area to compensate for low levels of solar energy in winter, both of these options lead to very high power output and surplus energy in the summer months. As the analyses in the previous section have shown, solar generation in particular, has difficulty in year-round supply due to seasonal variations in solar radiation. In the case of CST and hydroelectric generation, storage is clearly beneficial. However, storage is only as valuable as the ability to charge it, so the siting and operation of storage is critical.

Approaching a 100% renewable energy system requires particular attention to ensuring that short term supply and demand are balanced at all times. On those occasions when variable sources of renewable power (eg, wind and solar)

are not available during high demand periods such as winter evenings, a large capacity of peaking plant is required to meet demand. Although peaking plant has the desirable properties of lower capital cost and higher marginal cost than other forms of generation, a system requiring very high levels of peaking capacity is likely to have a high cost. Lower cost alternatives may include increased diversity in renewable sources, more effective storage regimes, energy efficiency to reduce peaks in demand, and using pricing to shift demand to better coincide with renewable generation.

8. Conclusion

This research demonstrates that 100% renewable electricity in the NEM, at the current reliability standard, would have been technically feasible for the year 2010 given some particular renewable energy generation mixes including high levels of variable resources such as wind and solar. This result is obtained by using renewable energy technologies that are in full mass production (wind, PV, hydro and biofuelled gas turbines) and a technology in limited mass production (CST with thermal storage). Achieving 100% renewable electricity also entails a radical 21st century re-conception of an electricity supply-demand system, already flagged in some of the studies cited in the Introduction. The focus is shifted away from replacing base-load coal with alternative base-load sources. Instead, generation reliability is maintained in a system with large penetrations of variable renewable sources by having as great a diversity of locations as possible, large capacities of peak-load generators, and storage. In such a 100% renewable electricity system, the concept of base-load power station is redundant.

In a geographic region with high levels of insolation, solar energy sources, both CST and PV, can together make the major contribution to energy generation. Then the principal challenge is to generate sufficient power during the evening peak periods in the winter months. On some of these evenings there are lulls in the wind and insufficient energy in the CST thermal stores. One solution is to install a high capacity (24 GW) of peaking plant, which is around 2.5 times the peaking plant capacity in the NEM today. Although only 14% of total electrical energy is sourced from biofuels, the power requirements are large. Another solution is to increase the solar multiple of the CST power stations. Yet another solution is to delay the dispatch of CST power in winter, to improve the matching of supply and demand. Demand reduction measures, especially for the heating load on winter evenings, could prove to be the least-cost solution, however an economic analysis is needed to rank the options.

There is more to be explored in this area. One of the next steps in the present research program is to reduce the required capacity of peaking plant by improving the diversity in wind generation, and employing more sophisticated demand side measures to improve the matching of demand and renewable electricity supply.

9. Acknowledgements

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