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The Chief Scientist is right, and why.

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Abstract

Australians are responsible for some of the highest values of CO_2 emissions per person. To lower CO_2 emissions the most effective policy is to eliminate coal from power generation. In principle all electrical power generation in Australia could be provided by renewables. The mismatch between renewables and actual electrical demand means that extensive storage in the form of pumped hydroelectric will be required. However considerable reductions in CO_2 emissions can be achieved by using nuclear power or combined cycle gas turbines for baseload and open cycle gas turbines for peak loads. Other options include combinations of renewables and rapid response gas turbines. At the present time more than 1/3 emissions come from transportation, so further progress can only be achieved with the electrification of ground transportation. This will require a considerable increase in both electrical power generation and storage if the aim is to rely totally on renewables.

Introduction

If emission of carbon dioxide is a big sin, then Australians are among the world's biggest sinners. The 16.2 t annual per capita emission of CO_2 by Australia is now higher than the United States,[1] generally considered to be the country with the most profligate lifestyle and lack of environmental consciousness. Energy demand and associated CO_2 emissions are greater in places with harsh, cold, climates. The heavily populated parts of Australia have particularly mild climates as measured by the degree days of heating and cooling, especially when compared with much of the US and Canada or Northern Europe (Rez 2017). So why does Australia have such an abysmal record?

	Cooling 27°C	Heating 21°C
Adelaide	102	2014
Melbourne	63	2718
Sydney	62	1212
Brisbane	102	900

Table 1 Degree Days of Heating and Cooling (www.degreedays.net)

The reason is the extensive use of coal in electrical power generation. What makes it worse is that Australia is a major exporter of coal and promotes its sale to developing nations in Asia. So if Australia wants to reduce CO_2 emissions, it has to eliminate coal from power generation. The "Letter from the 25 Scientists" in this issue talks about meeting commitments under the Paris agreement and managing entirely by using renewables: wind, solar, and hydroelectric power. However, for energy and electrical power, physical laws rather than laws passed by legislatures and international agreements limit what can be done.

1 https://www.eia.gov/international

Electricity use

As a start, let's look at electricity use in Australia at the present time. South Australia, Victoria and New South Wales show broad peaks in the winter months; for Queensland the peak is in the summer. The 1–2 day summer spikes in New South Wales, Victoria and South Australia correlate with maximum temperatures and are a consequence of increased use of air conditioning. This correlation is not so apparent for Queensland, where it's not just daytime high temperatures, but elevated nighttime low temperatures, that drive the demand for air conditioning. It's also apparent that the constant baseload accounts for most of the demand. In the analysis that follows, one option we will also consider is meeting the baseload with nuclear power. To see how large the effect it instructive to compare the CO_2 emitted per person for France and Germany. Despite having more renewable generating capacity in the form of solar and wind than coal and natural gas, the Germans are responsible for almost twice as much CO_2 per person per year than are the French.

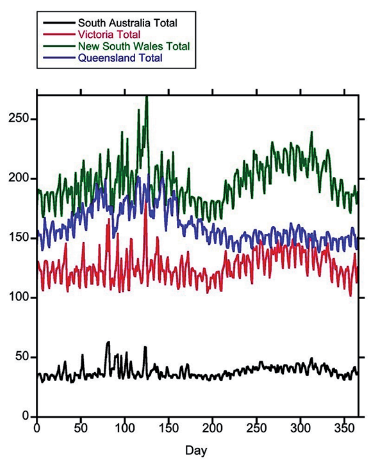

Fig. 1. Total Electrical Demand in GWh per day for Australian states for a year.

To a first approximation most of the population live in major urban areas separated by a distance of about 400 miles. In many respects this is similar to the Western United States. A simple analysis shows that transmission losses are proportional to the product of power transmitted and distance (Rez 2017). That means that electrical power trading between the states is in the range of a few hundred MW, out of total power demand in the range of GW, as can be seen from the data from the Open National Electricity Market Site.[2] That means we really should consider each state separately, unless a lot of extra transmission lines are installed.

Meeting demand

The problem with solar and wind is that they do not match actual electrical demand. Solar, especially in Queensland, can be dependable, since most days are sunny. However, the peak in solar output is around midday, while the demand peaks are partly in the early morning and mainly in the early evening.[3]

The output from solar is falling off steeply just as the demand is increasing. Right now the increased evening demand is being met by ramping up the output of coal-fired power plants. Given that they rely on a steam Rankine cycle, their start-up time and response time is slow, and so they are not ideal for meeting this sudden increase in electrical demand. Open-cycle gas turbines are a better option, and would provide the needed fast response with about half the CO_2 emissions.

2 https://opennem.org.au/energy/nem

3 We are assuming rooftop solar here, as this represents output from northward-facing flat PV panels. It's hard to tell from the utility solar data how much has been curtailed to try and better match actual demand.

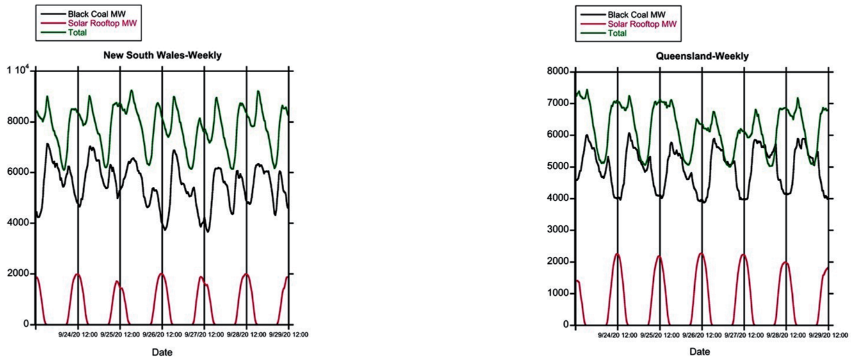

Fig 2. Electrical Demand for New South Wales and Queensland showing how solar peaks in the middle of the day and how coal is used to meet the evening peak demand.

Using solar and wind only

But what if we wanted to manage entirely from solar power? The issue of how to meet the evening demand becomes even more critical, especially in the winter months with reduced hours of daylight. This is an issue everywhere, not just Australia. Peaks are driven by domestic demand, which is at its highest when people come home in the evening or when they get up in the morning.

There are three choices:

1. Eliminate the evening demand, have everyone go to bed at sunset! (This is what people did before artificial lighting.)
2. Given the rapid fall off in solar output, provide lots of gas turbines that can be quickly ramped up to meet the evening demand. They'd also play a large role in meeting the morning demand in winter.
3. Over-generate during the day and store the excess electrical energy for use in the evenings and at night.

So how much storage would be needed? Based on this week in September, if Queensland were to rely on solar alone, it would need about 21 GW of solar generating capacity and 150 GWh of storage, taking account that storage isn't perfect and that one might get out about 80–90% of the energy that has been put in. That is almost as much as the daily electrical energy used. If the aim is to reduce CO_2 emissions, then the mismatch between solar and demand can be reduced by using nuclear to meet the baseload. In that case, 13GW of solar generation are needed and 90 GWh of storage. Also peak electrical energy demand is on hot days and nights in the summer, not relatively mild days in September. This would increase daily electrical demand and storage needs to approximately 200 GWh.

However, not every day, even in Queensland, is sunny so one must store enough to get through the days with reduced solar generation. Looking at the variation of solar with time of the year, we can see that there were 13 one-day periods and 7 two-day periods with half the peak solar output. The longest period was almost a week, although this was in winter and the reduced solar generation might be partly compensated by the availability of wind at that time.

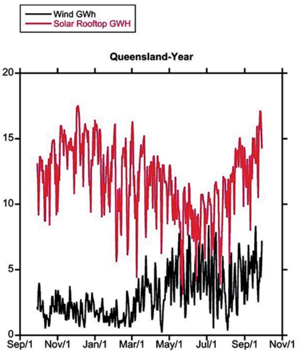

Fig. 3. Solar and Wind Power generated in GWh per day throughout the year.

If solar is relatively dependable, but does not cover the peak demand well, then wind, by comparison, is very unreliable, but can cover peak demand periods. South Australia has more wind than the other states but even for one week in September there's one day with no wind. Note the rapid fall in wind energy on the third day, comparable to the fall in solar energy as the sun goes down.

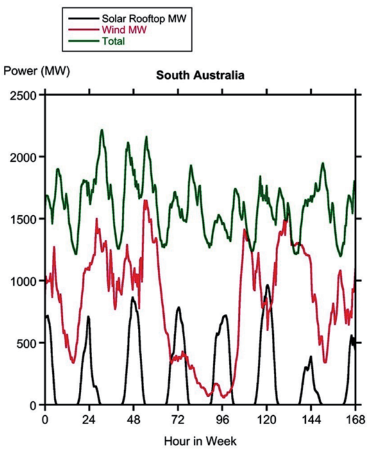

Fig. 4. Variation by the hour of solar and wind output in MW for South Australia.

Examining the annual variation of wind energy throughout the year, it's apparent that there are about 50 periods when the wind energy is 15 GWh or less, about half the 30 GWh output when presumably the wind turbines are generating their rated power. There's even one period where the wind energy is less than 15 GWh for 14 days. If the wind speed, v, isn't high enough for the wind turbine to generate its rated power, generally 11–12 m/sec, then the output is only proportional to v^3. This means in practice wind is either "on" or almost "off," which is again apparent from Fig. 5.

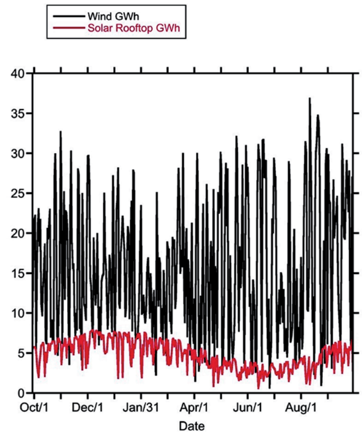

Fig. 5. Annual variation in solar and wind electrical energy in GWh per day for South Australia

How much storage?

So to rely on wind and solar means either having lots of open-cycle gas turbines available to fill in the gaps, or having some form of energy storage. To assess how much energy storage is needed I wrote a code where one could multiply the amount of wind and solar generated at present in each state and store the excess in a "bank" (or energy storage unit). Energy could also be withdrawn from the "bank" and the aim of the exercise was to come up with a plausible mix of solar and wind that would minimize the amount of energy stored. The results are given as Table

2 below. Ideally this would have been done for data points in half-hour intervals throughout the year, to take account of the variation of solar throughout the day that was discussed above, but the data from the National Energy Market[4] only gives energy per day so the result isn't quite as accurate as I would like, but the order of magnitude is probably correct. The analysis was done assuming solar and wind were going to meet all the electrical demand, or assuming the baseload was met with some appropriate low emission generation source like nuclear (France) or hydro-electric power or a combination of both (Sweden). Hydro electric could also be used for peaks, which makes it the most desirable of the renewable energy sources since not only can it match real time demand, large scale hydro electric also comes with a store of energy in the form of reservoirs.

As can be seen from Table 2, the energy storage requirements for these four Australia states add up to about 11.4 TWh. The energy storage required in each state is in the range of hundreds to thousands of GWh. The only practical way to meet this storage need is pumped hydro electric, but that depends on having suitable topography for the two reservoirs with a sizeable elevation difference (hydraulic head). Snowy 2 with 380 GWh is a commendable first step, but this will have to be replicated about 30 times to meet the total storage demands. Battery banks like the 129 MWh installed at the Hornsdale wind farm are too small to make a difference. A quick calculation shows that it can only store the equivalent of 25 minutes of output. As the late Dave MacKay (2008) said "every big counts." Using nuclear or hydro for base load as shown in Table 3 reduces the requirement by a factor of about 2.5, except in Queensland. That is because there is some need for inter seasonal storage, some of the excess electrical energy generated in summer has to be stored for use in winter. However, given that Australia has a third of the world's uranium and thorium reserves, it would make sense to use this locally available resource.

Transport emissions

Of course, this analysis does not address the CO_2 emissions resulting from consumption of liquid hydrocarbons by the transportation sector. Even now in Australia these emissions are slightly greater than the CO_2 emissions associated with coal burning and accounts for about 6 t per person per year out of the 16 t CO_2 emission per person per year. An electric vehicle can be at least 4 times as efficient at using stored energy. Dividing the energy available from liquid hydrocarbons used in ground transportation[5] by 4 gives about 175 TWh per year, almost as much as the electrical energy used at present. In practice vehicles will be mainly charged at night, so it will increase the baseload. This is not good for renewables like solar and wind, but is favourable for nuclear.

The need for storage

In conclusion, it is impossible to make solar and wind supply Australia's electrical energy needs without extensive storage. This will only be exacerbated with the electrification of ground transportation. The development of hydro and pumped hydro-electric is predicated on climate and topography. In most countries hydro-electric power has been fully developed. Furthermore pumped hydro requires not just one, but two reservoirs at dif-

4 https://opennem.org.au/energy/nem

5 https://www.eia.gov/international

	S. Australia	Victoria	New South Wales	Queensland
Wind	2.4	5.5	5.5	2.5
Solar	1.9	6.5	14.5	13.5
Storage	800 GWh	2800 GWh	5270 GWh	2550 GWh

Table 2. Proportions of solar and wind given as multiples of the current solar and wind generation, and storage requirements, for the four Australian states to manage totally from solar and wind renewables.

	S. Australia	Victoria	New South Wales	Queensland
Baseload	30 GWh	105 GWh	164 GWh	138 GWh
Wind	0.5	0.82	0.6	1.4
Solar	0.6	1.4	3.1	1.7
Storage	300 GWh	1245 GWh	2100 GWh	2050 GWh

Table 3. Proportions of solar and wind given as multiples of the current solar and wind generation, and storage requirements, for the four Australian states using solar and wind for peaks only and generating baseload demand from other low CO_2 sources such as nuclear or hydro.

ferent elevations. However, Blakers et al. (2017) claim that it is possible to develop pumped hydro storage capacity of sufficient magnitude with multiple relatively small units mainly in Victoria and New South Wales. They correctly point out that this is possible because inter seasonal storage needs are quite low in Australia, unlike in Northern Europe. However we differ in the magnitude of power hydro electric storage required. I can't comment on the cost estimates, but is it realistic to develop a thousand 1.6 GWh pumped hydro-electric storage systems, mainly in remote areas? How long would this take?

If the aim is to reduce CO_2 emissions, a considerable reduction could be achieved by using nuclear instead of coal for the baseload. (Again, compare France and Germany.) Solar and wind would then have to meet much less of the demand, and as shown in Table 3, the need for storage would be much reduced. Even if the peak load were met by open-cycle gas turbines, the CO_2 emissions per person for electrical power generation would be reduced from about 10t per person per year to 0.7t per person per year. Copying the United States and substituting combined-cycle natural gas for coal for the baseload while using open-cycle turbines for peaks would reduce CO_2 emissions from power generation to about 3t per person per year.

Conclusion

Managing totally off renewables (Blakers et al 2017) is an interesting theoretical possibility, but would be very hard to implement in practice, with lots of excavation in remote mountainous areas. As they say "The perfect is the enemy of the good." The Chief Scientist is right: in practice natural gas will be needed for power generation in Australia.

References

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