Optimisation of a renewable energy power system and electricity storage by means of pumped seawater hydro

Submission to ACRE 23/12/2010

Professor Peter Seligman, DEng

Preface

This submission is an edited extract from my book *Australian Sustainable Energy – by the numbers*, published by the Melbourne Energy Institute, July 2010, ISBN978-0-646-5316-0. The book is available online
http://energy.unimelb.edu.au/uploads/Australian_Sustainable_Energy-by_the_numbers3.pdf

and is free to download. For a printed copy please contact me on peter[at]seligman-family.net where [at] is @ or 0407 496 989 or 03 9337 9077.

Overview comments on ACRE Consultation draft strategic directions

The draft ACRE focuses more on components than systems. Evolution of components works well in a consumer environment where market forces and evolution produce continuous improvement. However in the case of a public utility, many components have to be in place before the system as a whole can function efficiently. If individual components need to wait for development of each other, before they become useful, progress will be slow or non-existent. For example, wind and solar need to have energy storage before they can be used on a large scale. Storage technology will not develop without the large scale wind and solar developments. In my opinion, there is a requirement of an integrative approach, to optimise the use of renewables to deliver low carbon power at the lowest price. System modelling would be essential to achieve this.

Comment on the recommendations

The recommendations specifically exclude hydro on the grounds that this is a mature technology that has been fully exploited in Australia and does not require further support. I would modify that recommendation to address the potential of hydro for pumped energy storage. While this is well developed and close to fully exploited, it does not include the use of seawater for pumped storage.

Comment of the key issues for consideration

Key issues which could be included would be co-generation and multiple use projects. For example both solar can be combined with multiple effect distillation. Wave power can be integrated with desalination. Air conditioning can be solar powered. Space heating can be combined with electricity generation.

Introduction

To supply a high proportion of Australia's electricity from renewable sources such as Solar, Wind and Wave power, the variable nature of supply must be matched to the variable demand. This requires electricity storage on a large scale. The cheapest form of large-scale electricity storage is pumped hydro, in which water in a dam is used to generate electricity but when surplus electricity is available, the same installation is used to pump water back up the hill, to be used when required. In this way the hydro installation is used as a very large battery, able to store electricity for use when required.

It is accepted that although the existing water storages would be sufficient in volume for this purpose there is not enough water in these dams and furthermore, there is not enough generating capacity to deal with the full grid load in the event of no renewable input. However, in this study, the concept is explored of using seawater instead of fresh water and locating dams on coastal cliffs rather than in mountains.

This is a study explores what it would take to build an electricity system to supply the existing Australian load with 90% renewable energy. It demonstrates that using a combination of renewable sources, pumped storage and high voltage DC (or AC) transmission lines, power could be economically generated, stored and delivered. The 90% target in this study is of course not a pre-requisite and the techniques described here would apply to any target where the variable renewable component of electricity supply is sufficiently large to be mismatched to the variable load.

Design of a renewable energy power system

To decide on the best mix of components, there is a computer program called HOMER, written by the National Renewable Energy Laboratory[1] of the USA for modelling hybrid renewable energy systems. This program allows input of a number of candidate sizes of each system component and the statistics of the load and renewable resources. It then evaluates all combinations of the components to give a ranking of the most cost effective or lowest energy solutions.

In the case of a country-sized "installation" a program would need to model the weather and load patterns of all the relevant centres. The analysis would include the cost of interconnecting the centres. For example, we could have a solid power network which can transmit all renewable power generated to the other side of the continent. That might not be the most cost effective solution. However a less solid network would

[1] http://www.homerenergy.com/

require more standby power. Comprehensive modelling is the solution to this problem. This study is an illustration of the method.

Assumptions:

Load: 25 GW annual average, 45 GW peak
Geothermal: 10 GW
Wave: 0.4 GW
Solar: variable to meet load and minimise cost
Wind: variable to meet load and minimise cost
Hydro: 1.6 GW
Total 26 GW

I have assumed an efficiency of 96 % for conversion and transmission of the power. Pumped hydro storage losses are included in the "battery" round trip efficiency[2] of 80%.

The electric load data was downloaded from AEMO Australian Energy Market Operation[3] .

In this feasibility study, I will use HOMER, but scale everything by a factor of 100,000. I will design a power system to supply 260 kW instead of 26 GW. Homer does not have the capability to model Wave and Geothermal power but it does have Hydro, and for the purpose of the exercise, I will lump these three together, ie provide 12 GW (i.e. 120 kW) from Hydro and assume this to be always-available power. The Solar and Wind data is from HOMER itself, based on geographical input. Statistical variation is introduced in the data to model fluctuations.

I will lump all forms of storage into one, i.e. pumped, even though thermal storage, Vanadium Redox batteries and electric cars could provide some as well. In fact, I found that HOMER best models pumped water storage by the Vanadium Redox flow battery. This type of battery splits the cost of the battery and the electrolyte, which can be individually sized. Likewise with pumped water storage, the cost of the dams (the "electrolyte") and the pipes and turbines (the "battery") are independent.

Note that although it is often said that the diversity of power from different sites makes renewable power more like "baseload" power, this does not appear to be the case as much as we would like it to be. For example when comparing the South Australian and Victorian Wind farms, there is a delay between one and the other but the basic shape is the same or at least similar. Solar data is also correlated from differing regions. Solar and Wind are less correlated, but not uncorrelated. So for the purpose of this exercise I will consider all solar and all wind data to be from single sites. This will give a worst case outcome.

Another factor to consider is that solar, whilst in general being well matched to the load, on an Australia wide basis does not work as well as we would like. The best Solar regions are in the West, whereas the bulk of the load is in the East. So when the eastern seaboard is reaching its maximum load the sun is only just rising in Western Australia. I have used solar data from Broken Hill in Western NSW as the basis for this exercise.

[2] Figures between 0.70 and 0.87 are quoted in the literature.
[3] http://www.aemo.com.au/

I have set up my 100,000th size scale model of the Australian renewable energy power grid. I have put in a battery so that by looking at its depth of discharge, I can get the size of storage needed to make fickle renewables into solid always-available, power.

Simulation outcome

Load: 25 GW annual average, 45 GW peak
Geothermal: 10 GW
Wave: 0.4 GW
Solar: 8.5 GW (40 GW peak)
Wind 5.5 GW (18 GW peak)
Hydro: 1.6 GW
Total 26 GW
Storage 200 GWh

The battery, translated into the full size system[4] is 200 GWh. If it were possible to drain the present 16 % of capacity of Lake Eucumbene down to the Blowering dam and then pump it up again, this would represent 427 GWh of storage. This is about double the storage we would need, estimated by my worst-case analysis using HOMER.

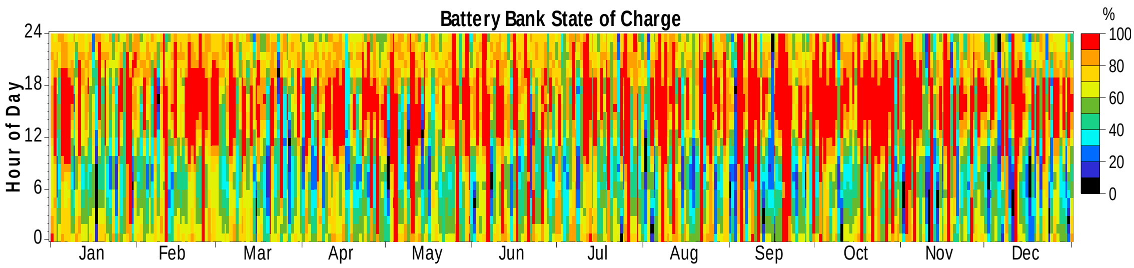
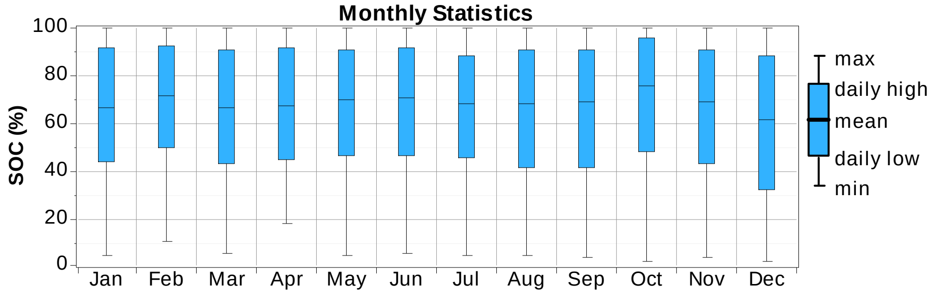
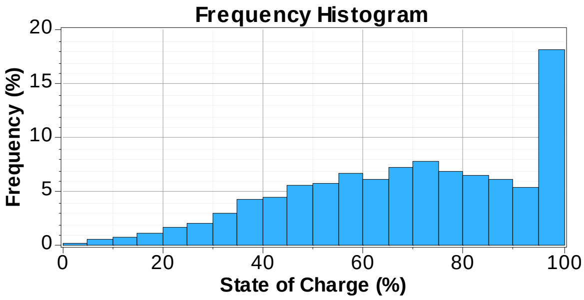


Figure 1 Daily and annual fluctuations in storage





[4] I used 2000 kWh in my scale model

Figure 2 Storage levels depicted on two different graphs

The dams of the Snowy Mountains, have sufficient volumes to provide the pumped storage required to maintain our electricity system using renewable energy from variable sources such as wind and solar. Even the height difference between the Talbingo and Blowering dams, about 165m, which could provide 1420 GWh, is about 10 times as much as we would need to serve our current electricity needs.

In this simulation, I have assumed that 10% of the power can still be supplied by the existing gas fired installations. The main reason for this is to limit the size of storage required.

If the idea of pumping a tenth of the contents of the Talbingo dam up to the Blowering on a daily basis sounds impractical, I would agree. The turbidity problems and erosion could be quite a problem, aside from the kilometres of large diameter plumbing that would be required. We would need turbines and pipes to handle about 32 GW which is 21 times as big as the installation there at present. The damage to the environment, which is mostly in national parks could be considerable. In any case, the volume of water in these dams is dropping all the time and the time might come when we won't be able to use them at all. Although we don't need to use any more water, the same water is being used over and over again. However to fill the dams we would need to stop the irrigation and environmental flows for a long time, a politically, environmentally and economically unacceptable idea.

However here's another idea: why use fresh water? Could we use sea water? What we need is a high place very close to the sea, preferably near somewhere where it is windy and sunny and where there is little or no population or national park. Could that place be in the Great Australian Bight?

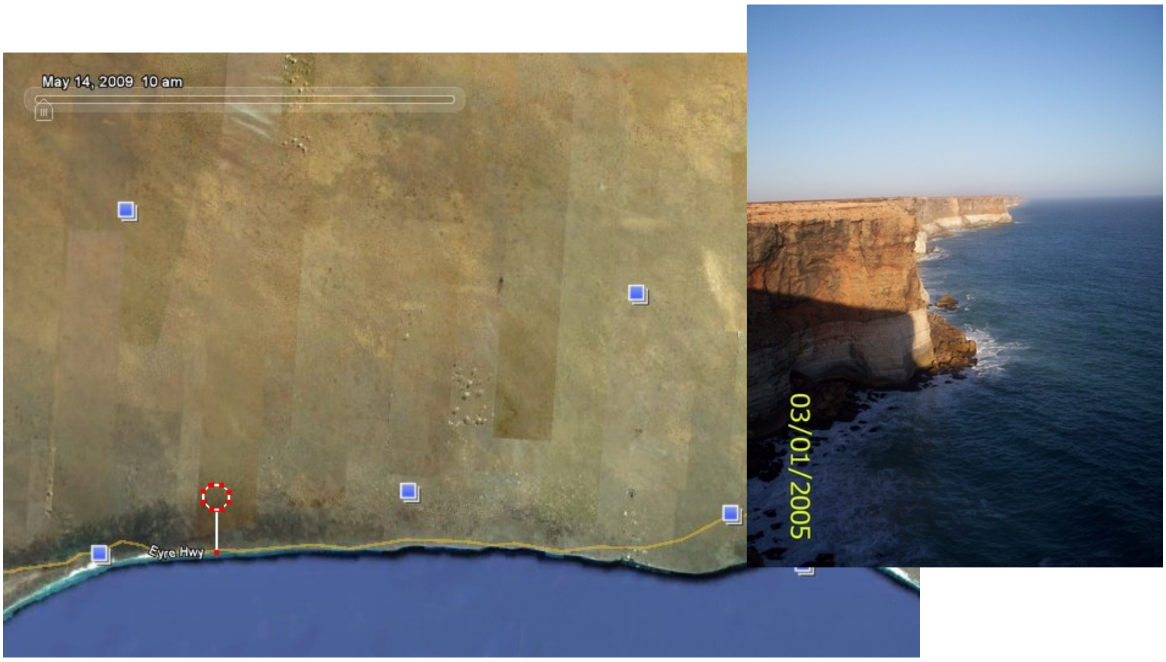


Figure 3 Bunda Cliffs. Suitable place for pumped storage? The octagon is 7 km across.

The Bunda cliffs on the Nullarbor place[5] are about 90 m above sea level. If we are after 200 GWh of storage, a "pond" about 37 km^2 (7 km diameter) and 20 m deep would do the trick. This "pond" could be close to the coast. Rather than digging it all out, it would be best to dig out a bit and build the wall with that material. That would add to the head, making the average head about 100 m. It would be more efficient to make it circular.

A big project, true, but possibly not as disruptive as trying to use the dams in the Snowy mountains[6].

Storage cost estimate

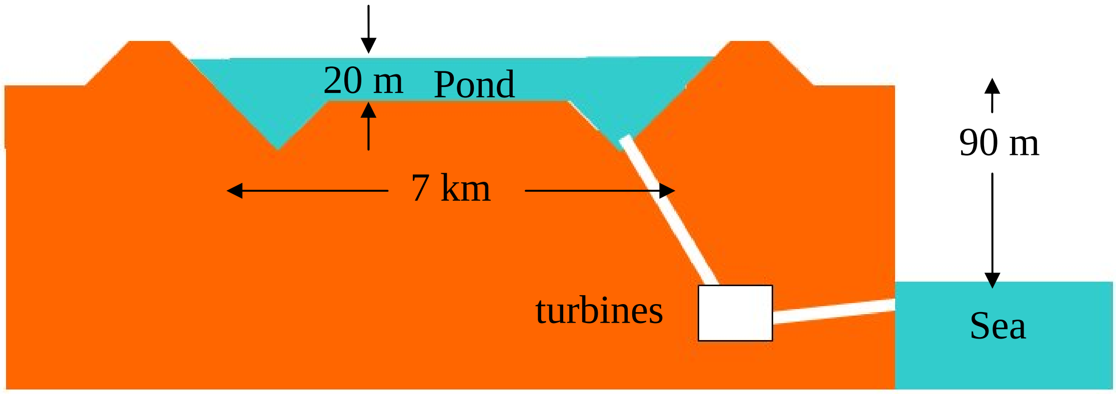


Figure 4 Saltwater pond on the Nullarbor to store all Australia's renewable energy

Here's a rough costing of this hypothetical pond on the Nullarbor[7].

1. Excavation cost
   a. Excavation cost: $10 /$m^3$
   b. Excavation: A trapezoidal trench 20 m deep, with excavated material used to build a dam wall to create a 20 m deep circular (or octagonal) pond.
   c. To provide a 37 km^2 pond, a diameter of 7 km is required. The trench/dam would be 21 km long. Volume of excavation 21 x 10^6 m^3
   d. Cost = $ 0.4 billion

2. Pond lining
   a. Line the pond with a plastic membrane (these are in common use in the area for various purposes)
   b. Membrane cost: $20 / m^2
   c. Area = 37 x 10^6 m^2
   d. Cost = $ 20 x 37 = 730 * 10^6 = $ 0.73 billion

3. Basic cost = 0.4 + 0.73 = $ 1.13

[5] 31° 38' 25.19" S, 129 ° 20" 51.35"
[6] Location proposed by Robert Veerman
[7] numbers from Rob Duncan

4. Total storage cost = say $2 billion including miscellaneous construction. I have not included a figure for concrete lining which may be required under the membrane

Pipes and turbines

To implement such a project would involve a lot of turbines and pipes. Let's say the sun is shining on a windy day. We need to store all the energy we can generate. To supply: Solar: 8.5 GW (40 GW peak) and Wind: 5.5 GW (18 GW peak) we would need up to 40 + 18 = 58 GW of turbines. However during the day the system is drawing about 38 GW on average already – so that can go directly to the load. On that basis, the turbines would only need to be 58 – 38 = 20 GW. How can we calculate how much that would cost? As it turns out we have a nice example on which to base our guesstimate the Bogong Power development in Victoria. This is an extension of an existing system and does not require further dams, just pipes and turbines. The 140 MW extension will cost $230 M, or $1.6 /watt. So 20 GW of turbines and pipes might cost $33 billion, a relatively small sum compared to the cost of the renewable energy power stations themselves.

	GW or GWh	capacity factor	cost $/peak watt	Cost $billion
Solar	40	0.21	2.73	109
Wind	17.5	0.32	3.00	53
Geothermal, hydro, wave	12	1	3.00	36
Turbines and pipes	20	1	1.64	33
Pond	200	1	0.01	2
Storage total				35
Power station total				198
Total including storage				232
Storage cost percent	15%			
Cost of electricity	0.11	$/kWh		
renewable fraction	0.9			

Table 1 Summary of a power system providing 90% electricity from renewable sources

Wiring it all up

To complete this project, let's see how one could link up the renewable resources and load in some sensible manner. It is obvious that with so much variability in load and supply, there will be a lot of power flowing around the system. Here is a table of proposed high voltage DC links their capacity, lengths and costs, calculated as before.

I am assuming that an average link size would be 10 GW. This would allow a Nullarbor pondage and a Geothermal complex in the Cooper basin near Innamincka to supply 30 GW to Melbourne, Sydney and Brisbane. It assumes that the Wind, Solar and Wave power installations would be spread along these routes to feed into this busbar.

Assumptions		
High voltage link size	10	GW
Link cost $M / GWkm	0.15	
Cost per end station $M / GW	61	

Link	**km**	**cost $billion**
Perth - Nullabor pond	1341	1.7
Null pond - Port August	786	1.0
Port Augusta - Melbourne	902	1.1
Melbourne - Sydney	740	0.9
Port Augusta - Innamincka	601	0.8
Innamincka - Brisbane	1202	1.5
Brisbane - Sydney	740	0.9
Innamincka - Sydney	1202	1.5
Power stations to storage	3000	0.4
Total	**10514**	**9.8**
End stations	**16**	**11.0**
Total including end stations		**20.8**

Table 2 Cost of high voltage links between renewable energy sources and major centres.

This rough calculation gives a total busbar cost of $20 billion, which is only a small part of the $200 billion cost of the renewable power stations, calculated at $10/average watt, a figure we can achieve today.

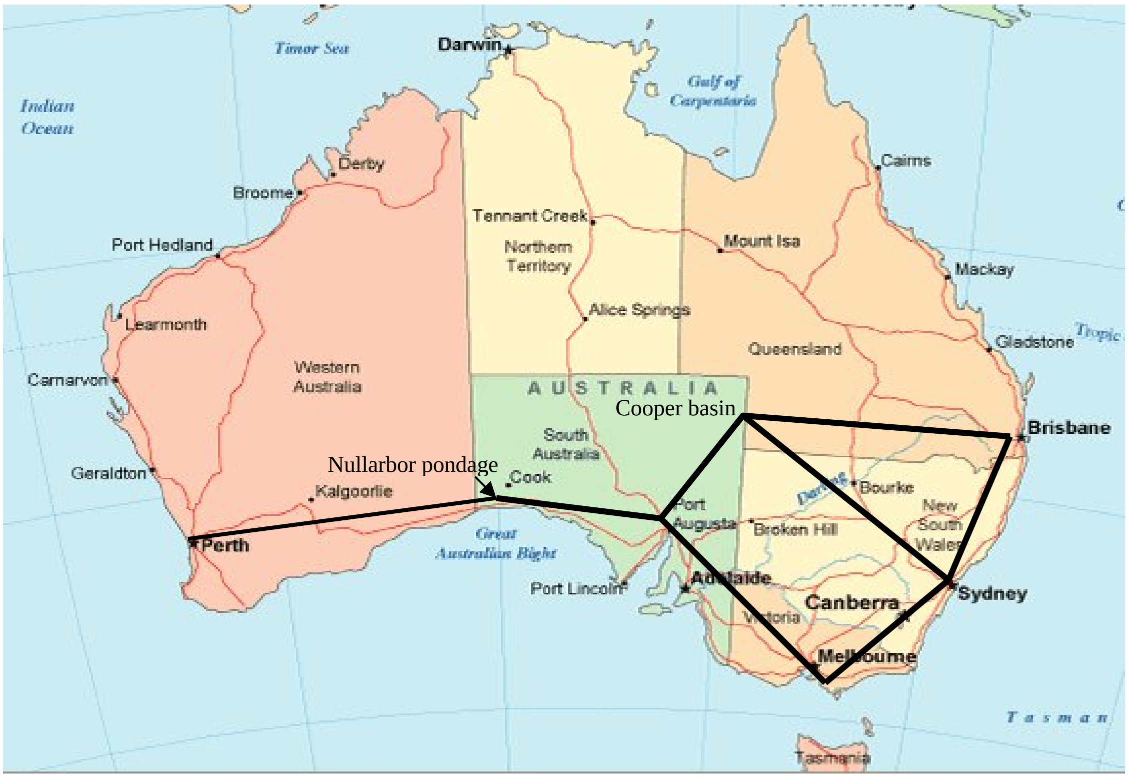


Figure 5 High voltage DC wiring diagram for Australia

I have bypassed Adelaide and used Port Augusta as a staging point. South Australia in total uses 7 % of our power. Tasmania already has a link to Victoria and uses mainly hydro power anyway.

Seawater pumped storage pilot project.

Seawater pumped storage is not a new idea. It has been in operation in Japan for 12 years.

An excellent paper on a seawater pumped storage pilot plant was published in the Hitachi Review[8] in 1998. The installation[9] is on Okinawa, Japan

The Yanbaru plant provides storage of about 400 MWh and input/output of 31 MW.

In pumping mode it delivers 20 m^3/s and in electricity generating turbine mode, uses 26 m^3/s. Based on these figures, the round trip efficiency is 77%.

Figure 6 Pilot Seawater Pumped-storage Power Plant, Okinawa Pref. in Japan.
The octagonal shape shows the upper dam. The outlet of the tailrace is surrounded by tetra-pods for protection from waves. The picture is from the 1998 Hitachi Review.

[8] *http://www.hitachi.com/rev/1998/revoct98/r4_108.pdf*

[9] Office in Kunigami Village, Okinawa but the facility is on the East coast of Okinawa. At 25^{o} 4’ N 128^{o} 16’ E

Figure 7 plant as seen in 2009

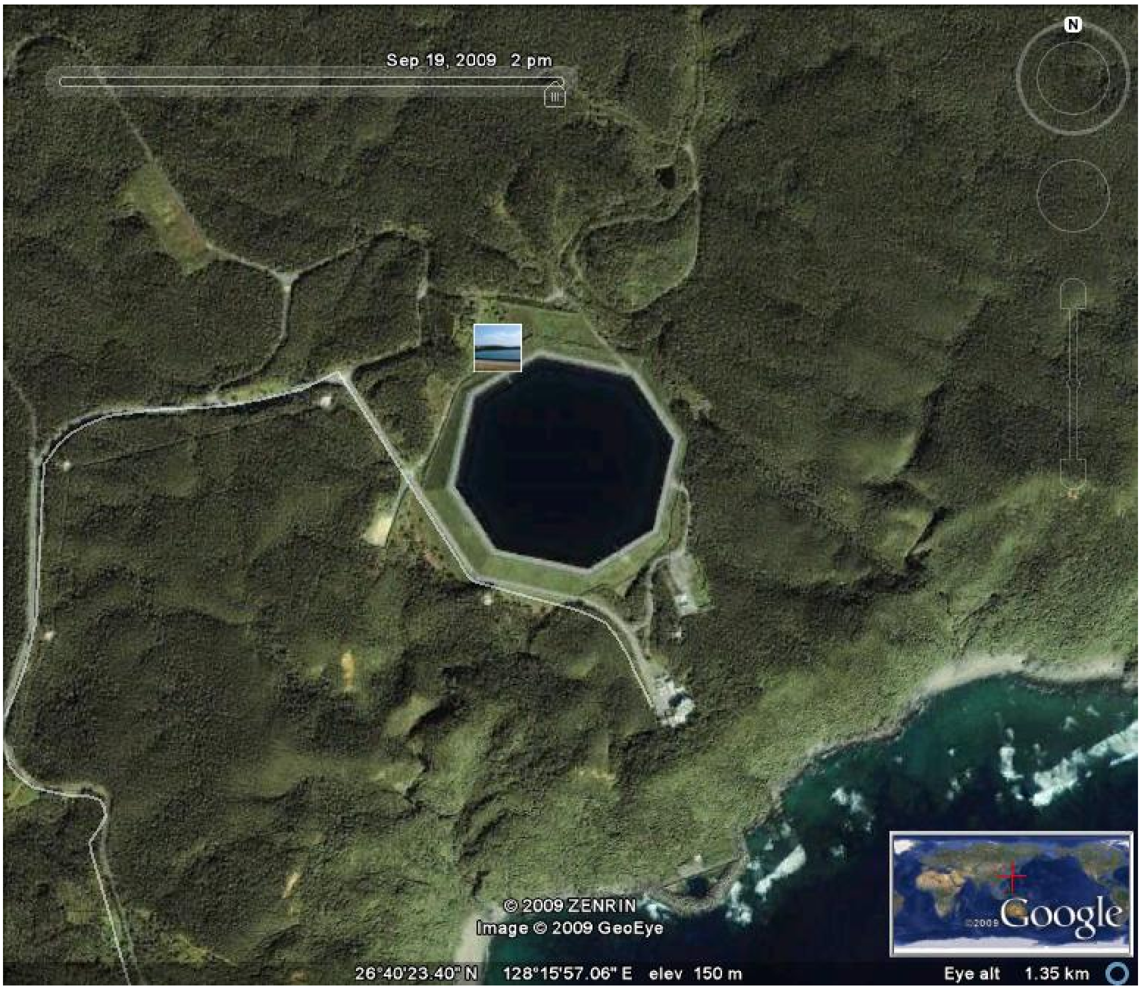


Figure 8 Okinawa seawater pumped storage facility as seen from Google Earth

From the Japan commission on Large dams website[10] it is clear that much attention to detail is required: "There are several issues facing seawater pumped-storage power plants. These issues are being examined during the test operation of the plant.

- Evaluations of measures taken to prevent permeation and pollution by seawater from the upper pond into the ground and/or into ground water.

[10] http://web.archive.org/web/20030430004611/www.jcold.or.jp/Eng/Seawater/Summary.htm

- Efficiency reduction in power generation and pumping as a result of adhesion of marine organisms to the waterways and the turbine.
- Corrosion of metal materials that come into contact with seawater under high pressure and high flow speed created by the pump-turbine.
- To ensure stable power output through steady intake and discharge of seawater at the outlet against high waves.
- Impacts on plants, animals and other biological systems around the site by the wind's dispersion of seawater from the upper pond.
- Impacts on coral and other marine organisms that live near the outlet."

In this design exercise, I have simply used the existing electrical demand which is 25 GW and tried to match the installed capacity of 45 GW. This "design" is not a proposal; in a real system it would be much more distributed and more integrated into the existing network. Many of the installations would have their own storage in the form of thermal or Vanadium Redox batteries. On the matter of supplying all Australia's needs, rather than just the current electrical use, a number of technologies will come into play. The electrification of private and other liquid fuel based ground transport might alleviate rather than exacerbate the problem.

Interestingly these High Voltage DC links could (in a loosely coupled grid) pay for themselves in a short time by exploiting the price differentials of electricity in different regions. For example a mean price differential of 4 cents/kWh can pay for a line in one year. Given that electricity prices can peak at $10 /kWh in contrast to the normal price of 5 cents/kWh and also go as low as *minus* 50 cents /kWh (when generators have to pay to get rid of the power), it is easy to see how one can make money by sending power from one place to another.

The bill

Including the cost of the pipes and turbines, to convert our existing electrical power system to completely renewable[11] sources, we will need:

Power stations (wind, solar and geothermal)	$198 b
High voltage power lines	$ 20 b
Turbines and pipes	$ 33 b
Storage pond (dam)	$ 2 b
Total	$253 b

over say 25 years. That's about $10 billion per year or about $500 per person per year, or $1.40 per person per day. Can we afford it?

If this sounds expensive, consider that total gambling expenditure in Australia is about $18 billion with the average NSW citizen losing about $1336 annually (2006) [12]. That's $3.70 per New South Welshman per day.

On the other hand, sometimes these systems will save money. Here's a rough calculation. Let's imagine that we managed to reduce our CO_2 emissions from our

[11] For the purpose of the exercise I'm calling Geothermal renewable
[12] http://kalimna.blogspot.com/2006/08/gambling-in-australia.html)

current 20 tonnes/person/year to zero in the next 25 years. Ramped gradually from 20 to zero, that would make for an average CO_2 production of 10 tonnes/person/year. At a CO_2 price (who knows what it could be?) of say $ 50 per tonne that would be about $ 500 per person per year, or about $1.4 per person per day, saved in CO_2 cost. A $50 / tonne of CO_2 price would effectively pay for this renewable power system.

Conclusion

This study demonstrates that electricity can be economically stored using pumped hydro and that mountains and fresh water are not necessary. It also shows that the transmission of power of the distances that may be required for transmission of renewable energy are not an obstacle. Indeed, the cost of both stage and transmission is only a small proportion of the cost of renewable energy. The study shows that electricity from renewable sources can be generated, stored and transmitted at a reasonable price.