# 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 develop scenarios for 100% renewable generation to meet current electricity demand in the five Australian states and one territory spanned by the National Electricity Market (NEM). The preliminary simulations reported here cover a scenario for the year 2010, where electricity demand is met by a renewable generation mix based on concentrating solar thermal (CST) power with thermal storage, wind, photovoltaics (PV), existing hydro, and peaking gas turbine plants running on biofuels. Generation from these sources in 2010 is simulated using meteorological records for that year.

A 100% renewable mix for the NEM is found to be technically feasible for the year 2010, meeting the NEM reliability standard with only six hours in the year where demand is unmet. However, this is achieved with a high capacity (24 GW) of peaking gas turbine plants to cover periods of insufficient power from other sources, typically winter evenings. Increasing the solar multiple of CST plants is helpful in allowing more energy to be captured and stored during winter, marginally reducing the required capacity of gas turbines. Overall, meeting evening peak periods in the winter months remains the principle challenge.

***Keywords:*** biomass, PV, renewable electricity, scenario, solar thermal, storage, wind

## Introduction

This paper reports on the preliminary development of energy system simulations to identify the challenges of supplying 100% renewable electricity in the region spanned by the Australian National Electricity Market (NEM). Current climate science suggests that the world must aggressively reduce greenhouse gas emissions over the next several decades to a point of near-zero emissions by 2050. If this goal is to be met, the highly emissions intensive electricity industry in Australia must be transformed to zero carbon sources and, preferably, from renewable energy. The technologies most likely to feature in future renewable electricity grids are variable in nature and it has been widely argued that they cannot be used to provide a secure electricity supply. Others argue that spatial diversity of these generators, together with limited storage, can meet daily and seasonal variations in demand.

The simulations reported here cover the year 2010 where electricity demand is met by electricity generation mixes based on current commercially available technology: wind, parabolic trough concentrating solar thermal (CST) with thermal storage, photovoltaics (PV), existing hydro, and gas turbines running on a sustainable level of biofuels. There is no fossil fuel generation in this mix, a marked contrast from the present NEM generation mix, which derives more than 90% of supply from coal and gas generation.

Numerous scenario studies have been published that model the potential for countries, regions, and the entire world, to meet 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), Japan (Lehmann, 2003), the United Kingdom (Kemp and Wexler, 2010), Germany (Klaus et al., 2010) and Denmark (Lund and Mathiesen, 2009). Regional studies exist for northern Europe (Sørensen, 2008) and the European Union (Zervos et al., 2010). Several studies of the global situation have been produced (eg, Sørensen and Meibom, 2000; Ecofys, 2011). These scenario studies do not typically specify a transition path. 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 studies make assumptions about future energy demand, potential for energy efficiency, and the future costs, performance, and rate of deployment for energy technologies. A difficulty with setting a scenario end-date decades into the future is in predicting demand factors such as population growth, geopolitical factors (eg, the collapse of the Soviet Union), economic growth and rapid technological shifts. Over the past 50 years, reliable forecasts of basic energy industry variables such as primary energy consumption and oil prices have been found to be extremely difficult (Bezdek and Wendling, 2002). This brings significant uncertainty into the picture.

In this work, we explore an alternative approach that is limited to the electricity sector in a recent year, providing a more straightforward basis for exploring this question of matching variable renewable energy sources to demand. We simulate a 100% renewable electricity system in the region spanned by the National Electricity Market for the year 2010, using demand data and weather observations for that year. This closely corresponds to the approaches taken by Mason et al. (2010) for New Zealand and described by Mills (2010) for the United States in 2006. By minimising the number of working assumptions, we hope to provide some insights into the reliability implications of 100% renewable electricity.

## Simulation overview

The simulation framework draws together various temporal and spatial data of renewable energy sources, the outputs of renewable electricity generators (actual or modelled), and electricity demand. The framework attempts to dispatch available generation to meet demand hour by hour over a year.

The framework is an object oriented Python program, producing a modular design that is easy to extend or modify. 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 multiple objects can be used to group sites or regions. The simulation framework maintains a list of the generator classes, with the list order specifying the dispatch order.

The entire region is currently treated as a “copper-plate”; that is, power can flow unconstrained from any generation site to any demand site. Demand across all NEM regions is aggregated, as is supply. The simulation runs hour-by-hour, calling on each generator, in dispatch order, to meet the current demand. If available power exceeds demand, then generators are either “spilled” (eg, wind) or are not dispatched (eg, hydro). If available generation does not meet the demand, the level of unmet demand is noted. At present, the dispatch of generators is unconditional, so it is not yet possible to specify more complex strategies such as dispatching only between certain hours of the day.

At the end of a simulation run, an hour-by-hour plot for the year is produced showing the demand and the sources of generation (see Figure 1 for example). Any hours of unmet demand are indicated on the plot. The simulation can also produce a summary report of figures such as the total energy spilled, which hours were unmet, and the unserved energy as a percentage of total energy demand. For reference, the NEM reliability standard is currently 0.002% of unserved energy per year.

**Data sources**

The simulation draws on a diverse range of data sources that have been assembled into a large database. Each data source used by the simulation is described below.

*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, demand is aggregated across all regions and averaged into hourly values.

*Wind*

Electricity generation data for non-scheduled, semi-scheduled and scheduled wind farms was supplied by AEMO. These data provide average wind power at each wind farm over the five-minute dispatch interval and were averaged into hourly values.

*Solar*

Satellite-derived estimates of global horizontal irradiance and direct normal irradiance in 2010 for the entire NEM region were provided by the Bureau of Meteorology (BoM) at 5km by 5km spatial resolution and hourly intervals. While the 2010 data set is largely complete, there are a limited number of hours with missing data. These missing values were interpolated.

*Other weather*

Hourly weather records for every BoM weather station in the NEM region were also obtained from the BoM. These records include 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, are used to automatically generate weather data files compatible with System Advisor Model (SAM), a performance model developed by the National Renewable Energy Laboratory (2011). SAM is used to simulate the power generation of PV and CST systems in chosen locations in 2010, allowing realistic generation data to be included in the simulation.

## Scenario generation mix

*Hydroelectricity*

Hydroelectric generation in the simulation corresponds to hydroelectric stations registered in the NEM in 2010. This is limited to 4.9 GW of hydro without pumped storage and 2.2 GW of pumped storage (Tumut 3, Kangaroo Valley/Bendeela and Wivenhoe). The scenario limits hydroelectric capacity to the existing hydroelectric stations on the basis that the potential for further expansion is limited by a lack of high quality sites, water availability, and environmental concerns (Geoscience Australia and ABARE, 2010). 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 hydro storage system is charged using off-peak power and dispatched during peak periods. In this scenario, pumped storage hydro plants are charged using spilled energy and dispatched first to maximise the energy supplied year round.

*PV*

PV serves about 10% of total energy demand at an overall capacity factor of 16%. The PV is deployed as distributed roof-top generation in the major mainland cities of the NEM (Adelaide, the greater Brisbane region, Canberra, Melbourne and Sydney). The installed capacity in each city is chosen in proportion to population (Australian Bureau of Statistics, 2011). The hourly generation of a 1 MW PV system sited in each city, facing due north, and tilted at latitude angle, was modelled using SAM. The hourly generation of the 1 MW plant was then scaled to the desired total capacity.

*Wind*

Wind energy serves about 30% of total energy demand at an overall capacity factor of 30%. The wind farms are sited in the current NEM locations, but the hourly generation is scaled up from the installed capacity of 1,555 MW in 2010.

*Concentrating solar thermal*

Concentrating solar thermal (CST) serves about 40% of total energy at an overall capacity factor of 60%. The CST plants are air-cooled parabolic trough plants 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 generation of a 100 $MW_e$ plant was modelled using SAM in six high insolation locations around the NEM. The generation data was then scaled to the desired capacity for each location.

*Gas turbines*

Gas turbines are included to meet demand shortfalls. In the scenario, the turbines are powered with biofuels derived from crop residues. Initially, these could partly be fuelled by natural gas as a transitional fuel. The amount of available fuel for the gas turbines is a free variable in the simulation, so that the effect of changes to the generation mix on biofuel consumption can be observed. The 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 consumes 70 TWh of bioenergy per year in the electricity sector (Geoscience Australia and ABARE, 2010). An estimate by

Diesendorf (2007, 138–41) suggests that about 30% of Australia's current electricity demand could be met from biomass resides alone in a year that is not subject to drought. Aiming for biofuel consumption below around 10% of total NEM demand is considered realistic.

The generators for the scenario are listed below, including location and capacity. The generators are dispatched in the following list order:

1. Pumped storage hydro with round-trip efficiency of 0.8 (2.2 GW)
2. CST (15.6 GW total): Woomera Aerodrome (2.6 GW), Nullarbor (2.6 GW), White Cliffs (2.6 GW), Roma Airport (2.6 GW), Longreach Aero (2.6 GW), Tibooburra Airport (2.6 GW)
3. Wind: all NEM sites in 2010 scaled up to 23.2 GW
4. PV: Melbourne (4.5 GW), Sydney (5.1 GW), south-east Queensland (3.3 GW), Canberra (0.4 GW), Adelaide PV (1.3 GW)
5. Hydro without pumped storage (4.9 GW)
6. Gas turbines, biofuelled (24.0 GW)

**Simulation results**

In 2010, total demand in the NEM was 204.4 TWh. Figures 1 and 2 show a more detailed section of the plot for one week in January and late June/early July, respectively. The simulation summary report is shown in Table 1. If spilled energy is used in a given hour to pump water uphill for pumped storage hydro, the pumping energy is deducted from the spilled energy. Spilled hours indicates the number of hours in the year when energy is spilled.

| | |
|---|---:|
| Spilled energy (TWh) | 9.0 |
| Spilled hours | 1442 |
| Unserved energy | 0.002% |
| Unmet hours | 6 |
| Electrical energy from gas turbines (TWh) | 28.1 |
| Largest supply shortfall of all unmet hours (GW) | 1.33 |

Table 1: NEM simulation 2010 summary report

This mix meets 2010 demand within NEM reliability standards, with six hours on winter evenings where demand was unmet: 15 June 6pm (1279 MW shortfall), 15 June 7pm (542 MW), 1 July 6pm (1333 MW), 1 July 7pm (755 MW), 2 July 6pm (706 MW), 7 July 7pm (392 MW). 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 does not permit the CST plant to 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 detailed 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. Reducing the thermal storage from 15 to 5 full load hours over the simulated year has the effect of increasing the gas turbine generation from 28.1 TWh to 35.9 TWh and decreasing the number of spilled hours from 1,442 to 980. The same six hours are unmet with the reduced storage.

The capacity of the gas turbine plants in this scenario was chosen arbitrarily, as this generator is the last to be dispatched. To determine the most appropriate capacity, the capacity was incrementally increased from zero to the maximum hourly demand in 1 GW increments. The number of unmet hours and percentage of unserved energy are plotted for each capacity value in Figure 3. When peaking capacity falls below 24 GW, the NEM reliability standard is exceeded. At 20 GW, there are 74 unmet hours in 2010.

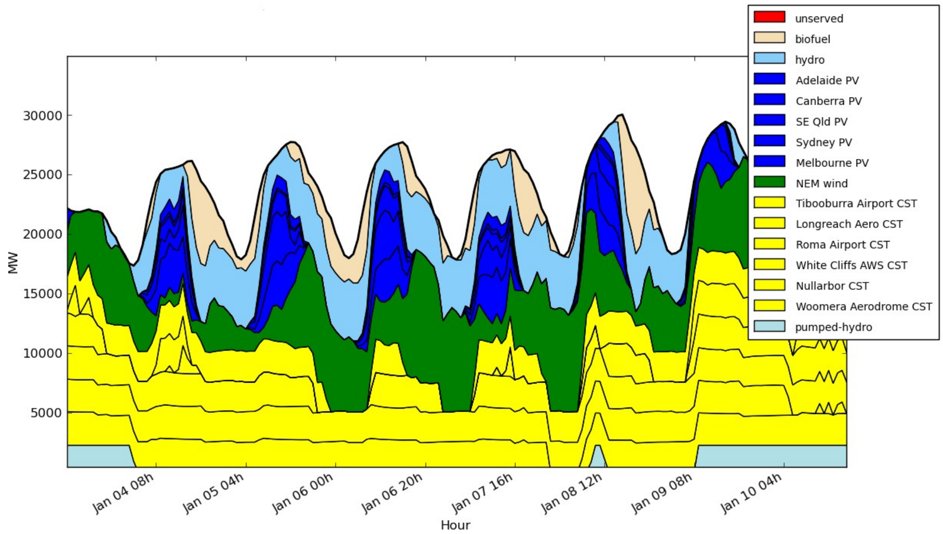


Figure 1: Supply and demand plot for the simulated NEM (January 2010)

A strategy to reduce the requirement for peaking plant was tested by increasing the solar multiple of the CST plants from 2.5 to 3.0, while keeping the CST generating capacity and storage capacity constant. In other words, the size of the solar field is increased. The results are summarised in Table 2. This change also allows the gas turbine capacity to be reduced from 24 to 22 GW before the NEM reliability standard is exceeded. Beyond a solar multiple of 3.0, the benefits of a larger solar field diminish.

In the baseline simulation, CST plants have a total capacity of 15.6 GW. To overcome the decline in CST generation during winter, we consider the effect of doubling the total capacity of CST plants, while keeping the solar multiple constant and the storage at 15 hours of full load for the expanded CST generating capacity (Table 3). This reduces the number of unmet hours from six to two, reduces the gas turbine demand, but increases total spilled energy significantly.

| Solar multiple | Unmet hours | Spilled hours | Spilled energy (TWh) | Gas turbine generation (TWh) | Gas turbine capacity (GW) |
|---|---|---|---|---|---|
| 2.5 | 6 | 1442 | 9.0 | 28.1 | 24 |
| 3.0 | 0 | 1737 | 10.8 | 22.9 | 22 |

Table 2: Effect of raising the CST solar multiple from 2.5 to 3.0

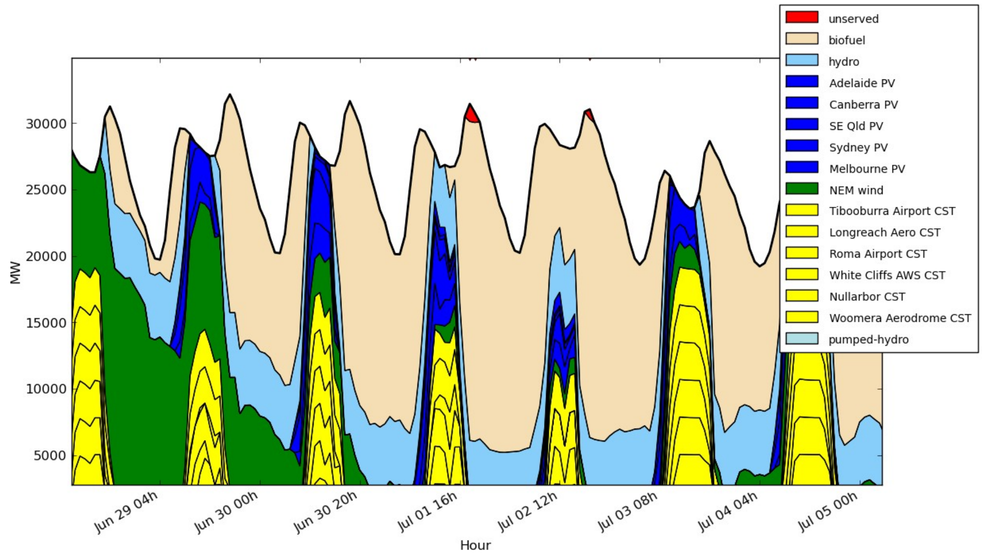


Figure 2: Supply and demand plot for the simulated NEM (June/July 2010)

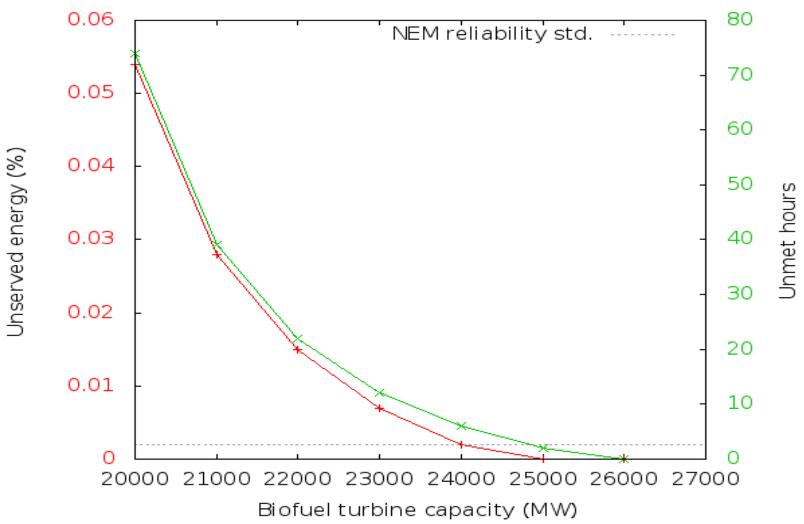


Figure 3: Effect on unserved energy and unmet hours of increasing peaking capacity

| CST capacity (GW) | Unmet hours | Spilled hours | Spilled energy (TWh) | Gas turbine generation (TWh) |
|---|---|---|---|---|
| 15.6 | 6 | 1442 | 9.0 | 28.1 |
| 31.2 | 2 | 4782 | 62.7 | 19.2 |

Table 3: Effect of doubling CST capacity

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 reducing demand during unmet hours. Table 4 shows that a reduction in these six demand peaks of 5% is sufficient to bring demand and supply into balance. As these peaks occur on winter evenings, this reduction could be achieved through energy efficiency measures, particularly to reduce residential heating demand, or by temporarily disconnecting controllable loads such as aluminium smelters. The total power demand of the six aluminium smelters sited around the NEM has been estimated at over 3 GW (Turton, 2002).

| Demand fraction | Unmet hours | Maximum shortfall (MW) | Demand fraction | Unmet hours | Maximum shortfall (MW) |
|---|---|---|---|---|---|
| 1.00 | 6 | 1333 | 0.97 | 2 | 389 |
| 0.99 | 6 | 1019 | 0.96 | 2 | 75 |
| 0.98 | 4 | 704 | 0.95 | 0 | 0 |

Table 4: Effect of peak demand reduction on unmet hours (24 GW peaking capacity)

**Discussion**

These preliminary simulations provide a number of insights into the challenges of constructing a 100% renewable electricity system in Australia. 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 in ways that are helpful for such a system (eg, calm winter evenings). 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 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 could be improved by choosing a wider set of sites around the NEM for wind generation that reduces the correlation between individual wind farms.

With the exception of pumped hydro storage with its limited capacity (2.2 GW), none of the generators in the mix could be described as having fully controllable dispatch. None provide 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 9 TWh of electrical energy spilled in total, and 28.1 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 a very large base-load component.

In this scenario, the limitations of existing NEM hydroelectric plants in supporting variable generation become apparent. First, the pumped storage hydro plants are extremely limited, with minimal storage (20 GWh) and limited power (2.2 GW). Likewise, the hydro plants without pumped storage have a limited capacity of 4.9 GW.

They are called upon high in the dispatch order to help meet peaks, but the benefit is limited when the power shortfalls can be large. In practice, rather than functioning as true peaking plants, these plants instead help to reduce the amount of biofuel consumed to operate the gas turbines. As mentioned in the introduction, it is unlikely that hydroelectric capacity will be significantly expanded in Australia, which rules out a technology well suited to the integration of other forms of renewable electricity.

While it is possible to meet more winter energy demand using greater levels of CST generation capacity, the increase in solar multiple, that is, the increased solar collector area to compensate for low levels of solar energy in winter, leads to very high power output and surplus energy in the summer months. In fact, in the summer months of 2010, the CST plants overproduce and lead to extended periods where wind power is spilled. This leads to the situation where some generators (eg, wind farms) are not utilised at all for parts of the year. 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% system requires that short term power requirements are met 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. In the limiting case where no other power source is available, a 100% renewable electric system would require peaking plant rated to maximum 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, distributed generation in the form of co- and tri-generation, energy efficiency to reduce peaks in demand, and shifting demand to better coincide with renewable generation.

## Conclusion

This research demonstrates that 100% renewable electricity in the NEM is technically feasible for the year 2010, meeting the NEM reliability standard with only six hours in the year where demand is unmet. This result is obtained by using renewable energy technologies that are either 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 earlier studies. 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.

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 (AEMO, 2011). Although only 13% 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 increase the CST generating capacity, keeping storage capacity and solar multiple constant. Demand reduction measures, especially for the heating load on winter evenings, could prove to be low cost solutions. However, an economic analysis is needed to rank the options.

There is more to be explored in this area. A goal to improve the feasibility of this scenario is to reduce the required capacity of peaking plant by improving the diversity in wind generation, employing alternative scheduling strategies for the CST plants, and employing demand side measures to improve the coincidence of demand and renewable electricity supply.

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