Solar Power Realities

Supply-Demand Characteristics, Storage and Capital Costs

by
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Abstract

This paper provides a simple analysis of the capital cost of solar power and energy storage sufficient to meet the demand of Australia's National Electricity Market. It also considers some of the environmental effects. It puts the figures in perspective.

By looking at the limit position, the paper highlights the very high costs imposed by mandating and subsidising solar power. The minimum power output, not the peak or average, is the main factor governing solar power's economic viability. The capital cost would be 20 times more than nuclear power. The least-cost solar option would require 400 times more land area and emit 20 times more CO2 than nuclear power.

Conclusions: solar power is uneconomic. Government mandates and subsidies hide the true cost of renewable energy but these additional costs must be carried by others.

Contents

Introduction

Renewable energy advocates claim that solar power could provide all our electricity needs and claim it is close to being economic now (e.g. David Mills, 2006 [1]).

This paper provides a simple calculation of the capital cost of installing solar power and energy storage sufficient to meet the National Electricity Market[2] (NEM)'s electricity demand.

The paper takes the approach of looking at the limit position. That is, it looks at the cost of providing all the NEM's electricity demand using only solar power for electricity generation. Looking at the limit position helps us to understand just how close to or far from being economic is solar power.

The electricity demand

Before we can determine how much solar generating capacity and energy storage capacity is required to meet the NEM's demand, we need to understand some characteristics of the demand. This section describes the characteristics of the NEM's demand, using the figures for 2007.[3]

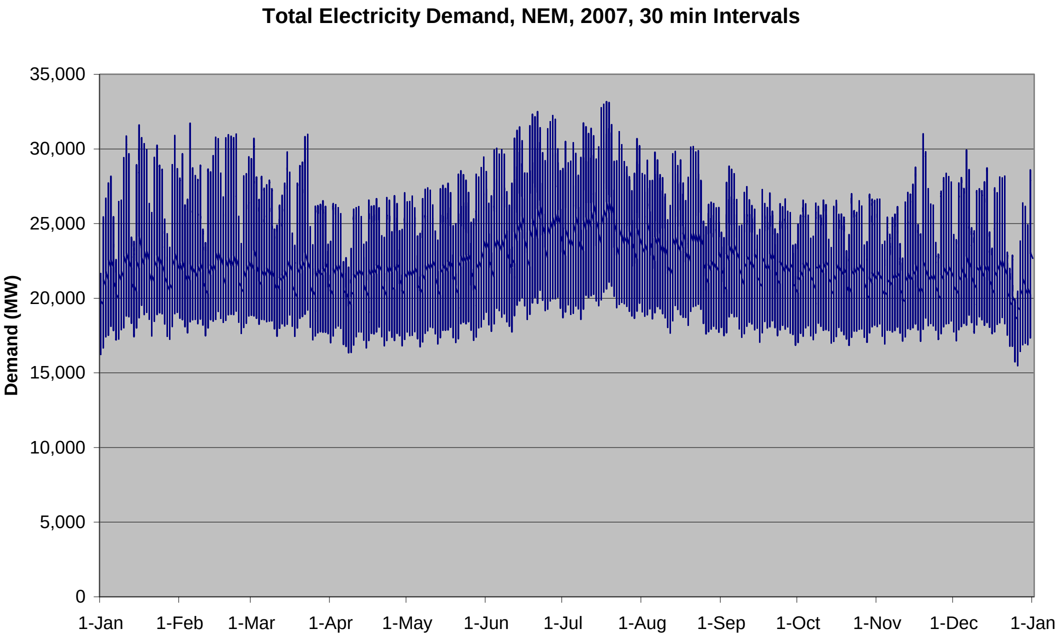

Figure 1 - the total electricity demand at 30 minute intervals throughout 2007. The peak occurs in July and shows we need 33,000 MW of generating capacity to meet the peak demand. (This is the equivalent generating capacity of twenty-two Tumut 3 Power Stations[4]). The base load[5] is about 18,000 MW for most of the year and about 20,000 MW in July.

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[1] http://www.physics.usyd.edu.au/~ned/warming/mills.pdf

[2] The NEM provides the grid connected electricity for Queensland, NSW, ACT, Victoria, South Australia and Tasmania.

[3] http://www.aemo.com.au/data/aggPD_2006to2010.html#2007

[4] Tumut 3 is Australia's largest hydro-electric power station and pump storage system. It can generate 1,500 MW of power, but only for as long as the water stored in the top 9 m of the reservoir lasts.

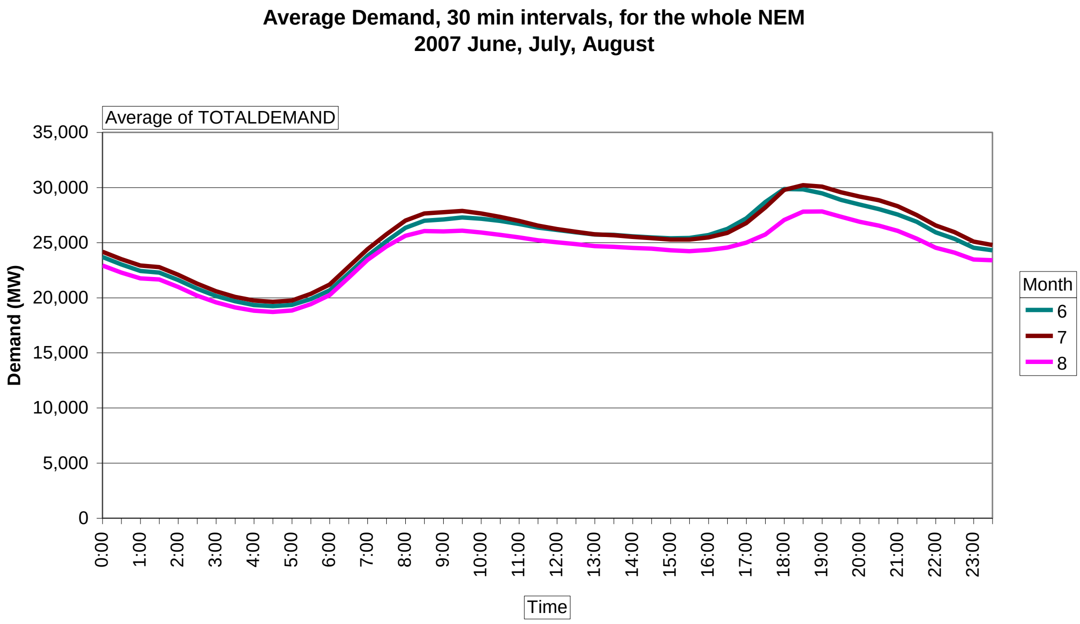

Figure 2 - the average demand per half hour for the NEM in June, July and August 2007. This shows that the peak demand, averaged across each whole month, occurs at about 6:30 pm in winter. That is after sunset. It means that, without energy storage, solar generating capacity cannot contribute to meeting the peak demand.

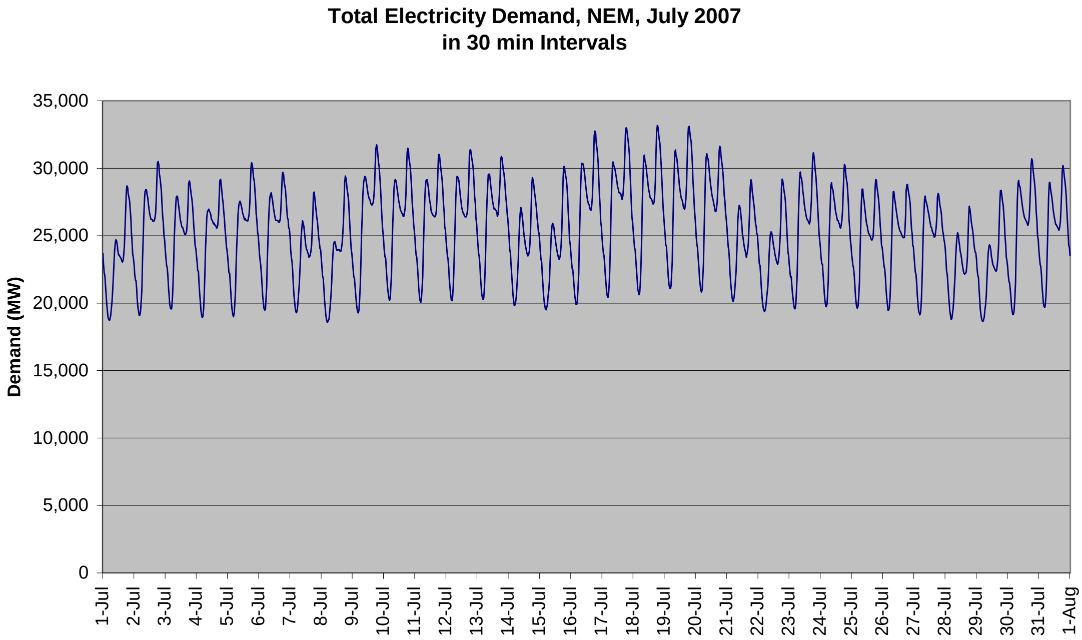

Figure 3 - the NEM demand at 30 minute intervals throughout July 2007. This figure shows how the demand changes throughout the day and week. The weekends can be recognised by their lower peaks, especially the morning peak. This chart shows that 20,000 MW of base load demand is present all the time in July. The base

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[5] Base load is the power that is required 24 hours per day.

load comprises about 75% of the total energy used[6]. The significance of this is that we need a system that can provide reliable base load power. Intermittent, non-dispatchable power does not satisfy the demand.

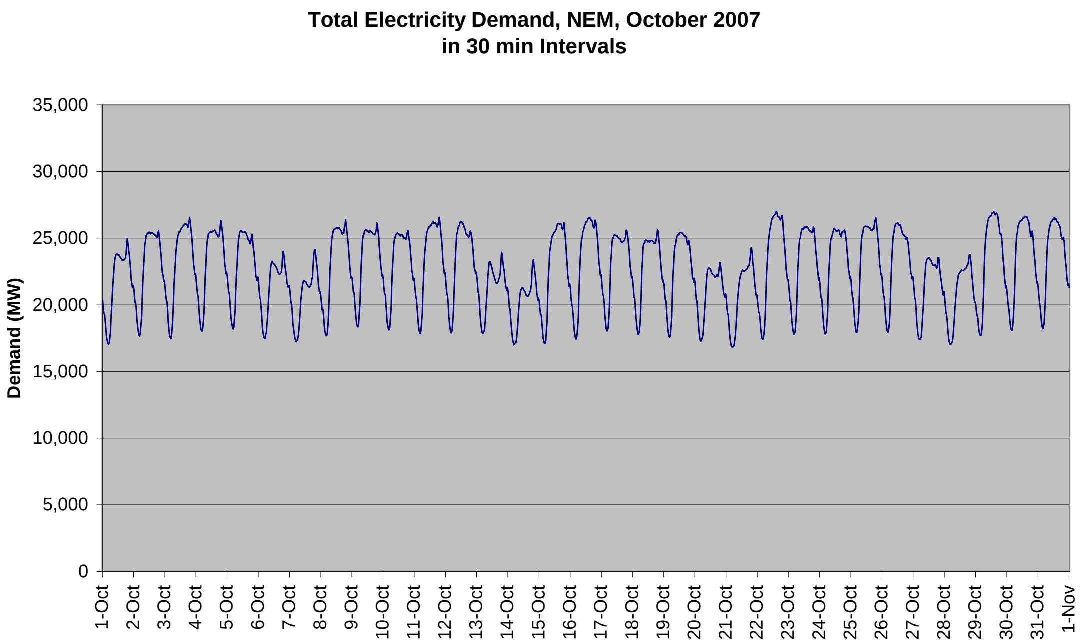

Figure 4 shows the demand throughout October 2007. October is representative of the month with the lowest demand.

The average power demand and total energy consumed for June, July and August 2007 for the whole of the NEM were as follows:

	Monthly Average Power Demand (MW)	Energy consumed per month (MWh)
June	25,010	18,006,991
July	25,356	18,864,720
August	23,900	17,781,513
Average	24,752	
Total		54,653,224

The key points to note are, we need sufficient solar generating capacity and sufficient energy storage <u>during 3 months of winter</u> to provide:

1. 55,000,000 MWh of energy (average 600,000 MWh per day);
2. At least 33,000 MW peak power at around 6:30 pm (after sunset); and
3. 20,000 MW base load power throughout the day and night;

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[6] Power is read from the vertical axis. Energy is the area under the curve.

How could solar power and energy storage meet the NEM demand?

Several technologies would have to be combined for the NEM's electricity demand to be met from solar power. The technologies are:

1. Solar electricity generation
2. Energy storage
3. Electricity generation from the stored energy
4. Transmission

First we will consider the characteristics of each technology and then consider how to combine them. Lastly we will estimate the cost of the combined system.

Characteristics of solar power

The key characteristics of solar power[7] are:

1. Power output is zero from sunset to sunrise.

2. Power output versus time is a curve distribution on a clear day: zero at sunrise and sunset, and maximum at midday (See Figure 5).

3. Energy output varies from summer to winter (less in winter than summer) (see Figure 5)

4. Energy output varies from day to day depending on weather conditions (see Figure 6)

5. Maximum daily energy output is on a clear sunny day in summer.

6. Minimum daily energy output is on a heavily overcast day in winter.

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[7] There are two technologies for generating electricity from solar energy: solar thermal and solar photo-voltaic. This paper uses solar photo-voltaic as the example because energy output and cost data are more readily available than for solar thermal. It is not clear at this stage which is the lower cost option for large generation on the scale required . (see: http://www.renewableenergyworld.com/rea/news/article/2008/05/the-cost-of-utility-scale-solar-pv-vs-cst-52436) so any cost difference is insignificant in the context of the simple analysis presented here.

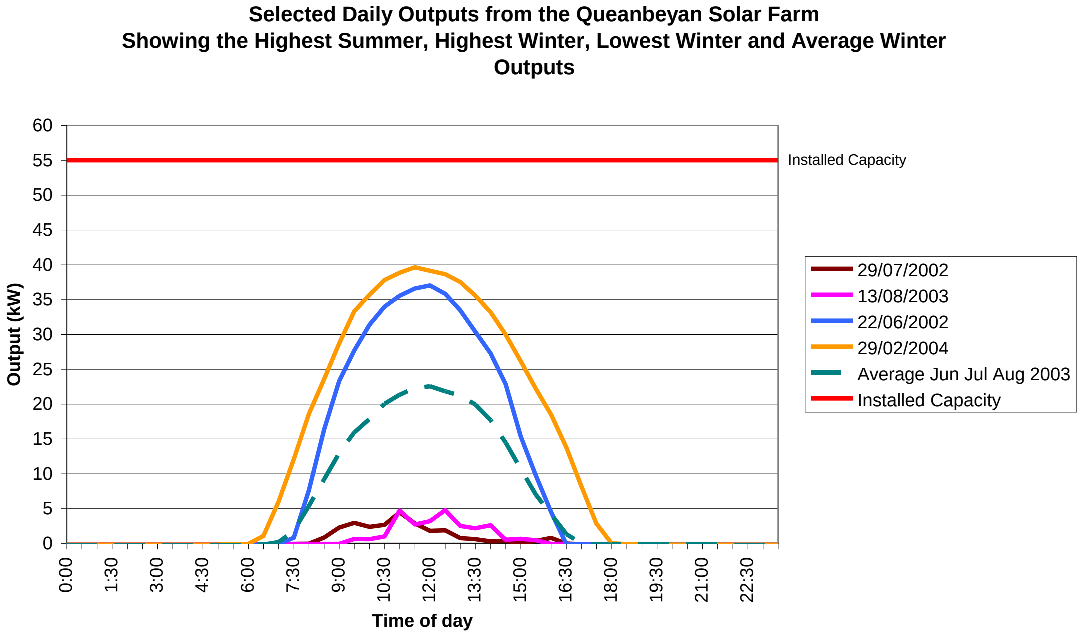

Figure 5 – Queanbeyan Solar Farm power output versus time of day for selected days. The days selected are the days with the highest energy[8] output in summer, the highest energy output in winter, the two days with the lowest energy output in winter, and the average daily energy output for June, July and August 2003.

The Queanbeyan Solar Farm[9] has an installed power capacity of 55 kW. The average power output over 2 years was 7.58 kW. The average capacity factor[10] over this period was 13.7%. The total energy output and capacity factor for the days shown in Figure 5 are:

Date	Energy Output (kWh)	Capacity Factor
29/07/02 (lowest winter 2002)	10.0	0.8%
13/08/03 (lowest winter 2003)	10.5	0.8%
22/06/02 (highest winter)	212	16.0%
29/02/04 (highest summer)	288	21.9%
Average daily for June, July, August	131	9.9%

Figure 6 (below) shows the total output per 1-day (blue diamonds) and the average output for 3, 5, 10, 20, 30, 60 and 90 day rolling averages. Figure 7 shows the same information presented as capacity factor.

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[8] Power is read from the y-axis. Energy is the area under the curve.

[9] http://www.ceem.unsw.edu.au/content/documents/ReportMarc-ValueofPV-25Jun05.pdf

[10] Capacity Factor is the actual energy produced over a period divided by the total energy that would have been produced if the generator had run at full power throughout the period.

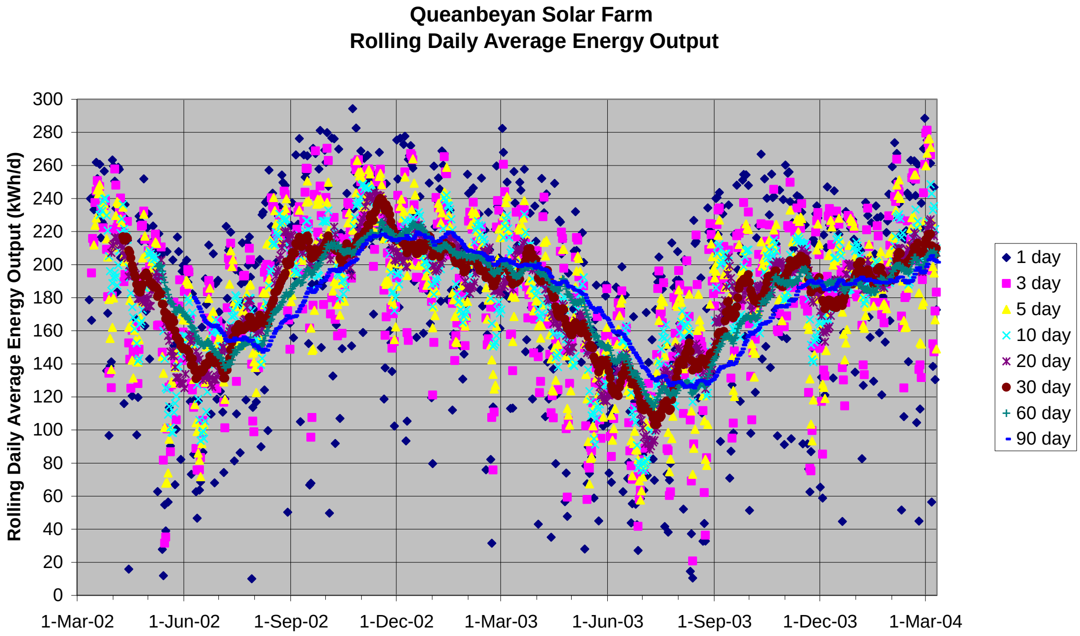

Figure 6 - the total energy output per day (blue diamonds) and the average energy output for 3, 5, 10, 20, 30, 60 and 90 day rolling averages.

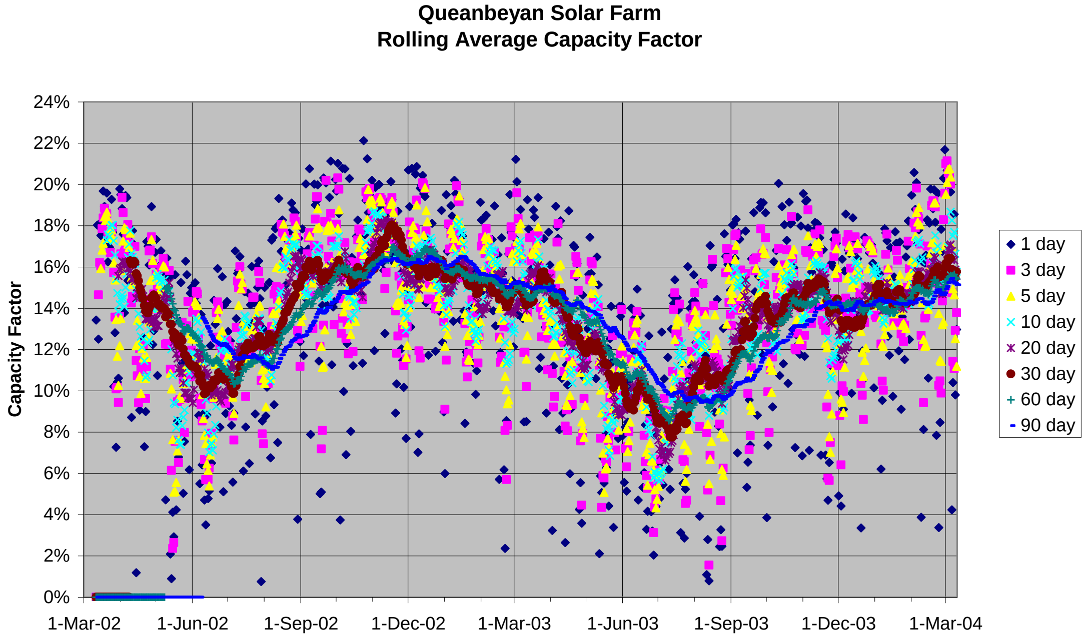

Figure 7 - the Capacity Factor for 1, 3, 5, 10, 20, 30, 60 and 90 day rolling averages.

Figures 6 and 7 show that the total energy generated by the Queanbeyan Solar Farm is as low as 10 kWh on some days (which is a capacity factor of 0.8%). The rolling 90 day average capacity factor bottoms at 9.4%.

The capacity factor on the worst days, or worst period of continuous days, defines how much energy storage is needed. If we have just one day of energy storage we need sufficient solar generating capacity to supply the NEM's daytime demand as well as to store energy to meet the demand when the sun is not shining. In July, the day-time[11] demand is about 150,000 MWh and the evening-night-morning demand is about 450,000 MWh. We must be able to generate the total of 600,000 MWh of energy on the worst case days – i.e. on days when the solar generating capacity factor is 0.8%.

If we have 90 days of energy storage we will need sufficient solar generating capacity to be able to generate the 600,000 MWh per day over 90 continuous days (i.e 54,000,000 MWh) with an average solar generating capacity factor of 9.4%.

Characteristics of energy storage

There are many types of energy storage[12]. We need to be able to store 450,000 MWh of energy in about 6 hours, on average in winter, and deliver it over 18 hours. It needs to be able to deliver peak power of 33,000 MW and base load power of about 20,000 MW (refer Figure 3).

Some characteristics of the three most viable storage technologies are listed below:

	Pumped-hydro storage	Compressed Air Energy Storage[13]	Sodium Sulphur Batteries
Peak Power (MW)	2,000	200	20
Discharge time at rated power (h)	24	50	5
Efficiency	80%	50%	85%
Capital cost per unit power (US$/MW)	$600,000 to $1,500,000	$400,000 to $900,000	$1,000,000 to $2,500,000
Capital cost per unit energy (US$/MWh)	$50,000 to $150,000	$20,000 to-$100,000	$200,000 to $900,000

Source http://www.electricitystorage.org/site/technologies/

Pumped-hydro storage is the least cost option that can meet these requirements [14]. The next most viable option is compressed air energy storage (CAES). Sodium Sulphur batteries and Vanadium Redox batteries have some advantages over pumped-hydro storage and CAES but they are higher cost. One advantage of batteries is that they do not require the special topographic, hydrological and geological site conditions that are needed for pumped-hydro storage or CAES.

Pumped-hydro energy storage

1. Pumped-hydro storage is the most economical energy storage technology for large amounts of energy storage (where suitable sites are available).

2. To provide the NEM's demand from pumped-hydro storage would require pumping 2.3 Sydney-harbour volumes of water up 150 m each day while the sun is shining strongly (a maximum of about 6 hours during winter), and then

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[11] For this analysis, 'day-time' means the hours when the sun is shining strongly to provide the full power required for pumping. The analysis is based on 6 hours from 9 am to 3 pm. See Figure 8.

[12] http://www.electricitystorage.org/site/technologies/

[13] The CAES costs are for the storage component only, and do not include the generation component

[14] Ignoring for the moment the fact that Australia does not have pumped-hydro storage sites available where needed, and with the capacity required, and even if it did, hydro is not acceptable on environmental grounds.

releasing it to generate electricity each night. This would require pairs of high dams and low dams linked by pipes, pump stations and generating stations. The top dams and the bottom dams would each need a total active storage capacity of 2.3 Sydney harbour volumes of water and would need to have a vertical separation of 150 m on average. The pumps would need the capacity to pump the volume of water up from the bottom dams to the top dams in about 6 hours in winter.

3. The pumps and pipes need to be sized for a fixed rate of pumping. The pumps need to be able to pump at a steady flow rate for hours at a time. So they need consistent power for the duration of pumping. It is not feasible to stop and start pumping the large amounts of water involved whenever the power output changes, as is the tendency from many types of renewable energy.

4. The total generating capacity needs to be sufficient to meet the peak demand.

5. The total area inundated by the reservoirs, for 1 day of energy storage, would be about 260 km^2. For 90 days of storage, 24,000 km^2 would be inundated.

Transmission

The National Grid's transmission capacity would need to be increased in two ways:

1. To transmit the power from the solar power stations to the pumped-hydro storage stations. All the energy to be stored must be transmitted from the solar power stations to the pumped-hydro storage stations in about 6 hours in winter. The solar power stations would need to be located inland where solar insolation is high. High capacity transmission systems do not currently exist to these areas.

2. The interstate connections would need to be enhanced substantially. Large energy transfers would have to be transmitted between states and regions (eg when the sun is shining in Queensland but not in the southern states).

Combining solar power and pumped-hydro storage to provide the NEM demand.

Combining the solar power and pumping technologies is problematic. The pumps need steady power. But solar power is highly variable, (and zero all night).

The only way to provide sufficient steady power for the pumps is to provide sufficient solar panels such that they can provide the required amount of power continuously throughout the worst days in winter. For most of the time the solar panels will produce far more power than can be used. Most of the energy that is generated by the solar panels cannot be used – it is wasted.

Solar generating capacity versus energy storage

There is a trade-off between the amount of solar generating capacity required and the amount of energy storage available. If we have just one day of energy storage (ie sufficient storage for the NEM's energy needs for one evening-night-morning) we would need sufficient solar generating capacity to power the pumps, at constant power, for the worst case day in winter – ie the day with the least output from the solar panels. But the output from the solar panels can drop to almost nothing at some times on an overcast day (refer Figure 5 and the power output for 29 July 2002). Notice that the average power output per half hour on this day never reached 1 kW from 1 pm to sunset and was as low as 0.09 kW from 3 pm to 3:30 pm. The pumps need to run continuously at constant power once they are started; so we need to install sufficient solar panels to provide the power the pumps require even when the output from the solar farms is at its minimum.

By having many solar farms, widely distributed, they will not all have their lowest output at the same time. But all of eastern Australia can be covered by cloud at the same time so the problem is reduced but not removed by having distributed solar farms.

If we have sufficient energy storage to provide the NEM's energy needs for 90 days we would need sufficient solar generating capacity to power the pumps, at constant power, for the worst continuous 90 days in winter – i.e. the continuous 90 days with the least output from the solar panels. The capacity factor was 9.4% for the Queanbeyan Solar Farm for the worst continuous 90 days in winter 2003 (Figure 7).

The table below shows, for the number of days of energy storage available: the total energy demand, the worst case capacity factor for that number of continuous days, and the peak solar generating capacity required (see example calculation in appendix).

Days of storage	Energy demand (MWh)	Capacity Factor	Solar Generating Capacity[15] (MW)
1	600,000	0.75%	3,958,333
3	1,800,000	1.56%	1,903,045
5	3,000,000	4.33%	685,624
10	6,000,000	5.67%	523,589
20	12,000,000	6.62%	448,452
30	18,000,000	7.75%	383,065
60	36,000,000	8.55%	347,222
90	54,000,000	9.42%	315,154

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[15] Refer to the Appendix for the method of calculating the solar generating capacity required.

Steps to calculate the capital cost

Following are the steps to calculate the capital cost of providing the NEM's demand with solar photo-voltaic panels and pumped-hydro storage.

1. Determine the characteristics of the NEM demand;

2. Determine the amount of energy storage required for 1-day of NEM demand for evening, night and morning, in winter;

3. Determine the characteristics of the power and energy output from solar power stations;

4. Determine the hours of the day when pumping can be maintained at constant rate;

5. Determine the pumping rate required to store the required amount of energy in the available hours of pumping;

6. Determine the amount of solar generating capacity needed so as to provide the power for the pumps, plus the daytime NEM demand, even when the output from the solar panels is at its lowest level during the pumping hours;

7. Determine the amount of transmission capacity needed to transmit the power required by the pumps from the solar power stations to the pumped-hydro storage sites;

8. Determine the capital costs of:
    1. Solar power generating capacity;
    2. Energy storage reservoirs (dams);
    3. Hydro-electric pumping stations and power stations;
    4. Transmission.

Meeting the demand with 1-day of energy storage

Refer to Figure 8 below. Note that the vertical axis is log scale. Figure 8 shows:

1. The NEM average demand for July 2007, by half hour.

2. The power required to power the NEM during the day time as well as power the pumps so they can store 450,000 MWh per day, in 6 hours.

3. The installed capacity of solar photo-voltaic panels needed to produce the power required by the NEM day-time demand and the pumps (4,000,000 MW)[16]. This is the installed capacity of solar power that would be needed on the worst days.

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[16] Refer to Appendix for method of calculation

This calculation assumes that, by having widely distributed solar farms, the total power output of all solar farms would never fall below the ‘Total Power Demand’, at any time between 9:00 am and 3:00 pm during any day.

4. The output from the Queanbeyan Solar Farm on the two days with the lowest total energy output. Note that the power output falls significantly below the ‘Total Power Demand’ at times during the day. The assumption in 3 above is that this situation would never happen if we had many, widely distributed solar farms.

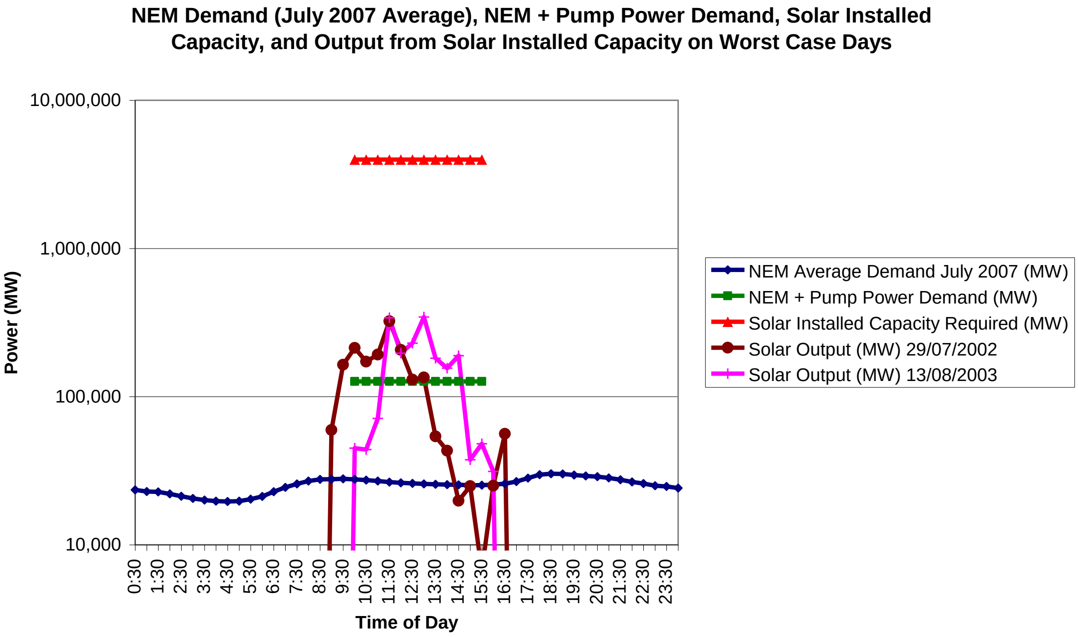

Figure 8 – NEM average demand per half hour in July 2007; power required to meet the NEM’s daytime demand plus power the pumps to store the energy for the rest of the day, in 6 hours; installed capacity of solar cells required to provide the power for the pumps on the days with the least energy output; and the output from the Queanbeyan Solar farm on the two days with the least output. The Output from the Queanbeyan Solar Farm is factored up from the Queanbeyan Solar Farm installed capacity to the capacity required for the NEM.

Capital cost of solar PV and pumped-hydro

Figure 9 (below) shows the capital cost of a solar photo-voltaic and pumped-hydro storage system to meet the NEM’s demand. The chart shows the cost of options with 1, 3, 5, 10, 20, 30, 60 and 90 days of energy storage. The figure shows the cost of the four main sub-system components – solar generating capacity, hydro energy storage (dams and reservoirs), pumping stations and power stations, and transmission. Note that the solar panels are the major cost component.

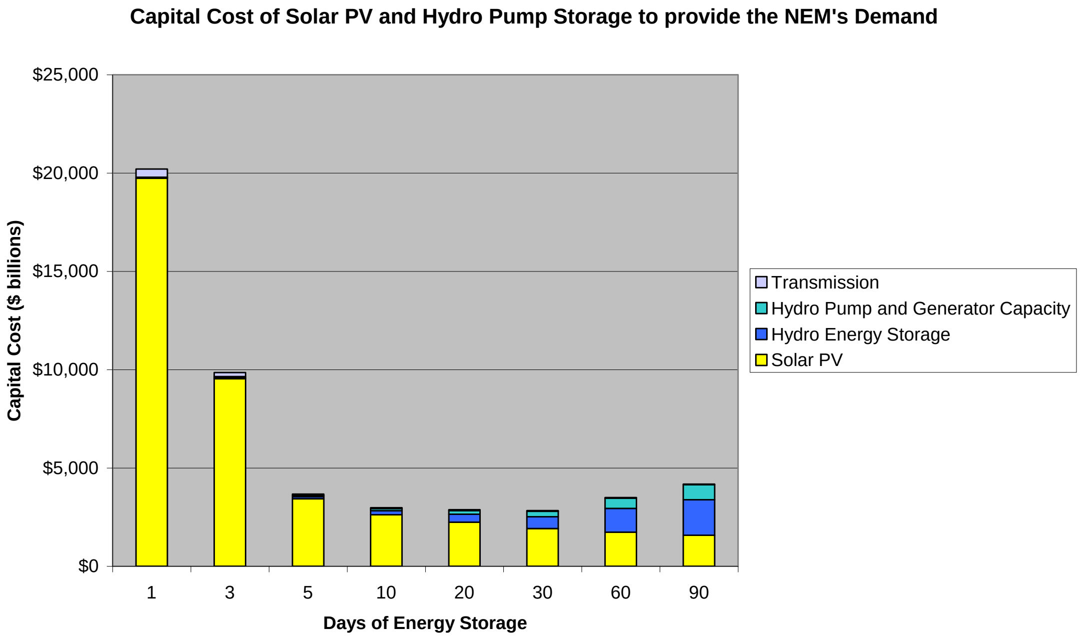

Figure 9 – The capital cost of solar photo-voltaic and pumped-hydro storage to provide the NEM's demand versus the number of days of energy storage available.

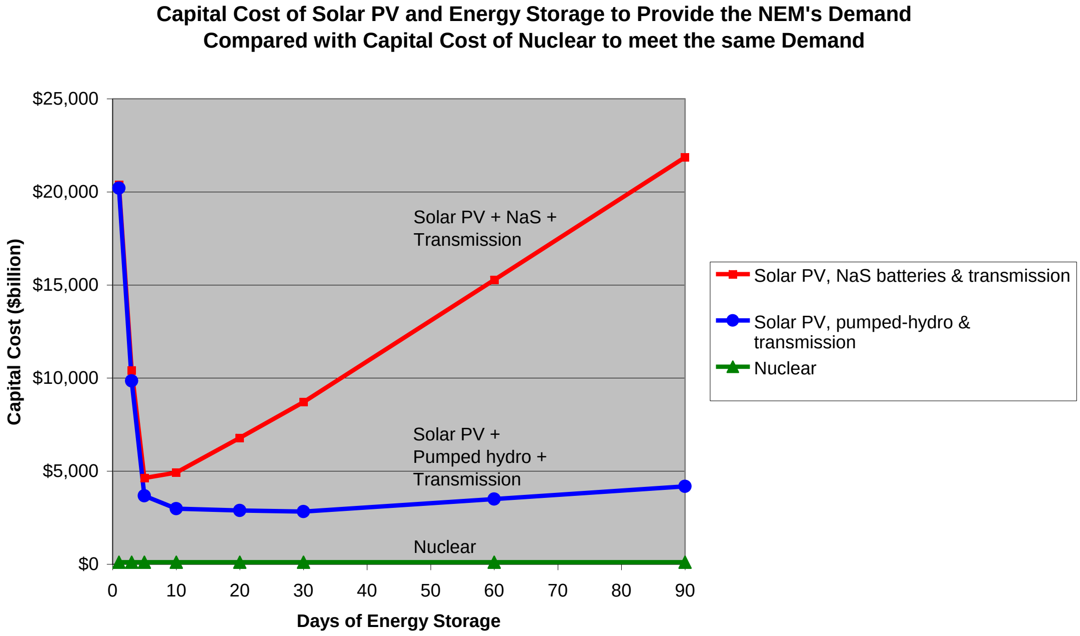

Figure 10 – Comparison of the capital cost of providing the NEM's demand with solar power and pumped-hydro storage, solar power and sodium sulphur batteries, or nuclear power. With pumped-hydro storage the least cost is with 30 days of storage (70 Sydney harbour volumes). The capital cost is $2,800 billion. With sodium sulphur batteries the least cost option is with 5 days of storage. The cost is $4,600 billion.

Putting the numbers in perspective

The installed generating capacity of solar panels (4,000,000 MW) needed to meet the NEM's demand, if only one day of energy storage is available, is equal to the world's total electricity generating capacity (4,000,000 MW).

The capital cost of solar PV, with 1-day of energy storage, is $20,000 billion, or 20 times Australia's GDP.

The capital cost of the least-cost solar option is $2,800 billion. That is 2.8 times Australia's GDP.

With 1 day of energy storage the reservoirs would inundate 260 km^2.

With 90 days of energy storage the reservoirs would inundate 24,000 km^2.

The pumps would need to pump 2.3 Sydney harbour volumes of water up 150 m in 6 hours, and release it to generate power to meet demand during 18 hours each day.

The number of Tumut 3 size hydro-electric pump storage schemes needed to meet the NEM demand depends on the basis of the comparison (see below):

Number of Tumut 3 size pump stations	170
Number of Tumut 3 size generating stations to meet NEM's peak demand	22
Number of Tumut 3 bottom reservoir storage capacities, for 1-day storage	49
Number of Tumut 3 top reservoir storage capacities, for 1-day storage	7

Comparison with another low emissions option – nuclear energy

The cost of providing the NEM's energy demand with nuclear power would be about $120 billion, or about 4% of the cost of the least-cost, solar power and pumped-hydro storage option.

The area required for the solar option would be 400 to 1000 times greater than with nuclear (not including mining; the mining area and volumes would also be greater for the solar option than for the nuclear option).

The table below shows the area required to meet the NEM demand:

Land area required (km^2)

Days of energy storage:	**1 day**	**30-day**
Hydro-electric water reservoirs	264	7,927
Solar panels	29,599	2,872
Total for solar panels and reservoirs	29,863	10,798
Nuclear power station	26	

The greenhouse gas emissions from the solar option with 30 days of storage would be some 20 times greater than from the nuclear option (full life cycle) (see Figure 11).

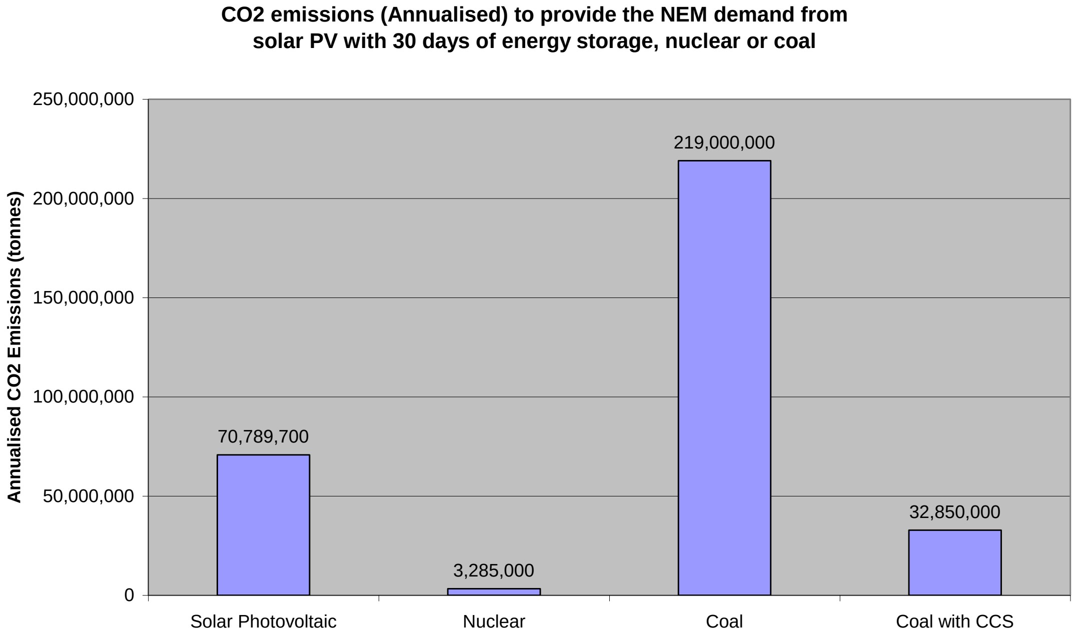

Figure 11 – Comparison of annualised CO2 emissions from the solar photo-voltaic generating stations sized for 30 days energy storage, nuclear, and coal (with and without carbon capture and storage).

Policy implications

Solar power is totally uneconomic and is not as environmentally benign as another lower-cost, lower-emissions option – nuclear power.

Solar power advocates argue that solar is not claimed to be the total solution, it will be part of a mix of technologies. But this is just hiding the facts. Even where solar is a small proportion of the total energy mix, its high costs are buried in the overall costs, and it adds to the total costs of the system. Government mandates and subsidies hide the true cost of renewable energy, but these additional costs must be carried by others.

Conclusions

Solar power is uneconomic.

The capital cost of solar power would be 20 times more than nuclear power to provide the NEM's demand.

The minimum power output, not the peak or average, is the main factor governing solar power's economic viability.

The least cost solar option would emit 20 times more CO2 (over the full life cycle) and use at least 400 times more land area compared with nuclear.

Government mandates and subsidies hide the true cost of renewable energy.

Appendix – Example Calculations

This appendix describes the steps for calculating the cost of the solar PV generating capacity required to meet the demand, for the case with 1 day of storage.

NEM demand between 9 am and 3 pm = 150,000 MWh
(actual for July 2007 = 159,180 MWh). This energy would be provided directly from the solar power stations each day

NEM demand between 3 pm and 9 am = 450,000 MWh
(actual for July 2007 = 449,340 MWh). This energy must be provided from storage each day

Average power to meet NEM demand from 9 am to 3 pm = 150,000 MWh / 6 hours = 25,000 MW

Average power for pump storage at 80% efficiency, for 6 hours, 9 am to 3 pm = 450,000 MWh /6 hours / 80% = 93,750 MW

Total continuous, reliable power required from 9 am to 3 pm = 118,750 MW (approximately; the NEM demand varies from about 18,000 MW to 33,000 MW, averaged across the month of July)

Hours that the solar panels can provide sufficient power in winter = 6 h/d

Required installed capacity of Solar panels = 118,750 MW / capacity factor

E.g., Installed capacity required with 1 day storage = 118,750 MW / (0.75% x 24/6) = 3,958,333 MW (say 4,000,000 MW).

At $5,000,000/MW, the total cost of the solar panels = **$20,000,000,000,000**

Notes on the basis of estimates for solar power, energy storage and transmission:
Solar panels: $5,000,000/MW[17].

Pumped-hydro storage: the costs are based on Tumut 3 inflated to 2007 dollars. These are less than the capital cost figures given in:
http://www.electricitystorage.org/site/technologies/technology_comparisons/

NaS battery costs and other relevant parameters were also obtained from this site.

Transmission capacity and length: Assume solar power stations are 100 MW (Peak), and we want to transmit 70 MW (close to peak in winter). Average distance from power stations to storage is 300 km.

Transmission unit cost: $500/MW-km.

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[17] Cost figures for utility scale solar photo voltaic systems are not readily available. The $5000/MW figure used here is about 50% of the price for >10kW systems in Australia in 2007 (ref: http://www.iea-pvps.org/products/download/rep1_17.pdf Table 6, p27).

About the author

Peter Lang is a retired geologist and engineer with 40 years experience on a wide range of energy projects throughout the world, including managing energy R&D and providing policy advice for government and opposition. His experience includes: coal, oil, gas, hydro, geothermal, nuclear power plants, nuclear waste disposal, and a wide range of energy end use management projects.