Australian Sustainable Energy – by the numbers

(inspired by Sustainable Energy – without the hot air,
by David J.C. MacKay, FRS)

by Peter Seligman

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Melbourne Energy Institute
The University of Melbourne

Growing concerns about energy resource security, the adverse environmental impacts of energy production and inequities in access to energy services are crucial to national and global policy considerations. The increasing recognition that our energy systems need to be made more sustainable, environmentally benign and adaptable, while also providing reliable and affordable supply to more and more people, presents a daunting challenge. In particular, the prospect that rising greenhouse gas concentrations are leading to unprecedented and potentially irreversible climate change makes redesigning our energy systems one of the most important challenges of our time. Framing clear pathways to a more certain energy future is inherently interdisciplinary. Such pathways must be informed by a deep understanding of emerging technologies, market economics, resource prospects, environmental impacts, regulatory frameworks and social equity issues. The delivery of such pathways requires new research strategies that transcend traditional lines of enquiry that link the many different ways of thinking that inform how modern societies work and prosper. The Melbourne Energy Institute brings together the work of more than 200 researchers engaged across seven faculties at the University of Melbourne to help to meet this challenge.

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Foreword

As we go about our daily lives, we tend to be blissfully unaware of the amount of science that surrounds us. Most of it is set in stone and there is little doubt that we can depend on it. We are surrounded by technology, we get weather reports that allow us to dress appropriately for each day, and through some wonderful combination of the work of Newton, Marconi and Einstein our GPS enabled phones can now tell us our location to within a few meters.

Despite this incredible faith and dependence, science at the moment, especially climate science, seems to be under siege. Well, that statement is not strictly correct, it is not science that is being attacked as such, but the process of science – falsification – that is the target.

Science gains its strength not by always being right, but by sometimes being wrong. As we test our theories in the real world we are occasionally surprised by the way the real world works. Consequently, theories evolve, become stronger, and are then again pitted against the complexities of the world we live in. Over time, this repeated process results in theories that are so robust that we no longer question them.

In thinking about the way science works, we cannot consider science as analogous to a single ’species’ at a point in its evolution. Science collectively is the equivalent of every species on earth simultaneously, each at a different point in its history. Some fields have naturally died out, whilst others are shiny and new. The ’extinct’ fields have been superseded by ones more adapted to their environment. The ’new’ fields are in many cases still finding their feet, making mistakes as they go but gaining strength in the process. And of course there are some fields that seem to be endangered. The process of science however, the part being attacked at present, is not changing, and continues to serve us well.

Over the last 16 years, as a science broadcaster for the 3RRR radio station in Melbourne, I have noticed a ground swell in the number of attacks on science that focus on the changing nature of the discipline. In recent years, as climate science has entered main stream political discourse, the abuse of scientific information has become a point of national shame. Messages about science are so entangled with the voices of particular interest groups that one can no longer trust the information we are receiving. The misuse of science has become a strong political tool.

Part of the blame for this situation must fall on the shoulders of the scientists involved. Due in general to a lack of training, scientists tend to present their work openly and honestly, with little thought to the complexity required to interpret for specific audiences. They focus on their own narrow field of expertise and deliver their ideas with a degree of passion fitting their efforts. Because the context of the broader picture is often not presented, audiences are left to fill this gap on their own. The result is a series of messages, all told with slightly different languages, and told from the point of view of particular interest groups.

In the case of energy, this presents us with a specific and immediate problem. Australia, and indeed the world, needs to look at all the energy options available to us and plan for the combination of technologies that will yield an environmentally responsible result. Of course without information on all energy sources, presented in one language and with appropriate comparison it seems inappropriate to move forward.

With this dilemma in mind, it gives me great pleasure to write the foreword to this book. For the first time I have found myself reading about energy without hearing the voices of lobby groups or government spin doctors. A clear path is presented without prejudice or self interest. Hopefully this book will be seen as an unbiased starting point for discussion, correcting the positions of so many soothsayers. The problem before us now is not one of technology of resources, but one of political will, and it is on this basis that our future will depend.

Shane Huntington[1]
February, 2010.

[1] Dr Shane Huntington has a PhD in Physics and has been a science broadcaster for 16 years. He is the science and engineering host of the University of Melbourne Upclose podcast program, an Australian company director and the Principal Strategy Adviser within the Office of the Vice-Chancellor at the University of Melbourne.

Preface

I'm an Australian Electrical Engineer. As an engineer I find it annoying that wherever you look, information on renewable energy is unreliable or presented in ways which are not meaningful without calculation and comparison to some relevant standard. The potential of any particular technology is often overstated or understated, depending on the particular bent of the writer. Then there is the simply wrong information, the megawatts per hour, (usually meaning megawatts) the failure to state whether power is average or peak (a factor of 3 to 8 between them).

The next irritation is scale and proportion. You would be led to believe by some, that just by switching off our mobile phone chargers, recycling bottles and cans and putting some solar panels on our roof, we can make a significant difference. How big a difference? What is it as a proportion of our total energy use? Telling us in tonnes of CO_2 or number of *homes* doesn't usually help. The Prime Minister announces that we are going to build the *world's largest* solar power station[2] – 1000 MW, *equivalent to that of one coal fired power station*. What he doesn't tell you, or maybe even realise himself, is that 1000 MW of peak power from solar is about 200 MW average power. He also doesn't mention that Australia is using 25,000 MW on average so this *world's largest* will supply less than 1% of our present use of electricity. He doesn't mention that electricity accounts for about half of our total energy use, hence the power station will provide less than 0.5% of our total energy. Instead he may tell you how many *homes* it will provide power for, or how many tonnes of CO_2 it will save. Big numbers that mean nothing to most people.

Finally, even reputable and very well known authors are capable of making any or all of the mistakes I have mentioned.

When I first encountered *Sustainable Energy - without the hot air*[3] (SEWTHA) by David MacKay, it was like a breath of fresh air, not hot air. Here at last was someone who spoke my language.

On a visit to Cambridge in August 2009 I had the privilege of lunching with David MacKay at Darwin College. At our enjoyable meeting I mentioned that

[2] Actually this is four separate contracts for solar power stations so it is perhaps only the world's largest announcement rather than the world's largest solar power station.

[3] UIT Cambridge Ltd. PO Box 145, Cambridge, CB4 1GQ, England. ISBN 978-0-9544529-3-3.

there were many people in Australia who would have been interested in an Australian version of *Sustainable Energy - without the hot air* (SEWTHA). I also mentioned some material that I have been writing on sustainable energy in Australia. David and I agreed that it would be good to write an OzSEWTHA and we informally agreed that I would attempt it. Rather than being a *translation* it would be a supplement, with information relating specifically to Australia. Further, I mentioned that I had included financial aspects of sustainable energy in my writing and David said that he welcomed that addition. This is the result. In the event, it has become more than a supplement; it is a book in its own right.

This book differs in one important way from David MacKay's. David's book uses a yardstick of kilowatt hours per day per person – kWh/day/person. He then calculates all renewable sources in terms of these units and calculates how much of the UK's needs could be provided by utilising all the available sources using the same units. The answer is that the UK cannot supply all its needs from renewable energy, it would have to go offshore, or treat nuclear as *renewable*.

In Australia, the situation is quite different. We could supply all of our needs many times over. In fact, in theory we could supply the whole world with renewable energy, if we were prepared to do it and could transport it. No, in the case of Australia the question is more, what proportion of the country (and it is usually in the order of a few percent), would we require to supply all our needs?

Peter Seligman, PhD., DEng.
January, 2010.

Summary and conclusions

It's official, Australians per person are the worst polluters in the world[4]. For a country so well endowed with renewable energy, that's quite an achievement. But then there's a big difference between having renewable resources and utilising them.

In this document I try to identify and quantify the most promising renewable resources. I then examine how they could be used in combination to reduce Australia's greenhouse gas emissions to practically zero. Following on I consider where we are at and the policy of the government.

As an exercise, I try to design a renewable power system for Australia, which could meet our needs for a comfortable lifestyle. I try to dispel the statement that renewables can't supply *baseload* power, not through dogma, but by calculating how it could be done. Contrary to popular belief, the numbers show it is not too expensive to store electricity on a large scale. In fact the cost of pumped water storage, including the powerlines, dams, pumps and pipes is only a fraction of the cost of the wind and solar power sources themselves.

Further I discuss some specific systems that are of particular interest in the Australian context (Wind Farm co-ops, Refrigeration & Cooling). I describe some personal strategies that people can use to reduce their greenhouse gas emissions. These are the ones you usually don't read about in the newspaper, and they are based on a *bang-for-buck* philosophy.

The thorny issues of Carbon offsetting, Renewable Energy Certificates and Rebates are discussed. Finally - and in implementation, this should come first - I discuss efficiency and waste using some examples drawn from personal experience.

In writing this document I found that costs varied, mostly due to changes in the exchange rate of the Australian dollar. Rather than continually update the document, I have stuck with what I had. The Australian dollar at the time of writing was about 90 cents US, 56 UK pence and 62 Euro cents. In some cases I used US dollars but since at the time of writing they were close to $1, I didn't

[4] The CO_2 Energy Emissions Index, released by risk assessment company Maplecroft, found Australia's overwhelmingly coal-based electricity supply meant the average person emitted 20.58 tonnes of carbon dioxide a year. Australia overtook the US – responsible for 19.78 tonnes per head – as the worst per capita emitter. *The Age* Sept. 11 2009

differentiate. I don't think that the rate of exchange will significantly change any of my conclusions.

Conclusions

1. In theory, Australia could comfortably supply all of its power requirements renewably.

2. In practice, for some interim period, the use of some non-renewable sources may be necessary but the overall carbon footprint can be reduced to zero in time.

3. The major contributors would be solar power, wind and geothermal.

4. To match the varying load and supply, electricity could be stored using pumped hydro, as it is at present on a much smaller scale. In this case, seawater could be used, in large cliff-top ponds.

5. Energy efficiency would be a key aspect of the solution.

6. A comprehensive modelling approach could be used to minimise the cost rather than the current piecemeal, politically based, *ad hoc* system.

7. Private transport and other fuel based transport could be largely *electrified* and batteries could be used to assist with storage.

8. In a transition period, liquid fuel based transport could be accommodated by using biofuels produced using CO_2 from any remaining fossil fuelled power sources and CO_2 generating industries.

1 Introduction

Sustainable Energy – without the hot air (SEWTHA)[5] by Cambridge physicist David MacKay[6], is an excellent, rational and quantitative appraisal of the UK's energy situation with references to other European countries. In essence, the story is that to supply European countries with sustainable energy requires country sized installations. If all available resources were used, there is not enough potential capacity to meet the demand, even when this demand is reduced through efficiency measures. SEWTHA provides five alternative plans (page 212 for the summary). All plans involve using nuclear and/or importing power from another continent.

Australia on the other hand, as is often the case, is the lucky country. Table 1 below compares the two countries.

	UK	Australia	Ratio (Aus/UK)
Land area	0.24 Million km^2	7.6 Million km^2	32
Population	60 Million	22 Million	0.37
Solar irradiance[7]	1000 kWh/m^2/year	2200 kWh/m^2/year	2.2
Power consumption[8]	125 kWh/day/person	190 kWh/day/person	1.5
Power consumption[9]	5200 W/person	7900 W/person	1.5
CO_2 from electricity[10]	0.55 kg/kWh	1.0 kg/kWh	1.8
CO_2e[11]	11 tCO_2e/person/year	20 tCO_2e/person/year	1.8

Table 1. Comparison of the UK and Australian parameters relating to energy.

On the positive side, Australia has 32 times the area of the UK with about a third of the population. Much of Australia has over double the solar irradiance. On the other hand, Australians use 50% more power per person and generate their electricity with the world's most polluting technology, i.e. coal fired power stations. Much of this power generation is from brown coal which is the worst

5 http://www.withouthotair.com is available free online. It is also available on paper.
6 Now UK government's scientific advisor on climate change
7 http://www.solar.coppe.ufrj.br/solar.html
8 p. 104 SEWTHA
9 p. 104 SEWTHA but recalculated into W/person
10 p. 335 SWETHA
11 p. 13 SEWTHA

of the worst. As a result, electricity generated in Australia is more than twice as polluting as that in the UK. In Victoria, it is three times as polluting.

In SEWTHA, David MacKay stacks up all conceivably available renewable resources in an attempt to make them match the load. In Europe and the UK, this is a tough ask. We have the luxury of using a different approach. In our case it is not a matter of if we can summon all the resources could we supply the load, but which resources to use and in what proportion? All this needs to be seen, in conjunction with using all reasonable efficiency measures available.

In this book I consider the costs of the technologies required and show how varying the mix of these technologies can minimise the cost.

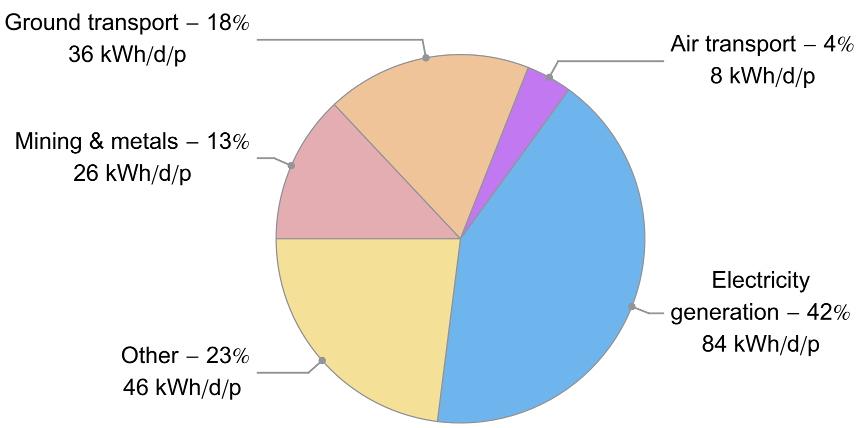

Figure 1. Composition of Australia's Energy use.

1.1 How much energy are we using?

David MacKay puts Australia's energy use[12] at 190 kWh/day/person (kilowatt-hours per day per person). By the time I was writing this it had risen to 200 kWh/day/person. It was divided as shown in Figure 1. I have compared it with David Mackay's estimate of 125 kWh/day/person, (p.104 SEWTHA)

> *"What about the average European and the average Brit? Average European consumption of primary energy (which means the energy contained in raw fuels, plus wind and hydroelectricity) is about 125* kWh/*day*/*person. The UK average is also 125* kWh/*day*/*person."*

David MacKay also says

[12] Don't use 'energy consumption' – you can't consume energy, just convert it to another form or let it pass you by, but it continues to exist.

> *"Our estimate of a typical affluent person's consumption (Figure 18.1) has reached 195* kWh/*day"*

You could say that Australia is a nation of *pretty affluent people*.

2 What can we do?

This segment reviews most of the known options that should be considered for an Australia wide Sustainable Energy Model.

2.1 Solar

With 32 times the area and one third of the population in a place that is twice as sunny as the UK, you might think that solving the problem is a no-brainer. Well yes and no. Let's do a few calculations, using solar as a starting point.

At an energy use of 200 kWh/day/person, how much of Australia would need to be covered with solar panels (or troughs or dishes) to manage on solar alone? Assume the solar irradiance in Table 1 and Figure 2[13].

2200 kWh/m^2/year = 2200/365 = 6 kWh/m^2/day or 6000 Wh/m^2/day.

At a panel (system) efficiency[14] of 10%, each Australian would need 200/6 x 10 = 330 m^2 of solar collection area. For 20% efficiency it would be half that area, but as we will see, other issues will bring the figure back up again.

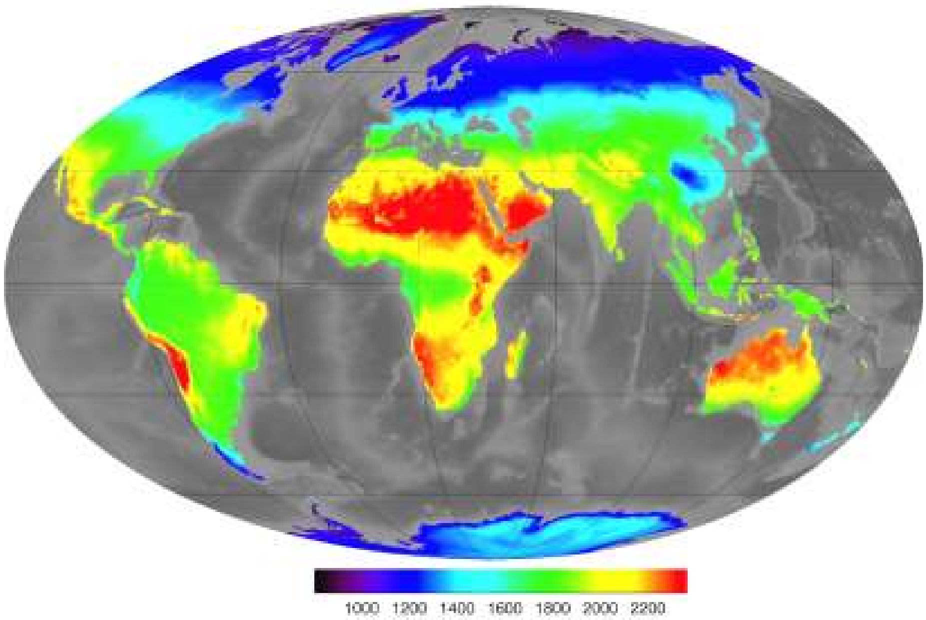

Figure 2. World solar irradiance. A large tract of Australia is in the range 2200 – 2400 kWh/m^2/year (or 6–7 kWh/m^2/day).

[13] http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/global.cgi?email=global@larc.nasa.gov
[14] p. 41 SEWTHA.

The theoretical power per land area is 6000/24/10 = 25W/m^2 at 10% efficiency. This includes the latitude of the installation[15].

However, the more a solar collection system is optimised for return on investment, the greater the land required will be. The optimal angle for maximum annual output for a fixed flat panel is an inclination of approximately the latitude angle. Consider the panels shown in Figure 3 and Figure 4. At the angle shown, you will see that these panels will shade a considerable distance behind them. In winter the sun will be 23° lower, adding to the required spacing. If the panels track the sun in an east-west direction, only the first row of panels will catch the rising sun.

Figure 3. Clever tracking solar array. Cylinders of ammonia on each side of the array are connected by a tube. Shading is arranged so that when the sun hits the cylinder on one side, the fluid boils and passes to the other side where it condenses. The weight tilts the panel until the cylinders are equally shaded. These panels are at Broome at latitude 17°S.

Consider too that for some of the time in summer, at the beginning and end of the day, the sun is actually behind the array.

If maximal solar collection for a given land area is the main consideration, panels which are horizontal or very close to it are the most efficient collectors per

15 I have assumed that the land area required is the same as the panel or collector area. As you move away from the equator, the horizontal land area required must be greater. If the solar power system is at say 25° from the equator, this adds 10% to the land area. At 35° it adds 22% to the land area. See page 38 of SEWTHA.

unit area, but not per unit of collector area. The point here is that if you want to minimise the amount of land required, then the efficiency of the equipment is compromised. On the other hand to get the maximum efficiency out of the equipment, a generous land area is required. In general, in Australia, the highest equipment efficiency approach is appropriate.

Figure 4. Concentrating solar thermal mirrors similar to those planned for the Cloncurry power station.

To use a practical example, a planned solar installation in Mildura[16], Victoria, has a peak output of 154 MWe. This system is based on reflectors focussed on photovoltaic collectors which are water cooled to keep them functioning efficiently and prevent them from melting. The system has an average power of 30 MW and occupies 600 – 800 hectares, say 700 ha. So that's about 4.3 W/m^2.

Another system built in Tucson Arizona, delivers 6 GWh/year on a 18 ha site. This is 4.5 W/m^2.

Having said that, there is a complex of nine solar thermal power stations at Daggett, Kramer Junction and Harper Lake in the US which were built between 1984 and 1990. This complex has a total average power output of 75 MW (354 MW peak) and occupies 6.5 km^2 giving an average power of 11.7 W/m^2.

It is not clear why systems that were built nearly 20 years ago, and which are still in operation have such a high output compared with similar systems built much later. But let's take the least optimistic path and assume 4.5 W/m^2. At this

[16] Unfortunately at present in limbo through lack of financial support.

power density, each Australian would need 7900/4.5 = 1800 m^2. David MacKay mentions values between 10 and 15 W/m^2[17].

Figure 5. An excellent illustration of why it is difficult to collect sunshine from all the land. At noon only one third of the sunshine hits collectors.

For 22 million Australians, that's 22 million x 1800 = 40,000 km^2. That's a square of 200 km. Noting that Australia has an area of 7,600,000 km^2, this is about 0.5% of the area of the country.

It would appear that land area is not the issue here. Given that land in the areas we are talking about can be bought for around $1 per acre, or $2.5 per hectare, the cost of that land is also not an issue. Even at this relatively low power density, the cost of the land required could be as low as 45 cents per person.

Using the example of the Cloncurry[18] Thermal storage solar power station[19,20] with an output of 10 MW peak at a capital cost of $31 million, the capital cost per average (not peak) watt is $15.

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17 p. 178 SEWTHA

18 Australian company, Lloyd Energy Storage, use a graphite block storage system with mirrors each three metres by two metres which reflect the sun's rays up into 50 10-tonne blocks atop 15-metre towers. Enough heat will be stored in the blocks to meet overnight demand. http://www.lloydenergy.com/presentations/Cloncurry\%20Solar\%20Thermal\%20Storage\%20Project.pdf

19 http://en.wikipedia.org/wiki/Solar_thermal_energy#Levelised_cost, states 30 GWh/year, which would be 3.4 MW average. I doubt it since the next reference states 10 MW peak = equivalent to 2 MW average for that area.

20 http://www.cleanenergy.qld.gov.au/cloncurry_solar_thermal_power_station.cfm

Figure 6. 200 km by 200 km square which would be sufficient to provide all of Australia's gross energy use from solar power at the conservative figure of 4.5 W/m^2. David MacKay uses 15 W/m^2. Note that in terms of end-use power, only half of this area would be required.

2.2 Wind

Using current technology, small community wind farms[21] are being built at about $8/average watt. The advantage of wind power installations is that they can be built closer to population centres and can share land with farming. However the power per unit land area is only 2 W/m^2, which is lower than the 4.5 W/m^2 produced by large scale solar[22]. To supply all of Australia's energy needs from wind power[23] would require something like 4000 m^2/person. Given the considerable outrage from many people, especially environmentalists, obtaining this amount of land in visible and accessible places is likely to be difficult. An approach of *buy in* by community members can considerably smooth the path. An example

[21] http://www.hepburnwind.com.au/

[22] p. 33 SEWTHA.

[23] In one example SEWTHA talks about wind turbine spacing on a grid as being 5 diameters in every direction. Wind turbines are not set up like this but are in fact set out 5 diameters between turbines in the prevailing wind directions on and 2 – 3 diameters in other directions from which the wind blows less often.

is the Hepburn community wind project referred to above. This project is being pursued as a model for future wind power expansion.

It is said that wind power, if dispersed over a large enough area, can provide continuous power in a way that is similar to fossil fuel power stations. I don't agree with this. True, on some occasions the wind will be blowing in one area when it is calm in other places. However the graph in Figure 7 is a concern. Look at the South Australian and Victorian wind farms. Despite being some 1000 km from each other, the similarity between their outputs is very striking. The report that this graph comes from shows that the correlation over 30 minute time periods is very low but over a longer time period it is not.

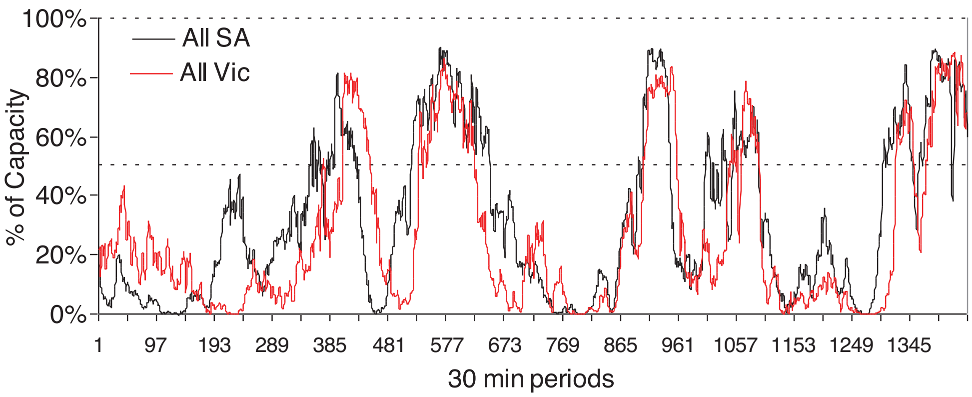

Figure 7. From Wind Farming in South East Australia.

I will return to the topic of dispersed supply and renewable sources complementing each other, later.

2.3 Offshore wind

As SEWTHA notes (p. 70) offshore wind power is about twice as expensive as land-based power. Given that Australia has ample space for land-based wind power, the only reason to consider offshore wind would be population resistance to land-based wind farms.

2.4 Geothermal

SEWTHA dismisses Geothermal energy relatively quickly as the UK and European resources are rather small. Basel had a rather unfortunate consequence of its attempts to utilise geothermal power[24]. Australia is only moderately well endowed with this resource, namely in the area of Hot Fractured Rocks.

24 http://www.swissinfo.ch/eng/front/Geothermal_project_lands_in_hot_water.html?siteSect=105&sid=7487307&cKey=1170398930000&ty=st

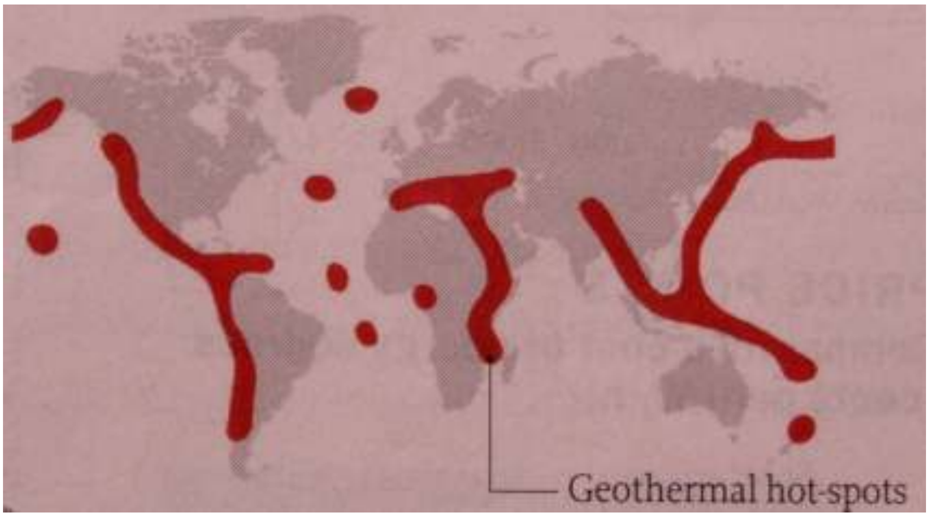

Figure 8. Australia is not even on the map of global Geothermal power – from Wikipedia.

Heat is generated by radioactive granites containing uranium, thorium and potassium, 3km or more below the Earth's surface. The heat inside these granites is trapped by overlying rocks which act as an insulating blanket. The heat is extracted from these granites by circulating water through them in an engineered, artificial reservoir or underground heat exchanger.

HFR geothermal energy uses existing technologies and engineering processes such as drilling and hydraulic fracturing; techniques common in the oil and gas industry. Standard geothermal power stations convert the extracted heat into electricity. Hot rock power is mentioned in SEWTHA as being liable to create earthquakes, such as in Basel. Fortunately in Australia the candidate locations are extremely remote and this is much less likely to be a problem.

A major advantage of geothermal is that it can provide continuous power.

Reports by the Wilson HTM investment group Geothermal Energy in Australia summarise the measured, indicated, inferred and total geothermal resources of Australia. Measured, indicated and inferred are specialist terms used in the mining industry to indicate levels of confidence and their definition is outside the scope of this book. Suffice to say that inferred can be tens or hundreds of times the measured resource. Total, is the sum of the three, i.e. it includes all categories. Between June 2009 and February 2010 the total as reported by Wilson HTM increased by 24% so this is a rapidly changing field.

Assuming that the total approximates reality, and lasts 400 years, as claimed by Geodynamics Ltd, 200 kWh/day/person of heat and 20kWh/ day/person of electricity could be delivered. This is because a geothermal power station works at a lower thermal efficiency than a conventional power station, about 10% rather

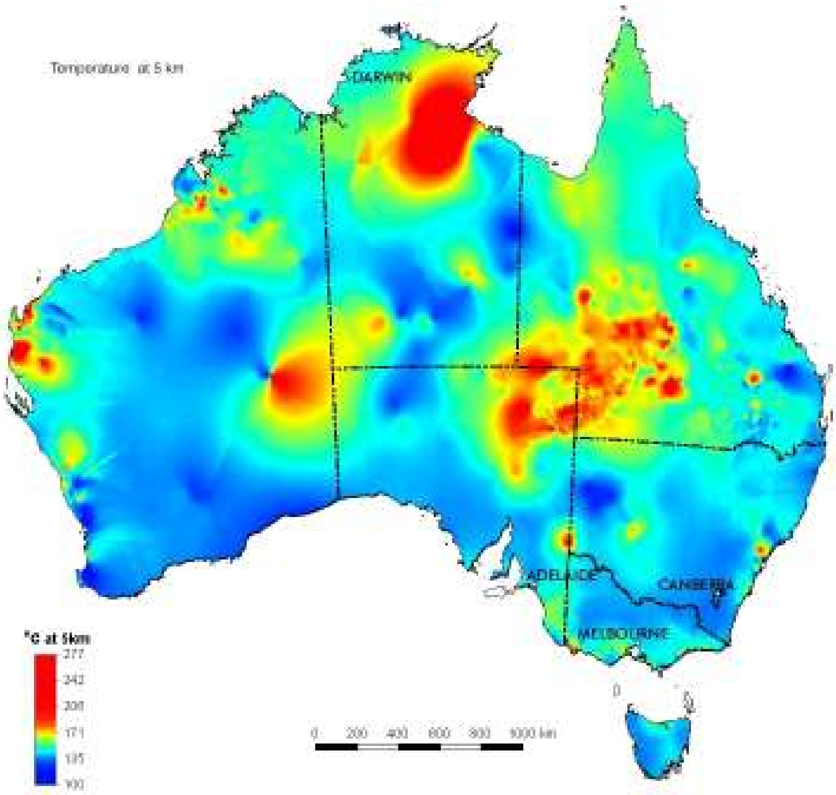

Figure 9. Estimated temperatures at 5 km depth in Australia. The most prospective areas for geothermal energy are shown in red.

than 25 - 40%. Assuming it displaces fossil fuel generation at 25% efficiency it is equivalent to about 80 kWh/day/person primary energy input. In terms of end-use electricity it is about 800 watts per person. Geodynamics states in their prospectus that their tenements have been assessed through preliminary studies that suggest they contain the energy to support power development of around 10 GW or about 500 watts per person.

Although geothermal is important because of its continuous power capability, it is not enough in itself to solve our energy problems in the long term. As pointed out on page 98 of SEWTHA, geothermal energy is a bit like mining. It doesn't get replenished at anything like the rate you can take the heat out. However, if we were prepared to bend the rules a bit and exhaust the resource over 80 years instead of 400 years, that figure of 20 kWh/day/person would be 100 kWh/day/person, a half of our gross use, or considering that it would already be in end-use energy rather than fuel, to be burned at 30% efficiency then we are right into the realm of a significant contribution. Hopefully over the 80 years we would be able to make better use of truly renewable resources.

2.5 Geothermal energy under coal mines

The idea of using old coal mines to extract low level heat has been previously explored. However a new development in Australia has been the discovery that under open cut coal mines, the temperature may be quite usefully high for electricity generation. The high temperatures are insulated by the thick layer of coal such as in the Latrobe Valley in Victoria, the site of existing open cut coal mines[25]. A major advantage would be that these sites are as close as you could hope to be, to existing electric power generation infrastructure. A project, called the Victorian Geothermal Assessment Report (VGAR), is under way at Melbourne University's Energy Research Institute[26] headed by Rachel Webster, professor of physics, and Edwin van Leeuwen, former head of BHPB's Global Technology Group. Watch this space!

2.6 Wave Power

The map in Figure 10 is from the Australian government website[27].

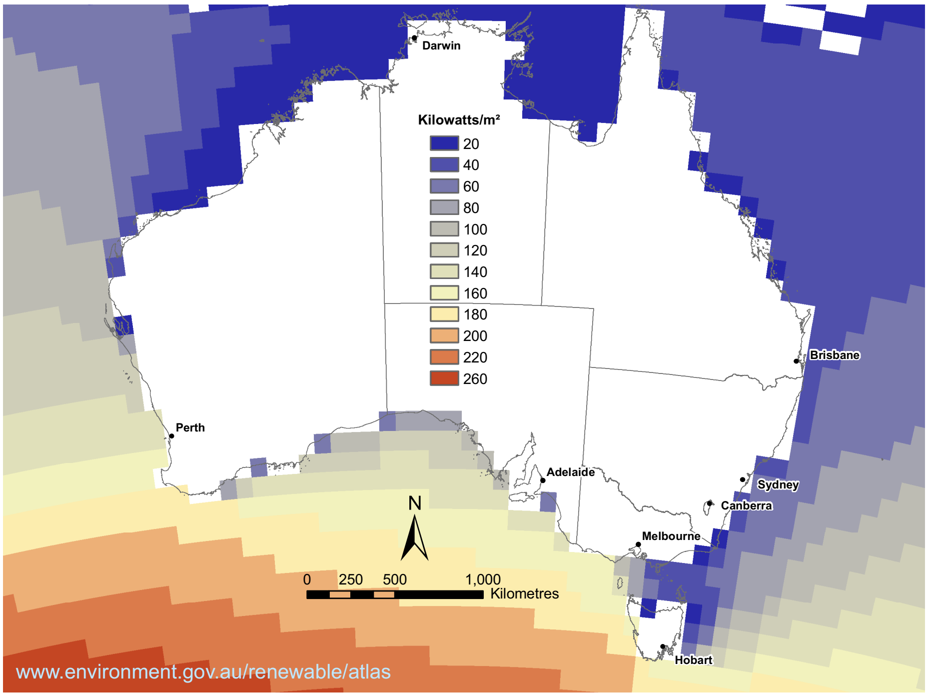

Figure 10. Australia's wave power resources are mainly from the south and south-west. Note that the caption says *Highest Wave Power*. Average power is not given.

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25 http://www.inside.org.au/the-new-geography-of-geothermal-energy
26 http://www.energy.unimelb.edu.au
27 http://www.environment.gov.au/settlements/renewable/atlas/maps.html

According to this data, about 4000 km of the southern and southwestern coasts are exposed to wave power[28] between 100 and 160 kW/m. Assuming 130 MW/km this would give a gross power of 130 x 4000 = 520 GW.

It is worth noting that Australia has significant freshwater problems and desalination is a power intensive process. A device developed by Alan Burns of Carnegie Corporation CETO[29] uses submerged buoys just beneath the surface to pump high pressure seawater to a conventional reverse osmosis desalination plant and turbine to generate electricity. Desalination plants already require high pressure water so there is some synergy here. It is claimed that the ratio of electrical generation to fresh water production can be quickly varied from 100% to 0% allowing for rapid variations in power demand.

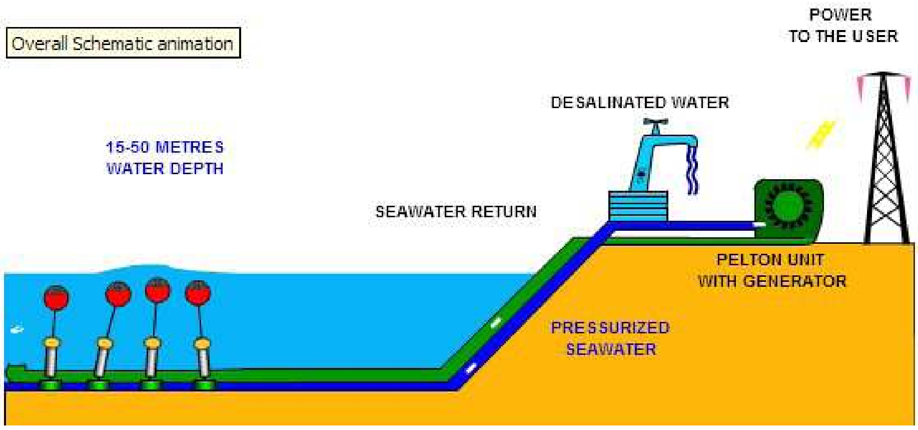

Figure 11. CETO Wave power system.

The conversion efficiency to electricity is not stated on the Carnegie CETO website. Nor does the website say what length of coastline their 50 MW pilot installation will occupy so it is not possible to calculate it. Let's assume the worst, as described on page 75 of SEWTHA where 5% of the gross power was extracted by the Limpet. On this assumption, 520 GW corresponds to 0.05 x 520 = 26 GW which would be 1300 W/person or 30 kWh/day/person.

The technology differs from other wave energy systems by pumping water directly ashore under high pressure rather than generating electricity offshore and transmitting it back to shore via high voltage cables.

[28] The legend says kW/m^2 but this is probably kW/m.
[29] http://www.carnegiecorp.com.au/index.php?url=/ceto/ceto-overview

Figure 12. Buoys used for an ocean powered combined desalination and electric power generation plant. From Carnegie website.

In an RPS MetOcean study[30], commissioned by Carnegie, the total estimated deep water wave resource for the southern coastal region of Australia, from Geraldton in Western Australia around to the Queensland-New South Wales border, was estimated to be in the order 170 GW in depths of around 25 metres.

However the report says 10% of that amount – 17 GW is economically extractable. This would be just 770 W/person or 18 kWh/day/person.

RPS MetOcean, claims the wave energy, powered by the circumpolar Southern Ocean, has 97.5% availability making continuous power generation possible.

As mentioned in SEWTHA (p. 310) typically 70% of the energy in ocean waves is lost through bottom friction as the depth decreases from 100 m to 15 metres.

A pilot 50 MW plant is to be announced shortly, at a cost of $300 Million. That would be about $6/average watt, slightly better than wind if it is true. Given that this is developing technology and not production equipment as with wind and solar, the costs, if successful are likely to come down.

A somewhat similar wave powered desalination plant is mentioned on page 310 of SEWTHA. The Oyster, developed by Aquamarine Power uses rigid structures fixed to the seabed rather than buoys. It is similar in that both devices pipe high pressure water to the shore[31] rather than trying to use it in-situ. The Oyster is also designed for desalination.

30 http://www.lloydenergy.com/presentations/Cloncurry\%20Solar\%20Thermal\%20Storage\%20Project.pdf

31 http://www.aquamarinepower.com/technologies/

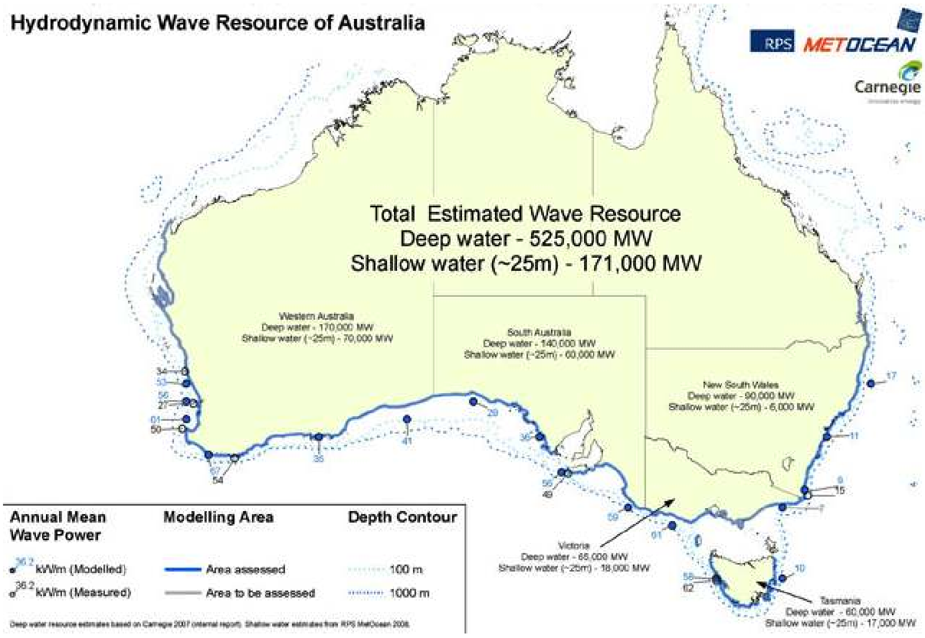

Figure 13. From a study by RPS MetOcean commissioned by Carnegie Corporation.

Another Australian company is Oceanlinx[32], founded by Dr. Tom Denniss (as Energetech Australia Pty Limited). This company uses an inverted container in which the air is compressed and expanded by the motion of the waves. An air turbine is installed in the outlet. This turbine uses variable pitch blades to keep the turbine running in the same direction as the air reverses. Oceanlinx has six projects underway, mostly comprising 1.5 MW modules, with a 15 MW array planned.

From all appearances, wave power is not to be ignored in Australia but can only make a minor contribution to renewable energy. The only way to supply a big chunk of Australia's power would be at the cost of taking a big chunk of the coastline whereas resources like wind and solar only use a fraction of a percent of our land.

2.7 Tidal

The northwest of Australia is identified as an area with significant tidal power capability. A quote from the Australian Institute of Energy:

> *"The North West of Australia has some of the highest tides in the world with up to 10 metres. Tidal power has been proposed in the Kimberley region of Western Australia since the 1960s, when a study of the Derby region*

[32] http://www.oceanlinx.com/history.html

Figure 14. Oceanlinx installation as seen from Google Earth.

> *identified a tidal resource of over 3,000* MW. *In recent years a proposal to construct a 50* MW *tidal plant near Derby was developed by Derby Hydro Power."*

The opposition to this Tidal project was very stiff on the grounds that it would damage the mangroves. A debate on the topic is to be found on the ABC website[33]. In any case, 3 GW spread over 20 million people is only 150 W each or 3.6 kWh/day/person.

Closer to a population centre, how about Port Philip Bay, where Melbourne is situated? The Bay is about 50 km in diameter and has an opening at the heads only about 3 km wide. Shipping would preclude damming this opening but could we use underwater turbines to capture the tidal energy passing through the heads? The body of water in the Bay has a tidal range of only about 0.75 metres but an area of 188,000 hectares. Over a tidal cycle an average of about 400 MW of power passes though that opening. Optimistically, if about 10% of this could be captured, that would be 40 MW, or about 10 W per Melbournian or 0.5 kWh/day/person – not nearly enough to warrant the furore that it would create. As it turns out, Tenax Energy Pty Ltd is planning a project along these lines to generate 34 MW (unknown if peak or average). The Victorian National Parks Association[34] has this to say:

> *"The proposal has potential to have a significant footprint with the establishment of 45 tidal turbines and 2 km of marine cable over an area of*

[33] http://www.abc.net.au/rn/science/earth/stories/s169239.htm

[34] http://vnpa.org.au/admin/library/attachments/Marine/Tenax\%20Energy\%20Turbine\%20Referral \%2013.10.08.pdf

169 ha. The cable will connect the turbines to the Pt Lonsdale electricity grid. Victorian National Parks Association (VNPA) believes this project is likely to have a significant impact on the immediate and surrounding marine ecosystem."

Tenax has two other projects[35] under consideration in Banks Straight Tasmania (320 MW) and Clarence Straight NT (450MW). Three more companies[36] also have submitted planning applications for tidal power totalling 50 MW.

2.8 Hydro

The total installed hydro generation plant in Australia is 8.5 GW. This supplied 6.1% of 226,000 GWh of electricity generated in Australia in 2006 – 07. This is an average of 1.6 GW. Hydro power in Australia provides about 80 W/person or 2 kWh/day/person.

In the last 12 years much of the southeast of Australia has experienced below average rainfall. The Eucumbene dam, the largest dam of the Snowy mountains scheme (the largest scheme) has had continually reducing levels[37]. Figure 15 is typical of the state of dams in southeast Australia in the last decade.

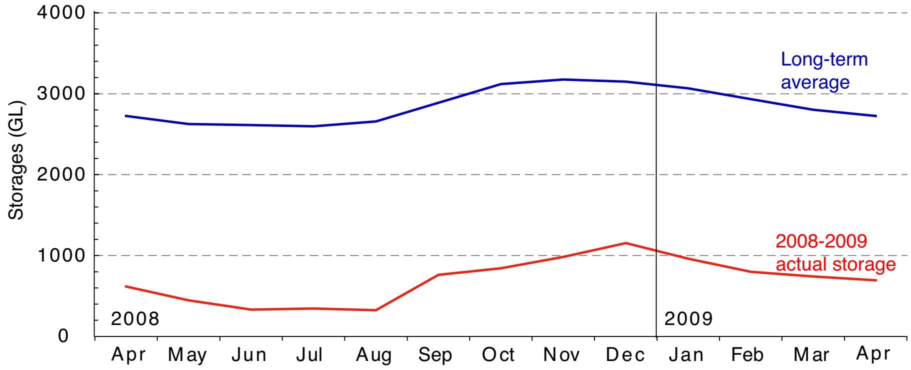

Figure 15. Snowy hydro storage levels for 2008-2009 compared to long-term average storage[38].

Like tidal power, hydro is likely to encounter stiff resistance to any major new projects. Indeed there has been ongoing discussion[39] of actually draining Lake Pedder a previously flooded Tasmanian wilderness. Environmentalists scored a

35 http://www.tenaxenergy.com.au/projects.html
36 http://www.abareconomics.com/interactive/09_Listings/eL09_Oct/
37 http://www.snowyhydro.com.au/lakeLevels.asp?pageID=47&parentID=6
38 http://www.snowyhydro.com.au/files/SHL_WaterReport_0809.pdf
39 http://www.aph.gov.au/house/committee/environ/peddinq/peddrpt/contents.htm

major win in blocking the development of the Franklin River in Tasmania. However, the role of hydro could be increased without extra dams being constructed. A quote from A National Energy Grid for Australia:

> *"Presently hydro provides 6.7% of electricity generation but up to 18% of short term peak capacity (8.5 GW). This could be expanded to 13.5 GW by the addition of 5 GW pumped storage capacity, to the existing 1.2 GW capacity, if improved transmission capacity was available."*

However, apart from the very important role of storage, it would be unrealistic to expect any further contribution from hydro to renewable energy in Australia.

2.9 Pumped storage

In theory, there appears to be a reasonable potential for hydro facilities for pumped storage. In the Snowy Mountains[40] vicinity alone, there are four major dams.

Dam	Volume Gigalitres	Altitude metres	Head (from Eucumbene)	GWh @ 75% efficiency
Eucumbene	4500	1156	-	-
Lake Jindabyne	690	914	242	340
Talbingo dam	920	545	611	1148
Blowering dam	1628	380	803	2570

Table 2. Theoretical pumped storage capacities of the Snow Mountains hydro system dams.

The figures in Table 2 are rather hypothetical in that they do not take into account the practicalities of piping water from one reservoir to another, although it is already done on a much smaller scale. The figures of thousands GWh storage compare very favourably with those in table 26.4 page 191 of SEWTHA which total 30 GWh. At the outrageous consumption of 200 kWh/day/person the Snowy storages could support the country's gross energy needs for about two days. This would not be required, since we would be storing end user electrical energy, not fuel yet to be burnt. The requirements would hopefully be lower too. It all comes down to how much civil engineering would need to be done and how much it would cost. Considering these dams as storage to supply the existing average electrical load of 25 GW, they could supply the county's electricity for two weeks.

40 http://www.powerhousemuseum.com/hsc/snowy/civil.htm

41 http://www.visitadaminaby.com.au/images/BROCHURE.pdf

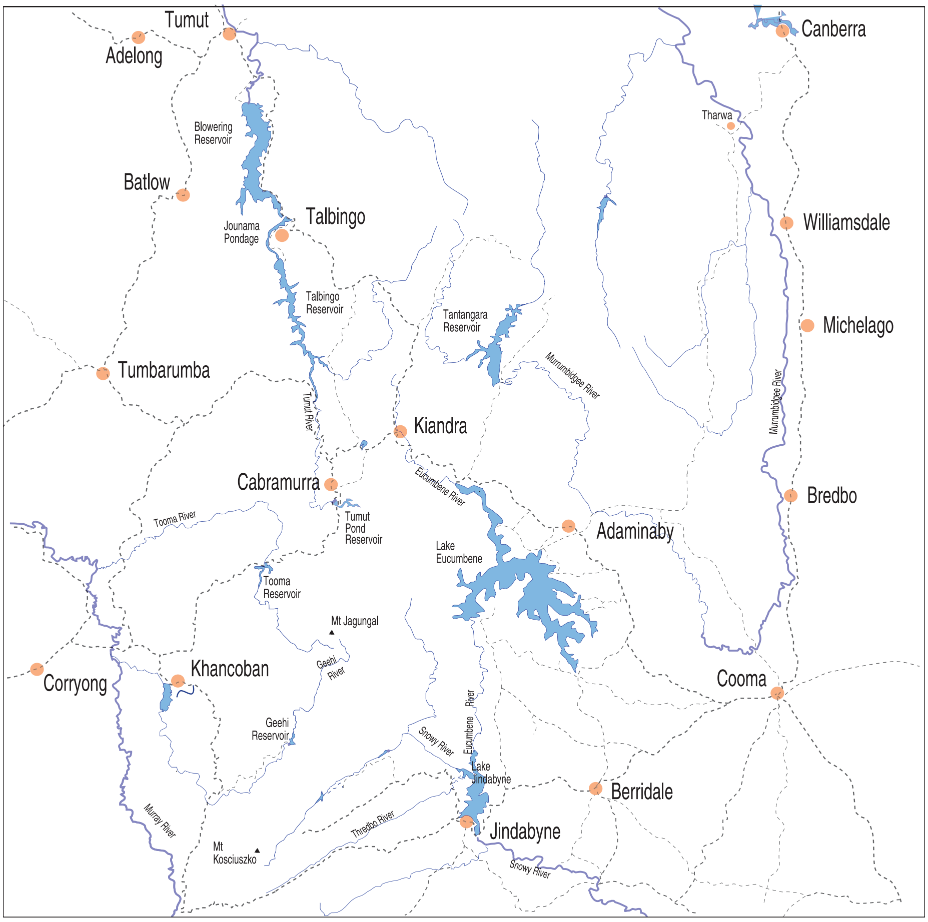

Figure 16. Snowy mountains water storages[41].

2.10 Biofuels – Bioethanol

Of the biofuel ideas on offer (p. 284 SEWTHA) bioethanol from sugar cane appears to be the most promising. Sugar cane grows well in Queensland where there is lots of water. Its power density is 1.2 W/m^2. If we assume that cars and planes amount to 37 + 8 = 45 kWh/day/person, we would need about 40,000 km^2 or about 9% of Australia's arable land. So we would need about 0.2 ha or 2000 m^2 per person. To supply our existing liquid fuels needs, we would need 10 times as much area as is already farmed for sugarcane[42].

Biofuels[43] from growing woody plants in the arid areas of Australia is showing good promise. Large areas are available and the process of fermenting cellulose is looking economic. *The Ligno cellulosic* process produces 350 L ethanol/tonne cellulose as opposed to sugar 600 L/tonne. However in the arid parts of Australia

[42] The area of irrigated land used for growing sugar cane in 1999 – 2000 was 200,000 ha. A similar areas is non-irrigated – a total of about 4000km^2.

[43] Bill Malcolm, University of Melbourne, personal communication.

the growth rates are much lower than for sugar cane so perhaps we would need 10 times the area of sugarcane approximately 500,000 km^2 which is similar to all of Australia's arable land and 10% of agricultural land.

If we needed to supply only Australia's fuels for flying from biofuels, a sixth of these areas would be required, something that appears more feasible – about 1.7% for agricultural land or about 1.7 times the area already used for growing sugarcane or a combination of the two.

2.11 Clean coal, carbon capture and storage

The terms *Clean Coal* and *Carbon Capture and Storage*, CCS are not well defined and are often used interchangeably. Logically, Clean Coal would simply refer to the burning of coal more efficiently. Such projects are under way. For example a process being developed by Ignite Energy Resources[44] improves the energy yield of brown coal by 30%. That doesn't make it any cleaner than black coal.

CCS on the other hand would take the process a step further and sequester the CO_2 that is produced.

Page 158 of SEWTHA mentions that the role of government should be to take the risk out of clean coal technology by building demonstration plants. Clean coal is the Australian government's favourite and a number of projects are under way[45]. Four projects are listed in the appendix. The government has promised $2.4 billion over the next nine years. The coal industry itself has committed $1 billion of its own money. Nevertheless, the government's own CCS institute has advised that clean coal power stations would not be viable until about 2030.

Coal is not renewable energy so neither is clean coal. Nevertheless, since we have so much of it, if the CO_2 could be completely sequestered, in theory it would solve our CO_2 emissions problems for a long time. For a good summary of the topic, I found a report by the World Nuclear Association balanced and informative[46]. The New Scientist has run a number of articles but their editorial[47] of 9th February 2008 is a good starting point.

In September 2009 a huge natural gas project was announced off Western Australia's Pilbara coast. The project is led by Chevron, in conjunction with Exxon and Shell, and is said to be the world's largest CCS project. Quoting from

44 http://www.Igniteer.com
45 http://www.newgnecoal.com.au
46 http://world-nuclear.org/info/inf83.html
47 http://www.newscientist.com/article/mg19726423.300-editorial-come-clean-on-coal.htm

the Australian Journal of Mining, which one could assume would put the most favourable spin on the project:

> *"While the Gorgon Project is set to operate the biggest underground storage site of CO_2,* ***it won't actually help Australia to lower its greenhouse gas emissions****. The CCS part of the program will sequester 40 per cent of the operation's total emissions which could be in the order of six to eight million tonnes per year.* ***The liquefaction of natural gas is a greenhouse gas intensive process, however the downstream use of LNG for power does reduce emissions by 34% compared with coal-fired power****."*

Given that gas fired electricity generation is already about 50% lower than coal-fired power in CO_2 emissions, a 34% reduction does not appear to be progress. The project is somewhat clouded by the fact that the electric power generation is only part of the operation, which is mainly a gas exporting operation.[48]

2.12 Carbon capture and conversion to biofuel

Here's a way to use carbon capture without storage to some benefit. Pages 284 and 285 of SEWTHA, *What about algae*? and *What about algae in the sea*?, deal with the idea of growing biofuels in CO_2 rich ponds. David calculates that even at 4 W/m^2you would need 420 square metres of pond per car.

> *"If all the CO_2 from all UK power stations were captured (roughly 2.5 tonnes/ year/person), it could service 230 square metres per person of the algal ponds described above – roughly 6% of the country."*

And that would for the UK be a rather unlikely scenario.

Let's look at the figures for Australia. Firstly, whilst the UK currently produces 2.5 tonnes of CO_2/year/person for electricity generation, we produce something like 10 tonnes. If the CO_2 from half of that were used for biofuel production, that would cover all our existing liquid fuel use.

Table 3 gives the details. Rather than 6% of the area of the country, it would cover 0.16%. However this would not necessarily be the best option, since (if we did nothing else) we would still be producing 15 tonnes of CO_2/year/person. It would be far better to decarbonise everything possible and use the remaining CO_2 to do only the part which can't be electrified. That is flying. A commercial electric aeroplane is not on the technological horizon[49]. However,

[48] http://www.austmine-event.com.au/news/september/september-10th-09gorgon-set-to-be-world2019s -biggest-CO2-storage-project

[49] A recreational plane is however available! See http://www.electraflyer.com

if we grew biofuels for aviation alone, we would be producing only 0.7 tonnes of CO_2/year/person. This would not be using renewable energy, it would just mean that the CO_2 wouldn't go into the atmosphere immediately, it would go into growing a fuel which is burnt and ***then*** go into the atmosphere.

Fuel	CO_2 tonne/person/year
Black coal	9.7
Brown coal	3.0
Petroleum	5.1
Natural gas	2.7
Total	**20.4**
Transport (ground)	4.4
Aviation	0.7
Electricity generation	10
Total	**15.1**

Table 3. Sources of CO_2. 10 tonnes/person/year is produced through electricity generation. If 5 tonnes of this were captured, it could be used to grow biofuels to cover our use. Only 0.7 tonnes would be needed to grow the fuel needed for flying.

So in summary, in Australia there is plenty of area to grow biofuels from Algae and there would be ample CO_2 feedstock. However it can only go halfway towards solving the problem. The CO_2 ends up in the atmosphere anyway. If we were hooked on carbon capture and continue to be hooked on liquid fuels, then it would make more sense to reuse CO_2 rather than store it at great expense somewhere whilst elsewhere burning some liquid fuel and putting that CO_2 into the atmosphere.

If we did go the path of growing biofuels from the emissions of fossil fuelled power stations, some promising technology appears to be emerging. One such process claims to produce 300,000 tonnes per year of biodiesel from a 5000 ha (50 km^2) *unit*.

> *"PetroAlgae-produced green diesel is designed to run in any standard diesel engine, is refined in existing refining facilities and is compatible with existing fuel infrastructure."*

It is claimed to be capable of utilizing non-arable land, recycling 98% of the water and is not competitive with food growing. It claims to be able to be used in combination with steel and coal-fired power plants, cement factories and manufacturing facilities.

Claims of this sort are very common and a startup company WM Moss Jr. Corporation claims *"algae cultured at industrial scales can produce over 100,000 gallons of oil per acre each year."*

This is equivalent to 105 W/m^2 or 42% of the incident radiation on the sunniest places on the planet.

Based on the more believable figures claimed by PetroAlgae at 6.3 Wm^2, all Australia's petroleum based fuels could be grown on 5000 km^2or a 70 km x 70 km square. This is 0.1% of the area of Australia or 230 m^2/person.

PetroAlgae is in some illustrious company, Craig Venter, founder of the Human Genome Project, has joined with Exxon in a $600 million oil from algae project. Venter in an interview with New Scientist in 2007 said

"Over the next 20 years, synthetic genomics is going to become the standard for making anything. The chemical industry will depend on it. Hopefully, a large part of the energy industry will depend on it. We really need to find an alternative to taking carbon out of the ground, burning it, and putting it into the atmosphere. That is the single biggest contribution I could make."

The Venter – Exxon venture, in press releases is quoting potential yields of 30,000 – 50,000 L/ha/year, of the same order as PetroAlgae.

High yield algae suffer from the potential problem that, in contrast to wild algae, they have no immunity to disease, so could be easily knocked-off by an infection.

2.13 Biochar- Negative carbon fuels?

We have seen that if we wanted to grow enough biofuel to meet our liquid fuel requirements, growing sugarcane would overwhelm the current level of agricultural activity. We could provide some of our needs for biofuel from algae grown in large ponds fed by CO_2 from fossil fuelled power stations, also not a complete solution. Is there another way?

An article in Nature, *Black is the New Green: putting the carbon back*[50] methods are described in which farm waste is smouldered or pyrolysed, giving off volatile organic molecules, which can be used as a basis for biodiesel. After the pyrolysation, half of the starting material is used up and half will be char. That can then be put back on the fields, where it will sequester carbon and help grow the next crop. A for-profit, for social-purpose enterprise called Eprida is developing this concept.

50 Black is the new green: Putting the carbon back Nature 442, 624-626 (10 August 2006); Published online 9 August 2006.

"Combining this char with ammonium bicarbonate, made using steam-recovered hydrogen, creates a soil additive that is now one of his process's selling points; the ammonium bicarbonate is a nitrogen-based fertilizer."

Eprida works with NREL, National Renewable Energy Laboratory and ORNL the Oak Ridge National Laboratory. With associations like this and an article in Nature their claims deserve scrutiny.

It is claimed that this process can sequester carbon at the same time as producing useful fuel. Robert Brown, an engineer at Iowa State University in Ames, says that

"250-hectare farm on a char-and-ammonium-nitrate system [using corn stalks] can sequester 1,900 tonnes of carbon a year. A crude calculation on that basis suggests the US corn crop [stalks] could sequester 250 million tonnes of carbon a year."

Using these figures, how much of Australia's CO_2 emissions could be sequestered using these methods? At 20 tonnes CO_2/year/person, that would require 2% of Australia's area. About 6% of Australia is arable, so that would be about a third of our arable land. The point here is however that the land would not be used exclusively for sequestering carbon or growing fuel. This is a by-product of existing agriculture. Note that this area would be sufficient to sequester all our CO_2 emissions from all sources, not just our transport emissions. Table 3 shows that about a quarter of our emissions are due to transport so it would appear that Biochar could be a way of negating our emissions from that source without using any extra land.

Does 1900 tonnes of carbon a year on a 250 ha farm make sense? SEWTHA (p. 246) says

"The best plants in Europe capture carbon at a rate of roughly 10 tons of dry wood per hectare per year – equivalent to about 15 tons of CO_2 per hectare per year."

That's 15 x 12 / 44 = 4 tonnes of carbon/ha/year compared to the Eprida figure of 7.6 tonnes of carbon/ha/year. So maybe the claim is optimistic.

I said that the Eprida process can produce fuel at the same time as sequestering carbon. Figures are not given. It appears that the process can be tweaked. Day [founder of Eprida] says

"We don't maximise for hydrogen; we don't maximise for biodiesel; we don't maximise for char ... By being a little bit inefficient with each, we approximate nature and get a completely efficient cycle."

Whilst the sources for this information appear reputable, the idea that about twice as much carbon is being sequestered per hectare as the best plants in Europe and biofuel is being produced at the same time, you have to wonder.

How long could this go on for? The argument is that this has already been done over a very long time in the Amazon Basin. *Terra Preta* patches metres deep were once agricultural areas that the farmers enriched with charred trash of all sorts. Some soils are thought to be 7,000 years old. Compared with the surrounding soil, terra preta can contain 9% carbon, compared with 0.5% for plain soil from places nearby.

In Australia, Stephen Joseph of the University of NSW set up a company; Biomass Energy Services & Technology Pty Ltd. In 2007 this company was building increasingly larger plants to implement biochar processes. Following up in 2009 led to Best Energies based in Wisconsin. The information on the site[51] refers to biodiesel agricultural oils and animal fats as its feedstocks. So the hype of Eprida appears to have largely evaporated.

2.14 Thorium fuelled nuclear power

Thorium is a fuel that can be used in nuclear reactors but produces very little nuclear waste and what there is, has a half-life of hundreds, rather than millions of years. Thorium reactors are what is called sub-critical, so no runaway reaction can occur. Furthermore, thorium is 10 times as abundant as uranium and Australia[52] has 20 - 25% of it! Sounds too good to be true? Maybe, and certainly if you search on the web[53] [54] you can find plenty of both criticism and support for the idea. Norway, which currently bans the use of nuclear power, is now investigating it. India is well advanced in a thorium reactor programme. Obviously the jury is out, but who knows – it might be that a more benign form of nuclear power will emerge.

Thorium is well covered in SEWTHA (p. 166). Thorium is however still under criticism[55].

> *"Because thorium is not fissile, you need either a breeder reactor or an accelerator to produce U-233 which is fissile; then you can "burn" the*

[51] http://www.bestenergies.com/companies/bestbiodiesel_cashton.html
[52] Thorium reserve report: http://tinyurl.com/USGSThoriumReserveReport
[53] http://www.feasta.org/documents/energy/nuclear_power.htm for a scathing review.
[54] http://www.theoildrum.com/node/4971 for a rave review.
[55] Personal communication Mark Diesendorf.

U-233 in an ordinary reactor to generate electricity (or use it to make nuclear weapons.)"

2.15 Fusion and hybrid reactors

I was not planning to include fusion in this book, dismissing it as fantasy as David MacKay described it. It always seems to be 30 years away. However in the past year developments have occurred which make it seem more promising. One is laser fusion where a number of lasers are used to compress and contain isotopes of deuterium and tritium contained inside a beryllium sphere. This could then spark ignition, at which point the deuterium and tritium should undergo sustained nuclear fusion that produces excess energy. The plan is to do this within a year. The work is being done at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California[56]. A layman's report on the project was on the Science Show by Robyn Williams[57].

The other fusion development is the idea of a hybrid reactor in which the fusion takes place within a conventional fission reactor[58]. This approach is said to address the two biggest problems of fusion reactors: the size of plasma required and containment. In a hybrid reactor, the size of the fusion ball required is much smaller than in a pure fusion reactor. The fission reactor provides the containment because it absorbs high-energy neutrons from the plasma, reducing the energy flux reaching the outer wall by a factor of 50. If that is not already enough, the other advantages of a hybrid reactor are:

- It can burn the high level nuclear waste produced by fission reactors
- It overcomes the potential problem of shortages of high-grade uranium because it can run on low-grade uranium or thorium
- The power output of a hybrid reactor can be easily varied, which would allow nuclear power to be combined with renewables

The Institute of Plasma Physics in Hefei, China, is planning to build a prototype by 2020. Both US and UK governments are taking interest in these developments.

Having built up the promise of viable fusion power in the foreseeable future, we come back to earth by reading the article in March 2010 Scientific American *Fusion's False Dawn* by Michael Moyer. Amongst the many problems mentioned

[56] http://physicsworld.com/cws/article/news/41595#comments
[57] http://www.abc.net.au/rn/scienceshow/stories/2010/2844460.htm#transcript
[58] http://www.newscientist.com/article/mg20527505.900-hybrid-fusion-the-third-nuclear-option.html

in the article is that of producing the target capsules of deuterium-tritium fuel. These have to be precisely machined to ensure that they compress evenly from all sides. Currently such pellets cost about $1 million each to produce. A working fusion power plant would need some 90,000 targets per day. Even with a thousand-fold reduction in price; this would be $90 million per day for a power plant that might produce 1 GW. The price of the power for targets alone would still be $4/kWh. A fifty-thousand-fold decrease in the cost of targets would be required to get the price of electricity down to a competitive level. How likely is it that a price reduction of 50,000 times will happen? We could draw parallels with the price of computers or sequencing the human genome. As far as computers are concerned, the uncannily accurate Moore's law predicts a doubling of the number of transistors on a chip every 18 months. That process has been going on for 40 years. If we were to fantasise that the cost of producing targets would follow such a law, in 28 years it would be economical. However there is a big difference between the cost of transistors and cost of fusion targets. The first computers were useful and saleable even at their million dollar price tags. So the ongoing development could always be subsidised by the product sales. In the case of the human genome, the cost of sequencing has decreased by a factor of 200,000 over 10 years. At that rate, nine years would be enough to get the price of targets down to a competitve level. But sequencing the human genome has had an ever increasing market to drive down the cost. On the other hand a power plant producing power even at $4/kWh let alone $4000/kWh is not a saleable item.

Although fusion may become reality, it would seem that given the extremely high-tech nature of the work involved, the straightforward solar/wind/geothermal/wave option might still be the most practical, given the abundance of renewable energy available in Australia.

3 How are we travelling?

The Australian government determined that we will supply 20% of our electricity from renewable resources by 2020. That's only 10 years away so this sounds like a significant target until you consider the following.

1. Australia's population continues to expand. Figure 17 from the bureau of statistics does not show any curvature consistent with a slowing of population growth. Rather, in the last year there was a surge in population. Some of this increase is due to immigration and through taking in refugees[59]. One cannot ethically exclude these people. One thing is for sure, when they arrive in Australia they become big consumers like the rest of us.
2. We are getting more power hungry. The next graph shows that between 2000 and 2008 we increased our electricity use by 20% per person.

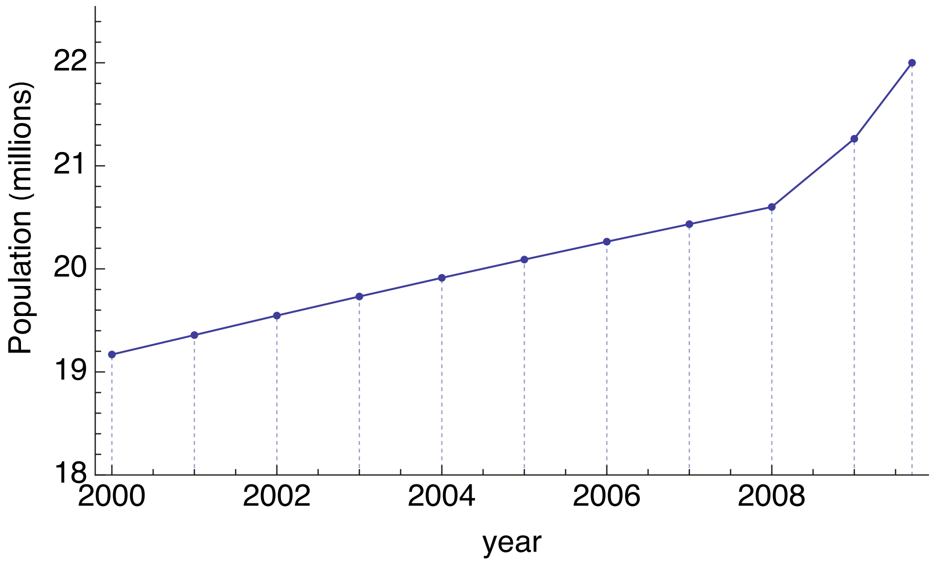

Figure 17. The population (March figures) of Australia was increasing at 0.9% per year until recently when it surged. By November 2009 it was 22 million, an annual increase of 2.1%.

[59] Australia's population grew by 2.1% during the 12 months ended 31 March 2009. Natural increase and net overseas migration contributed 37% and 63% respectively to this total population growth http://www.abs.gov.au/ausstats/abs@.nsf/mf/3101.0

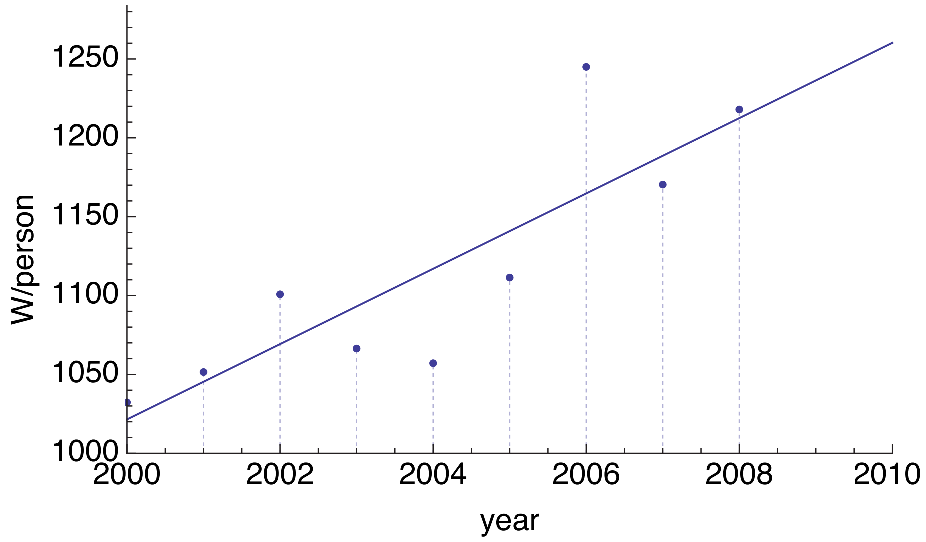

Figure 18. Power use per person has increased by 2.2% per year.

Finally let's look at the combined effect of increasing population and increased per person electricity use. This estimate does not include the recent sudden population jump.

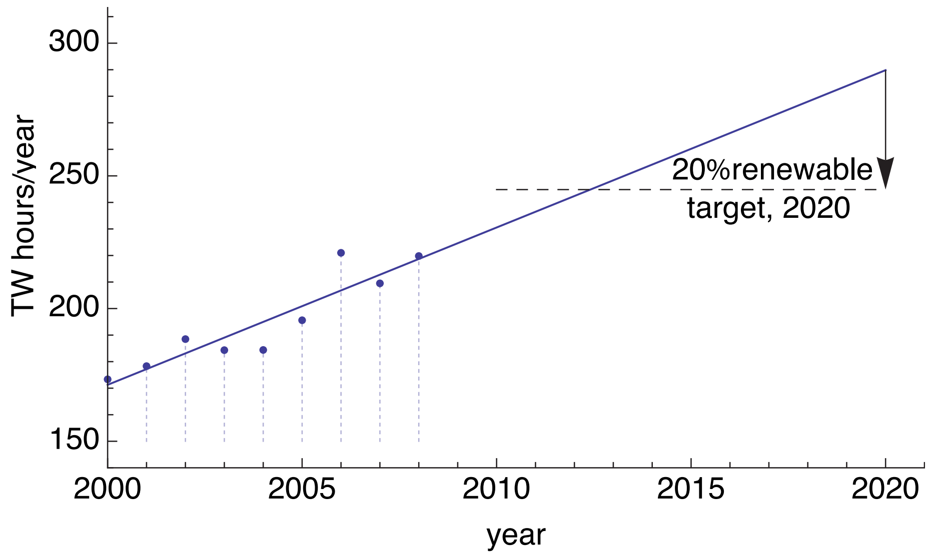

Figure 19. On previous trends, even 20% renewable energy will still result in a net increase in the use of fossil fuels. Note that the 20% renewable target may be partly achieved by buying Renewable Energy Certificates, for power which will be generated over the next 15 years, not now. It may also be covered by certificates for power saving, through the use of solar hot water services – not generation. The target is not actually a 20% target but a fixed 45 Terrawatt hours per year. So the target will not increase if our electricity use increases. Finally, this graph does not include the recent jump in population.

So yes, 20% renewable would be a significant achievement and yes, *per person* hopefully we will have reduced our use of fossil fuels. But in the meantime Australia overall, will have increased the consumption of fossil fuels. If the 20% renewable target is reached, the *increase* will be 37% on year 2000 levels.

Note too that the 20% target is not the *actual* target. The actual target is 45,000 GWh or 45 TWh. So if our electricity use goes up more rapidly than anticipated before 2020, we will achieve less than 20%.

Finally, much of this target will be met by buying Renewable Energy Certificates (See later section on RECs). As things stand:

1. certificates are issued for 5 times their actual value as renewable energy for small photovoltaic systems (I'm not making this up)
2. certificates are issued for hot water systems on the assumption that they replace electric systems, even though they may replace gas which produces only a sixth of the CO_2 (Vic. govt's own data)
3. the RECs are issued for systems on holiday houses, where the occupancy may be only 10%
4. the RECs are given in advance, for the energy saved/generated over the next 15 years, not as it is generated

The result of these government-sponsored scams (or ill advised schemes?) is that the bottom has dropped out of the RECs market and unless things change, the electricity producers will be able to buy them very cheaply.

3.1 Uptake of renewable energy

Data from ABARE[60] (Australian Bureau of Agricultural and Resource Economics) lists all electricity generation major development projects. This comprehensive list is regularly updated. As of October 2009, a total of 3,464 MW of black and brown coal power developments were listed. Wind projects amounted to 11,000 MW but since wind has a capacity factor of about a third, that is equivalent to 3,600 MW, the same as the additional coal generating plant. So wind power is just keeping up with coal expansion. However coal seam gas is also on the increase – 2,500 MW. A total of 786 MW of wave and tidal power projects are underway, with startup dates between 2011 and 2013. The capacity factor of these projects is not available. As far as solar is concerned only 100 MW is listed, with a capacity factor of between 4 and 7, say 20 MW average power. ABARE, 2007 – 2008 lists existing solar as providing 0.4 PJ/year of the 926

60 http://www.abareconomics.com/interactive/09_Listings/eL09_Oct/

PJ/year of electricity generated. A more recent listing is awaited but 0.4 PJ/year is 12 MW average power.

Exact data on the federal government's highly popular $8000 rebate for solar PV systems is hard to find. However at the conclusion of the scheme a spokesman for, Mr Garrett, the Minister for the Environment, said (The Age, 22 December 2009[61])

> *"the scheme was on track to deliver 120,000 solar panels to homes since November 2007."*

The majority of these systems are 1 kW peak so that equates to 120 MW peak or 20 MW average power.

Average power generation from all sources in Australia is 25,000 MW. Suffice to say that solar power is presently insignificant in Australia; about 0.2–0.3%.

Interestingly, although domestic solar PV takes the overwhelming share of publicity in the media, wave and tidal power at about seven times the size gets almost no coverage.

Figure 20. Australian approach to the problem so far. Reproduced with permission from Andrew Weldon *The Big Issue*.

[61] http://www.theage.com.au/environment/household-solar-rebates-burn-through-extra-500m-20091220-l7j3.html

3.2 The government plan

The Australian government, amid much furore is attempting to introduce a Carbon Pollution Reduction Scheme (CPRS)[62]. CPRS-5, i.e. 5% below 2000 levels by 2020 assumes a slow start to global emission reductions and stabilisation at 550 ppm; CPRS-15, i.e. 15% below 2000 levels by 2020, assumes a faster start and stabilisation at 510 ppm. CPRS-5 is being opposed by both the Greens who think that it doesn't go far enough and the establishment (or Liberal/National Opposition party) who claim it will be devastating to the economy.

Figure 21 shows the CO_2 trajectories for various plans and the effect on GNP according to the government modellers. This effect is shown to be negligible. Australia is not proposing to follow the recommendations of Professor Garnaut[63] (Our equivalent of Nicholas Stern) who set much more aggressive targets. Interestingly, according to the government's own modelling, this should have no more impact on the economy than the much watered down proposals. If that's the case why not go for the best?

Whatever happens, given the increasing energy use per person and the increasing population, the targets will be a challenge and an exciting time for engineers. At present however interest in power engineering at Australian Universities is at an all time low.

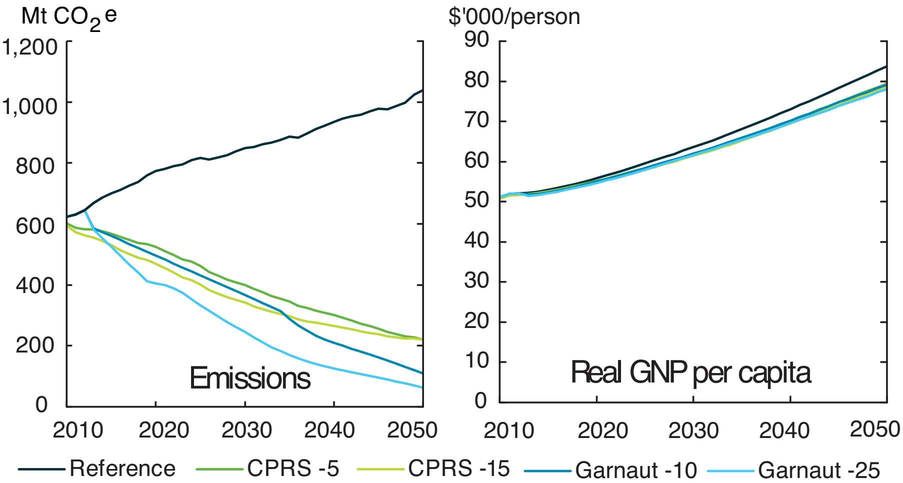

Figure 21. Extract from *Australia's Low Pollution Future* summary report.

[62] http://www.treasury.gov.au/lowpollutionfuture/
[63] http://www.garnautreview.org.au/

4 A strategy for Australia

Consistent with SEWTHA, let us contemplate a strategy for Australia to become a sustainable energy country. We have the potential to do it. I have not devised a number of strategies but simply a mix of the most promising technologies. I'm imposing *shocking efficiency measures such that we [are] reduced to the misery of living on the mere 125* kWh/*day of an average European or Japanese citizen*[64]. A primary energy use of 125 kWh/day/person is 5200 W/person but for this calculation I'm assuming 2600 watts each, end use power, since we don't need to go through the step of burning something to provide about a quarter to a half of the electrical or motive power.

The following table gives a mix of renewable power sources which could be used as a basis for an Australian supply. The mix is arbitrary and in practice would be varied to optimise the cost, taking into account transmission distances and storage requirements.

Resource	GW	kWh/day/ person	W/ person	Proportion of resource
Hydro	1.6	1.75	73	As it exists
Geothermal	15	16.4	682	Currently measured resource fully used
Wave	0.4	0.4	18	3% of coastline
Solar	20	21.8	909	0.06% of country
Wind	20	21.8	909	0.13% of country – compatible with farming
Total	**57**	**62**	**2600**	

Table 4. A possible combination of renewable resources to meet current demand.

Since fuel for flying is not easily produced from electricity, I have assumed that use of conventional fuel for that application will continue. I will assume the impact of flying and a proportion of other liquid fuels will be offset by some bio-sequestration, possibly the method mentioned earlier. The table takes an arbitrary mix of technologies which would be open to vigorous debate. Very few Australians would be happy with filling even 3% of our southwest coast with wave power installations. On the other hand 0.06% of the country covered with solar installations could be more acceptable. That's a 68 km square, much smaller than the 200 km square mentioned in chapter 1, which assumed we were

64 p. 234 SEWTHA.

providing primary energy and that solar alone, without any wind, geothermal etc.

4.1 Getting the mix right

An outback power example

In the design of a solar power system, one must choose the size of the array, the battery size, backup generator capacity and inverter capacity. Whilst it is possible to make some judgments on these components, it is difficult. A smaller battery will be worked hard and last a shorter time. A battery that is too large may leave too little money for solar panels. A small standby generator will cost less but run more often and wear out quickly. Finally the cost of energy efficiency measures must be weighed against the cost of providing more power. It is nearly always more cost effective to use less electricity through efficiency measures than to generate more, but there is a point at which it is not.

To decide on the best mix of components, there is a computer program called HOMER which was written by the National Renewable Energy Laboratory[65] of the USA. This program allows you to put in a number of candidate sizes of each component and the statistics of the load and renewable resources. It then churns through 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 require more standby power. Comprehensive modelling is the solution to this problem.

4.2 Design exercise

Chapter 26 of SEWTHA deals with Fluctuation and Storage. Let's see what it would take to build an electricity system to supply the existing Australian load with renewable energy. Later we can consider such factors as electric cars adding to this load and efficiency measures reducing it. The exercise here is to see what it would take to replace our *current electricity requirements* from renewable sources.

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

Assumptions:

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

I have assumed an efficiency of 96% for conversion and transmission of the power. This is achievable using high voltage DC links. Pumped hydro storage losses are included in the *battery* round trip efficiency[66] of 80%. The electric load data was downloaded from AEMO Australian Energy Market Operation[67].

In the absence of access to a team of engineers, 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, i.e. 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 hydro, 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 battery. This 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 *base load*[68] power, this does not appear to be the case as much as we would like it to be. For example look at Figure 7

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66 David MacKay assumes that generation has an efficiency of 0.9 and that pumping has an efficiency of 0.85 giving a round trip efficiency of 0.77. Figures between 0.70 and 0.87 are quoted in the literature.

67 http://www.aemo.com.au/

68 Comments from Rob Veerman about the use of the term *base load*. Not even the coal lobby actually likes it, except for propaganda. Firstly it is not *load* but *supply*, and the real load is not steady (or *base*) but variable. The only steady, regular, constant is the need for revenue (read profit). Secondly *off peak* rate was created to fabricate or emulate *base load* on the demand side. Thirdly pumped hydro was created on the supply side, as a 'work around' to cope with the unreality of *base load*.

which compares 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.

So now 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 results

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

The battery, translated into the full size system[69] was 200 GWh. Referring to Table 2, 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. The statistics of the storage level are shown in Figure 23.

[69] I used 2000 kWh in my scale model

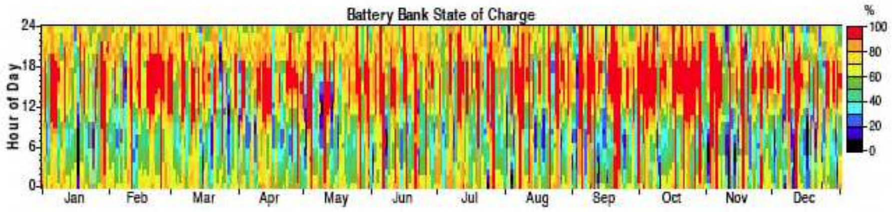

Figure 22. Daily and annual fluctuations in storage. In this graph a whole year is depicted, with days on the horizontal axis and hours of the day on the vertical axis. Red represents fully charged whilst black represents empty.

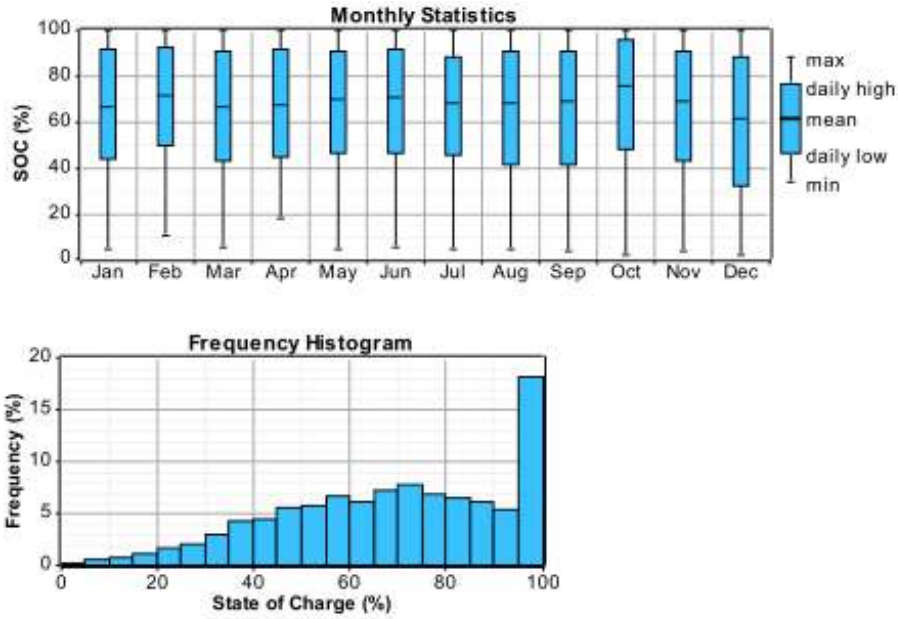

Figure 23. Storage levels depicted on two different graphs.

Referring back to Table 2, concerning the storages of the Snowy Mountains, the volumes are sufficient 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 165 m, which could provide 1420 GWh, is about 7 times as much as we would need to serve our current electricity needs, 30 kWh/day/person. At this point I'm not including the electrification of transport and heating which would multiply the requirements by as much as three – assuming that in the process, we drop our gross energy use from 200 kWh/day/person to 125 kWh/day/person.

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 over the top, 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 (I'll explain where that figure comes from shortly) 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. You might think that 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? This idea is mentioned in SEWTHA (p. 194). 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 24. Bunda Cliffs. Suitable place for pumped storage? The octagon is 7 km across.

This place[70] is 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,

[70] 31° 38' 25.19" S, 129° 20' 51.35"

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[71]. Incidentally, the place I have chosen is in the Nullarbor National Park. Whoops! Well there are other spots at the Head of Bight.

In this design exercise, I calculated that the 200 GWh pumped hydro storage in connection with the renewable energy sources would provide 90% renewable energy. Why didn't I go for 100%? The reason is that there is a law of diminishing returns. We will look into this idea later.

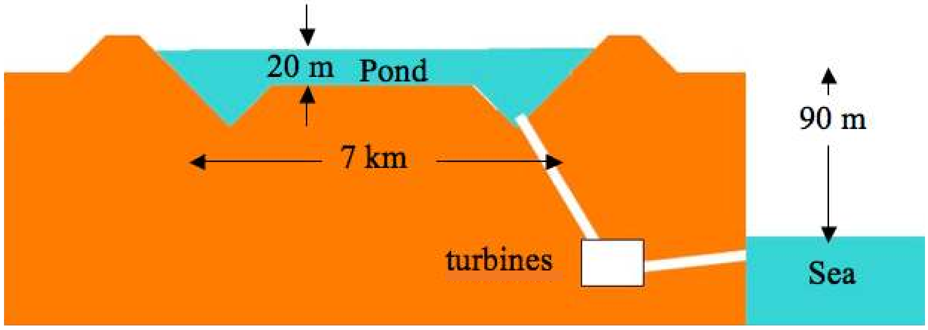

Figure 25. Saltwater pond on the Nullarbor to store all Australia's renewable energy.

Here's a rough costing of this hypothetical pond on the Nullarbor[72].

1. Excavation cost
   - Excavation cost: $10/m^3
   - 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[73].
   - 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 40 x 10^6 m^3
   - Cost = $0.4 billion
2. Pond Lining

[71] Location proposed by Robert Veerman.

[72] Numbers from Rob Duncan and Anthony Kahl.

[73] The wall would not necessarily be symmetrical, dam walls are typically 4 metres wide on the top and have a natural fall of -1:1 on the outside and a minimum of 8:1 for a more robust wall on the inside. The dimensions of this wall are an optimisation exercise. The solution, depends on the costs of lining vs excavation. The more expensive the lining, the more incentive there is to build a higher dam with a smaller area. The dimensions here are optimised for the quoted costs. Costs for excavation of $1.5 and $10 per cubic metre were quoted. I chose $10.

    - Line the pond with a plastic membrane (these are in common use in the area for various purposes)
    - Membrane cost: $20/m^2
    - Area = 37 x 10^6 m^2
    - Cost = $20 x 37 x 10^6 = $730 x 10^6 = $0.73 billion
3. Basic cost = 0.4 + 0.73 = $1.13
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

4.3 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 will need to pump 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 million, or $1.6/W. 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. A summary of such a power system is given in Table 5.

4.4 Wiring it all up

To complete this student's 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. Table 6 gives proposed high voltage DC links their capacity, lengths and costs, calculated uaing data from Rudervall et. al.[74].

I am assuming that an average link size would be 10 GW. As an electrical engineer, I'm calling it a busbar. Again, in the absence of a team of engineers I can't give an exact figure for the optimal sizes of the links. However 10 GW links

[74] Rudervall, Roberto (ABB Power Systems), J.P Charpentier (World Bank), and Raghuveer Sharma (ABB Financial Services), *High Voltage Direct Current (HVDC) Transmission Systems: Technology Review Paper'*(19 pages) http://www.trec-uk.org.uk/elec_eng/world_bank_hvdc.pdf .

	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				232
Storage cost percent	15%			
Cost of electricity	0.11 $/kWh			
Renewable fraction	0.9			

Table 5. Summary of a power system providing 90% electricity from renewable sources.

would allow our 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 sprinkled along these routes to feed into this busbar.

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

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.

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 (p. 200 SEWTHA). 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

Assumptions		
Busbar size	10 GW	
Link cost ($ millions/GW/km)	0.125	
Cost per end station ($ millions/GW)	61	
Link	**km**	**cost ($billion)**
Perth – Nullarbor pondage	1341	1.7
Nullarbor pondage – Port August	786	1.0
Port Augusta – Melbourne	902	1.1
Melbourne - Sydney	740	0.9
Port Augusta – Cooper Basin	601	0.8
Cooper Basin – Brisbane	1202	1.5
Brisbane – Sydney	740	0.9
Cooper Basin – Sydney	1202	1.5
Power stations to storage	300	0.4
Total	**10514**	**9.8**
End stations	**16**	**11.0**
Total including end stations		**20.8**

Table 6. Cost of high voltage links between renewable energy sources and major centres.

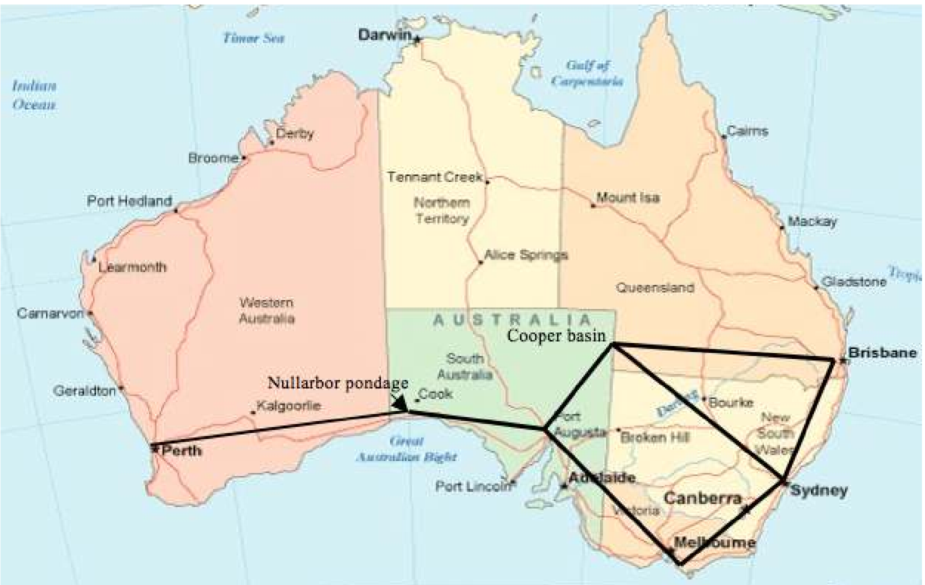

Figure 26. High voltage DC wiring diagram for Australia.

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 (this is not a typo) 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.

5 The bill

Including the cost of the pipes and turbines, to convert our existing electrical power system to completely renewable[75] sources, we will need:

Power stations (wind, solar and geothermal)	$198 billion
High voltage power lines	$21 billion
Turbines and pipes	$33 billion
Storage ponds (dams)	$2 billion
Total	**$254 billion**

Table 7. The renewable power bill.

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)[76]. That's $3.70 per New South Welshman per day.

Of course, the cost of the electricity generating systems themselves is only part of the total cost. The cost discussed here is the cost to generate the required total only – not the cost of the new transport system, new heat pumps, etc.

On the other hand, sometimes these systems will save money – as we will see in *The bang for buck approach to CO_2 abatement* to follow. Here's a rough calculation, which is about all one can hope for. Let's fantasise that we managed to reduce our CO_2 emissions from our current 20 tonnes/year/person to zero in the next 25 years. Ramped gradually from 20 to zero, that would make for an average per person CO_2 production of 10 tonnes /year/person. At a CO_2 price (who knows what it could be?) of say $50/tonne that would be about $500/year/person, or about $1.4/day/person, saved in CO_2 cost. A $50/tonne of CO_2 price would effectively pay for this system. Note too, that when we power the country from renewables, the cost of fuel we don't use needs to be subtracted.

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

5.1 Job creation or damage to the economy?

At the risk of sounding like a politician, let's look at the possible financial effects of implementing the schemes we have been examining. It is a fascinating thing that when people are against something expensive, then it will *damage the economy* and when they are for it, it will *create jobs*. Let's take the *create jobs* line. Otherwise, how were the multi-billion dollar stimulus packages supposed to work?

The average Australian weekly earnings in 2009 were $1,257 for full-time adult employees[77] or about $65,000 per year. Simplistically, at that rate, spending $10 billion a year would add about 150,000 jobs to a workforce of 11 million, an increase of 1.4%.

Looking at it even more simplistically; in 2009 our GDP was $1000b. Spending $10b would increase employment by 1%, or lower unemployment from 5.7% to 4.7%.

5.2 Could we go 100% renewable?

The following calculations refer to our electricity supply only.

My calculations above seemed to indicate that going beyond 90% renewable energy did not make sense. But let's make use of HOMER's optimisation capability to see what it would take to go to completely renewable energy. Well that's assuming geothermal is renewable but we will leave that issue aside for now. Let's call it minimal carbon instead.

This time, to calculate what it would take to go 100% renewable, I will consider many combinations. These will include six different sizes each of solar and wind installations, pumped storage pond sizes and turbines.

The result of the optimisation was the following:

1. Load:
   - 25 GW annual average, 45 GW peak
2. Supply:
   - Hydro: 1.6 GW
   - Geothermal: 10 GW
   - Wave: 0.4 GW
   - Solar: 10.6 GW (50 GW peak)

[77] http://www.abs.gov.au/ausstats/abs@.nsf/mf/6306.0/

- Wind 8.7 GW (28 GW peak)
- Total 31 GW

3. Storage:
   - Turbines and pipes: 28 GW
   - Storage ponds: 1800 GWh

	GW or GWh	Capacity factor	Cost $ / peak watt	Cost $ billions
Solar	50	0.21	2.73	136
Wind	20	0.32	3.00	60
Geothermal, hydro, wave	12	1	3.00	36
Turbines and pipes	28	1	1.64	46
Ponds	1800	1	0.01	18
Power station total				232
High voltage power lines				21
Storage total				64
Total				**317**
Storage cost percent				20%
Cost of electricity				0.12 $/kWh
Renewable fraction				1

Table 8. Summary of calculations for a completely renewable electric power system.

The notable difference between this system and the 90% renewable one is the huge increase in storage requirement. I have upped the size of the store from one 200 GWh pond to 1800 GWh, or about 9 such ponds. It might be best to do this on a modular basis. In any case, the cost of the storage is still only 20% of the total system cost. The ponds themselves account for only 6% of the cost. I have increased the size of the solar and wind installations but only slightly.

The total cost of this system is about $320 billion, rather than the 90% renewable option at $250 billion.

5.3 What will the electricity cost?

Whether we go the 90% renewable route or 100% renewable does not appear to make much difference. Both simulations came out at about 12 cents/kWh. The wholesale price of electricity in 2009 was about 5 cents/kWh and retail about 17 cents/kWh. Given that Europeans pay approximately double the retail price that Australians pay, a wholesale price of 12 cents/kWh does not seem unmanageable.

The cost estimates are based on an annual real interest rate of 7%, reflecting a cost of money as that percentage above inflation. A capacity shortfall penalty $10/kWh (in contrast to the normal price of $0.05/kWh) was applied. These are parameters which can be set in HOMER. I kept the default values.

But something must be wrong! How could 100% renewable energy cost much the same as 90% renewable. In the case of the outback power systems this is certainly not the case. You pay heavily for that last 10% in battery costs. The answer is that the extra storage is very cheap. It's just more seawater ponds, and they are the cheapest part of the package.

5.4 How much CO_2 will be produced in building this system?

The topic of CO_2 produced in building something is covered in the section: Bang for Buck in CO_2 abatement. But first here's the answer. The systems we are talking about cost around $300 billion. In Australia, we generate about 1 tonne of CO_2 per $2000 of GDP. On a project as complex and varied as this, it is a safe assumption that the spending of $300 billion will generate a proportionate amount of CO_2. That's about 300/2000 = 0.15 billion or 150 million tonnes of CO_2. Sounds like a lot. It's only about 7 tonnes per person. We currently produce 20 tonnes[78] of CO_2 each per year.

Let's now see how much CO_2 our venture will save. It will displace 23 GW of fossil fuel power (assuming 2 GW is provided by existing renewable sources, mainly hydro). Electricity generation in Australia produces 1 tonne of CO_2 for each MWh. The amount of CO_2 displaced by the scheme per year would be 23 x 365 x 24 = 200,000 GWh/year equivalent to 200 million tonnes of CO_2 or 9 tonnes of CO_2 each, per year. At that rate, the CO_2 payback period is less than one year.

5.5 Security of supply

The normal scepticism regarding renewable energy includes security of supply. With the first system we looked at, using fossil fuel backup, would we need to maintain the complete existing power generation system just to provide backup? Actually, no.

The HOMER program introduces adjustable statistical variations in all relevant parameters. I have tried to match the statistics in the program with the published data. The simulation in Figure 27 shows that on the 9th of February we came

[78] Interestingly the Australian Greenhouse Office puts this figure at 26 tonnes per year per person.

close to running out of seawater storage. The level dropped to 4% of capacity but quickly rose to 15% by the following day. In anticipation of days like this, which can be predicted from normal weather forecasting, some moderate boosting from existing gas fired power stations could be used. These would not be needed to supply the entire load but only avert the possibility of completely running out of water in the storage ponds.

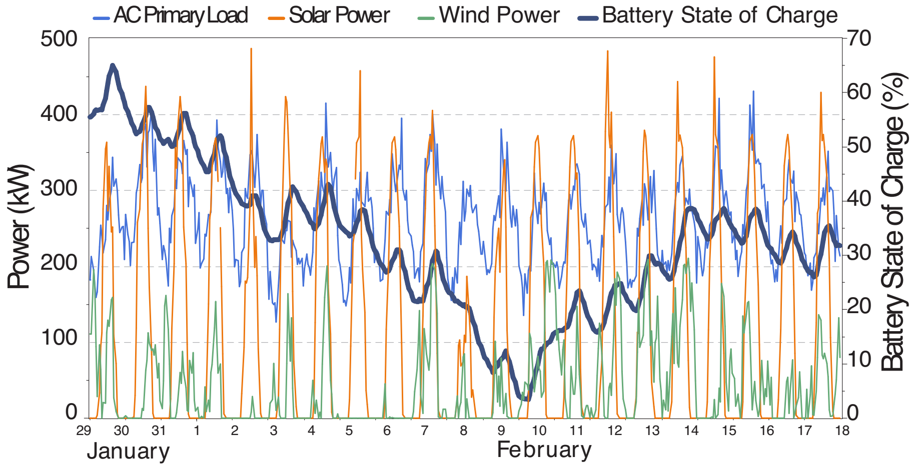

Figure 27. Low wind period in February resulted in a brief low storage level. Note the strong correlation between wind and solar output.

5.6 Electricity grid stability

It is commonly stated that the electricity grid is incapable of dealing with substantial input from renewables because of their fluctuations of supply, in combination with the variability of demand. In some respect this is true. Injecting more than about 20% of the power from wind turbines would cause significant problems in the grid as it stands. To understand why this is so, imagine the grid to be a large number of masses, (loads and power sources) strung together with a large number of elastic bands (transmission lines). If you hit one of these masses, or nodes, the entire system will shake and oscillate, with the problem that circuit breakers will trip, transformers will overheat etc. Without completely redesigning the system, this will be a huge headache. The method of overcoming this problem is inherent in the scheme proposed in *Wiring it all up*. The idea is to leave the existing grid alone and to decouple the variable supply from the variable load. The storage system, together with the high voltage DC links will supply power to the same nodes as it is being supplied at present. The control of the amount of power being supplied to those nodes would be under greater control than it is at present, because hydro turbines can vary their output on a time scale of minutes rather than many hours as with coal fired power stations. Thus the renewable energy power system proposed is a *drop-in* replacement for the existing system. Whilst the system proposed is not as efficient as a system that would be designed starting from a clean sheet, it overcomes the major stumbling block of system stability.

5.7 Thermal storage

Haven't I forgotten something? What about solar with thermal storage? In the case of the smaller system, with 90% renewable energy, thermal storage would certainly help; the exercise of working out the balance of thermal vs pumped storage would be, as before, an optimisation process. In the case of the 100% renewable system, with much longer storage period requirements, I don't think thermal storage would help. Thermal storage is great through the night after a sunny day but I have not heard that this technology can be extended to several days in a row. Another factor to consider is the operation and maintenance of solar thermal systems. A solar thermal power plant requires a round-the-clock crew[79]. Furthermore, solar thermal stations based on steam generation require cooling water, just like fossil fuelled power stations. This has become a real problem with coal fired stations and the problem is not easily solved without impacting on efficiency.

5.8 What have I left out?

In this design exercise, some factors have been pessimistic, others optimistic

- Pessimistic
  - Costs of renewable technologies based on today's costs. It is a fair assumption that they will get cheaper.
  - Figures are taken from relatively small scale installations. They would be cheaper on a large scale.
  - The potential of thermal storage to reduce the storage requirements is not included.
  - The use of load shifting and smart metering to remove load in times of reduced supply is not included.
  - Carbon pricing is ignored.
  - The data is from one solar site and one wind site. There is no diversification included in the model.

[79] New Scientist, 24 October 2009, p. 41.

- The cost of fuel will continue going up – in future the benefits will be greater.
- I have assumed no gains in efficiency – there is plenty of potential there.

All these factors make the scheme more promising than I have assumed.

- Optimistic – not included
  - Operation and maintenance of the system.
  - Compensation for land use, litigation, environmental effects statements, etc.
  - Cost over-runs, common in large public projects.
  - Cost of dealing with corrosion, barnacles etc. in the seawater storage.
  - The proposed storage area is littered with limestone caves and might be subject to subsidence.
  - Salination due to evaporation (may be overcome by rotating pond use).

These are the factors that will make the scheme less promising than I have assumed.

So let me emphasise that this is not the design of a minimal carbon power system. It is a feasibility study, which would need far more detailed input data than I can possibly provide. Apart from that, only electricity usage, not our total energy use has been considered. So this proposal only addresses half of the problem.

5.9 Could we build it? The liberty ship approach

Between 1941 and 1945 the USA built 2751 Liberty Ships, to replace the depleted Allied merchant fleet. The first ship took 230 days to build but this dropped eventually to 42 days. In 1943, three new Liberty ships were being completed every day. An ongoing contract to build a large number of renewable energy installations at a fixed price would bring the required resources out of the woodwork.

However, while we have situations such as that with the Australian company Solar Systems Ltd, nothing is going to happen. Solar Systems had been promised a total of $125 million in funding from the state and the federal governments towards its $420 million Mildura project, but it was forced to go into receivership when a major investor pulled out and it was unable to find replacement funding. The Victorian Government has handed over only $500,000 of its $50 million grant to Solar Systems. None of the Federal Government's $75 million funding has been delivered.[80]

While companies have to deal with a tortuous funding regime, and that in the face of highly uncertain carbon prices and the vagaries of the economic climate, it is unlikely that the situation will change.

A big difference between the wartime situation of the building of the Liberty ships and a 21st century peacetime initiative for a large scale ongoing project is the extreme sensitivity to any adverse effects. Whatever goes wrong will be all the incumbent government's fault. Perhaps if we called the problem the *War on Global Warming*, such collateral damage inherent in all industrial activity would be more acceptable. A classic case was the roof insulation rebate scheme. In its implementation, some shonky operators entered the scheme with unfortunate consequences of fatalities and house fires. Whilst the opposition made much mileage of this and the scheme was cancelled, or at least delayed it was not quite the disaster they proclaimed. The following is an extract from a letter from John Watson published in The Age[81].

> *"Officials in Garrett's department told a Senate committee hearing that the pre-program rate of installations was 65,000 to 70,000 a year, with 80 to 85 insulation-related fires a year. Roughly 30 per cent were linked to new installations, on industry estimates. The program insulated more than 1.1 million homes. If 94 fires have been linked to this, the implication is that the fire risk was roughly four times lower than before, even as the number of installations rose 15-fold. As for the four deaths of installers, one of them through heat exhaustion and another using foil insulation that Garrett had barred from the program months earlier, they are subject to coronial inquiries. The fact is, however, that the program introduced the first national training program for installers."*

It is pretty well inevitable that when a major project is undertaken, there will be casualties. Whilst obviously all measures must be taken to avoid them, they will not always be successful, and it is not always the government's fault. The Snowy Mountains Scheme claimed 121 lives.

In more recent times, annual work related casualties in the construction industry, are about 5.6 per 100,000 workers. Let us say we embarked on spending $10 billion per year on building a renewable energy system for Australia. Of that amount, let's say half will be spent on construction workers' wages and the other half on materials. That would be about 100,000 workers with the statistical

[80] *The Age* 8 Sept. 2009.

[81] Insulation fire risk was worse before rebate, March 4, 2010

average of 5 or 6 fatalities per year. Regrettable, and if they could be avoided, of course you would do whatever possible to avoid those casualties. Wouldn't one do it in all industries, not just in the renewable energy construction industry? However it is not likely to happen. There would be a public outcry about irresponsible government with the likely consequence that the scheme would be cancelled.

None of this is to say that those construction workers were killed by this industry specifically. It is a consequence of employment in a tough working environment in general and the government and public needs to recognise this and prepare for it. Incidentally the fatality rate in the mining industry is 9.6 deaths per 100,000 workers so the eventual total fatalities through a renewable energy could be lower than in the business-as-usual scenario. The point here is that the government needs to be not only proactive in reducing casualties but also upfront that such things are likely to occur.

6 What about all the other energy we use?

Now we come to the hard part. At the beginning of this book, I said you might think that solving the renewable energy problem in Australia is a no-brainer. I said: Well yes and no. This is the *no* part. Well at least it's the part that is not so easy.

So far I think I have shown that if we had the will, we could pretty well go renewable for our existing electricity supply. That would deal with about 1200 W/person or about 29 kWh/day/person end use energy or about 83 kWh/day/person gross or primary energy of the 200 kWh/day/person we are using. What about the other 117 kWh/day/person?

In the section on Biofuels, I said that if we supplied all of Australia's liquid fuel current usage from biomass, we would need about 9% of our arable land. That was composed of 37 kWh/day/person for ground based transport and 8 kWh/day/person for air travel. So the air travel could be dealt with by using only 1.6 % of our arable land, but if it is in the form of sugar cane, it would have to be in the very high rainfall areas, and would still represent almost twice the area that is currently used for growing sugar cane. It doesn't seem likely that we will be able to grow the biofuels we need.

In the section on Carbon Capture and Conversion to Biofuels, we found that if we did continue to use some fossil fuels for electricity generation and industry, we could capture the CO_2 from that and pass it through the system again, by converting it to liquid fuel using algae. That did seem to be a viable option, but it meant that there was still some CO_2 ending up in the atmosphere, albeit maybe only a quarter of what we are putting out now. Where to from here?

Let's start by being more reasonable. If Europeans can live in countries where it snows, on 125 kWh/day/person we could do it too.

Secondly, let's see what could be achieved by converting some of our ground transport fleet to electric vehicles. How much would we need to expand our renewable energy electricity grid to do it?

Let's assume that a present-day car uses 10 litres of petrol per 100 km. A litre of petrol (or diesel) contains about 10 kWh of energy, so that's about 1 kWh/km. On the other hand electric cars achieve about[82] 0.2 kWh/km. Let's say that they are about 5 times as efficient.

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[82] This kind of statement usually creates a rash of complaints that the figure is both too high and too low. For the purposes of the discussion, it doesn't matter. It is important however not to be

6.1 Electrifying the transport fleet

If we were to take the radical approach of electrifying the entire ground transport fleet – would that blow our renewable electricity plans out of the water?

Taking the 36 kWh/day/person from Figure 1, we could convert to electricity based transport, either in the form of more trains to carry freight and people or electric cars and trucks and do it at about 7.2 kWh/day/person. That would be end-use energy. In our renewable electricity "Design Exercise" we found we could supply 25 GW from renewable sources. That would be 27 kWh/day/person. So supplying an extra 7.2 kWh/day/person would not be a show stopper, increasing the size of the system by 30%.

Our energy use compared to the UK would then look something like this:

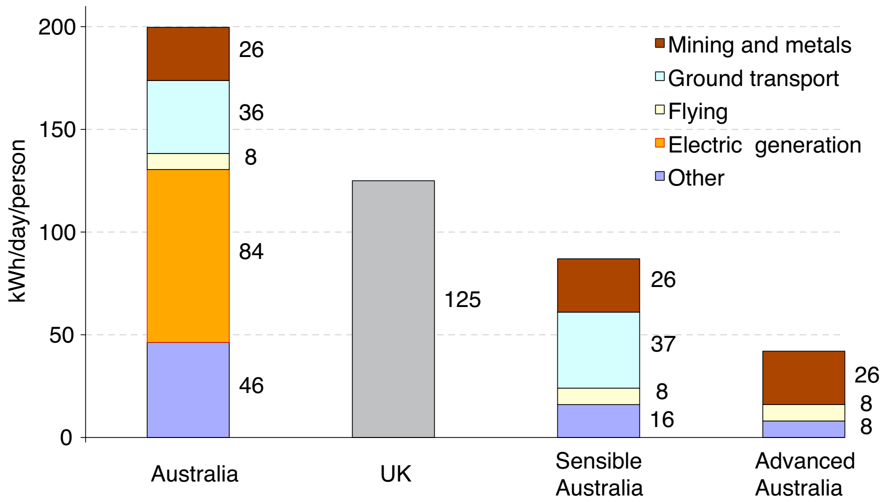

Figure 28. Comparison between UK and Australia if Australia first converted all electricity generation to renewable sources (sensible Australia) and then converted all ground transport to electricity (Advanced Australia).

In Figure 28 I have assumed that fuel from flying has been derived from Algae fed from CO_2 from some industrial processes in the Other sector. This is a rather rough assumption but demonstrates the point.

comparing 2 seater runabouts with 5 seater cars suitable for going on holidays. See page 157 of SEWTHA.

6.2 What about the rest?

So far we have looked at electricity generation and transport. What about the rest of the energy that Australians use? Table 9 from ABARE[83], *Energy in Australia*, gives the breakdown by sectors in Petajoule[84].

	PJ/year	W/person	kWh/day/ person
Agriculture	92	133	3
Mining	457	659	16
Manufacturing	1369	1973	47
Electricity generation	1695	2443	59
Construction	26	37	1
Transport	1359	1959	47
Commercial	252	363	9
Residential	442	63	15
Other	78	112	3
Total	5770	8317	200

Table 9. Energy use in Australia by sector from a publication by ABARE 2009. This table needs careful interpretation. All categories include end-user electricity use, and the category Electricity generation is basically the losses involved in the electricity generation.

You could say that I was a bit hasty saying that just because Europeans and Britons can live on 125 kWh/day/person that so can we. I dropped the Other category from 71 to 16 kWh/day/person without comment. We need to look a bit more carefully into where that extra energy is going.

Leaving aside Electricity generation and transport, which we have just discussed the breakdown is as shown in Table 10.

You may notice that the figures in these tables don't quite line up with Figure 28 and Figure 1. Nevertheless the Other category for Australia is 6 times as high as for the UK. Explanation is needed here.

The figures from ABARE in each category include the electrical energy used by that category but do not include the losses involved in generating that electricity. That is included in a separate category called Electricity Generation, which does not include the energy dispatched. Table 11 excludes the electrical component of each category so that we can try to work out how much energy we will need

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83 http://www.abare.gov.au/publications_html/energy/energy_09/auEnergy09.pdf

84 Petajoule = 10^{15} joule = 1 million GJ (Gigajoule).

	PJ/year	W/person	kWh/day/ person
Agriculture	92	133	3
Mining	457	659	16
Manufacturing	1369	1973	47
Construction	26	37	1
Commercial	252	363	9
Residential	442	637	15
Miscellaneous	78	112	3
Total	2716	3915	94

Table 10. Breakdown of non-transport and non-electricity generation energy use in Australia.

	Non elec. PJ/year	W/person	kWh/day/ person
Agriculture	86	124	3
Mining	377	543	13
Manufacturing	919	1324	32
Construction	26	38	1
Commercial	82	118	3
Residential	216	312	7
Miscellaneous	63	91	2
Total	1768	2548	61

Table 11. Non-electrical energy use in Australia.

to supply which is not presently provided via electricity, This is the *rest* in *What about the Rest*?

Here we see that even after we have excluded the electricity component, our *other* category is still about 4 times the UK equivalent: 61 vs 16 kWh/day/person.

At this point have I encountered the *too hard* basket? I cannot really say that we should close down mining and manufacturing in Australia. In manufacturing I have included metal refining. Most of this activity is carried out for export to other countries. For a quick answer go to *Putting it all together*.

You can see that the Commercial and Residential sectors are relatively small compared to the mining and manufacturing sectors. Nevertheless it is worth looking at how that energy is being used.

A startling thing about Australia in the 21st century is how oblivious we seem to be of the impending crunch on resources. Ever larger houses are being built.

Australian houses are even bigger[85] than US houses and three times the size of UK houses. Despite improvements in building standards in terms of energy efficiency, the mean energy use in the residential sector increased by 16% since the new standard was introduced! One reason for this is that the standard did not include house size. The other reason is that the standard did not include lighting, and builders and architects are fitting galaxies of halogen downlights. It is not uncommon to find 16 lights in a room. These lights typically use 65 watts each[86] so that's one kilowatt to light a single room. But I digress.

We were considering the *rest* of the energy we use. Although Australia can be very hot, it can also be cold enough to have space heating. In Victoria and NSW, which is where 60% of the population lives, space heating is used in winter. The energy used for this purpose can be judged by the difference between summer and winter gas use as shown below[87] in Figure 29.

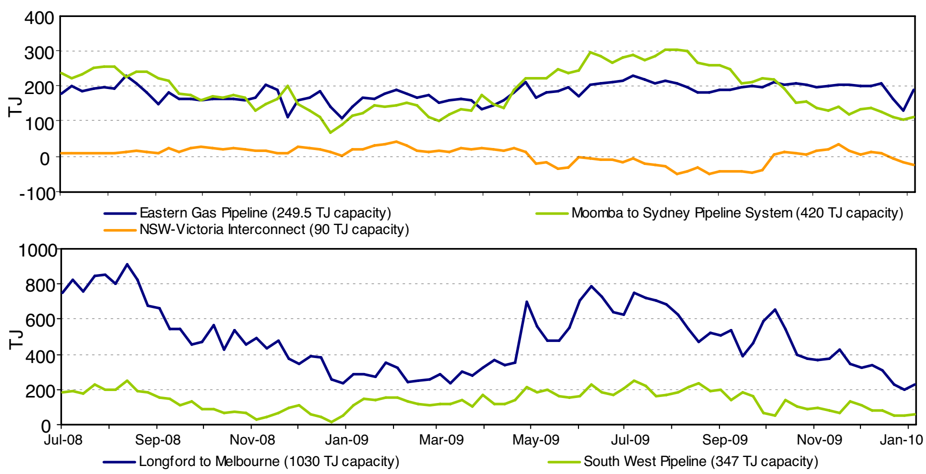

Figure 29. Natural gas use in NSW and Victoria. The seasonal demand is apparent and Victoria uses about twice as much as NSW even though its population is smaller.

From these graphs it can be estimated that the summer/winter difference is about 2300 TJ/d[88] or translating that into our standard unit: 19 kWh/day/person, quite an achievement given that Australia is much warmer than the UK and the

85 Bureau of Statistics data, published 29 Nov 2009, found that new houses in the past financial year reached 215 m^2 in size – bigger than US houses (202 m^2) and almost three times the size of houses in Britain, (76 m^2) http://www.theage.com.au/environment/houses-too-big-say-greens-20091130-k17c.html

86 The lamp is 50 watts but the transformer wastes 15 watts.

87 From the Australian Energy Regulator website http://www.aer.gov.au/content/index.phtml/itemId/729309

88 TJ = Terrajoule which is 10^{12} joules or 1000 GJ (Gigajoules)

UK uses 16 kWh/day/person. I have spread the energy use of this group over the whole Australian population, so the actual use of this part of the population is much higher.

I leave this section with no simple message as to how we can reduce our non-electricity based energy use other than be more efficient. If we could get down to the current level of the UK and Europe that would be a start. That leads on to the next section.

7 Bang for Buck in CO_2 abatement

bang for the buck –
value for the money spent; excitement for the money spent; a favourable cost-to-benefit ratio. (Expressed as an amount of bang for the buck.) I didn't get anywhere near the bang for the buck I expected. How much bang for the buck did you really think you would get from a twelve-year-old car – at any price?

McGraw-Hill Dictionary of American Idioms and Phrasal Verbs. © 2002 by The McGraw-Hill Companies, Inc.

7.1 Random acts of senseless greenness

Our cruise ship is leaking badly. The captain is advised by the engineer to start the bilge pumps but the accountant says this will be too expensive and would cut into profits. The captain makes a tough decision; the passengers will have to bale. An argument breaks out between the staff and the passengers about whether to bale with spoons or glasses. The passengers argue for glasses but the staff for spoons because of the likely breakage of glasses. The hospitality manager comes up with a brilliant solution. The passengers should drink more beer and champagne and pee over the side.

Are we engaging in random acts of senseless greenness? That's a bit harsh. Almost any act of greenness should be good but how do we know? A more calculated and systematic approach is needed. Just to give an example, all around our suburb I see street lights on 24 hours a day. Yet the same council is putting up solar powered lamps. How much does it cost to fix the faulty light activated switch versus putting up a solar panel and short-lived battery? A switch repair for $50 might save as much power as the solar lamp at $5000. I'm making the figures up but you'll get the point. But the solar lamps probably are more about promoting a green council image than anything to do with saving energy.

7.2 The calculated approach

As SEWTHA has pointed out, our energy use goes far beyond our domestic activities. Only about one quarter of our energy use is under our own control (See Appendix *Proportion of private vs total energy use*). Any attempt to be *carbon neutral* should include all the activities carried out on our behalf – pro rata as

Figure 30. Example of well-meaning (or PR driven?) futile greenness – the solar panel supplies power to lights right next to the power poles. Nearby, a mains powered light burns in the broad daylight

members of society. This load includes the health system, public infrastructure, defence, education, shopping centres and manufacture of all the things we buy. So attending to one small part of the problem is really just reducing one's toe-print rather than footprint.

To calculate one's environmental impact for these activities is not easy. The range of activities is so large and varied that a broad brush approach is required. One way that this might be calculated is to look at the total impact of the country, its GDP and then one's own proportion of the GDP. This is as fair a method as is practical and the result is surprising. You might be proud of your low power use. For an economical household, domestic electrical power consumption might be about 150 W/person or 3.6 kWh/day/person. However, in Australia or the US, the overall primary power use is 8000 W/person or 200 kWh/day/person. Although this is a fossil fuel input measure, when converted into electrical units, it still comes to about 4000 W of end use power.

Now for someone who wants to compensate for of all the agricultural and industrial energy being used on their behalf, with the means available to the householder, the generation of 4000 W of electricity (per family member) from renewable energy is not easy. Domestic rooftop solar photovoltaic (PV) systems typically generate about 150 – 300 W average (the usually quoted figure 1000

– 2000 W is *peak* power and refers to the power in full sunlight at noon only). For a fully installed system, domestic rooftop solar power comes at a capital cost of about $50 per average watt (for comparison the capital cost of a coal power station is about $1 to $2 per watt. Large wind turbines cost about $7 per average watt.) To supply your total needs from this kind of solar PV system would cost $184,000 whereas to do it via a wind farm would cost $28,000. It is a mystery that governments are subsidising domestic rooftop solar when much cheaper options are available.

7.3 Money equals carbon dioxide

Spending money results in energy use – no matter what you spend it on. Have a look at Figure 31. Nevertheless there are good and bad, better and worse, ways of spending money and this is an attempt at a guide to a better way.

1. The efficiency of CO_2 abatement measures varies widely and can even be negative. It is not easy for a lay person to calculate. However there is a quick and robust shortcut – which I will describe, with examples, e.g. hybrid cars and LED lighting.
2. Alternative energy generation is expensive and offsets look attractive. Why are they so cheap? I explain how some offsets are effectively a 50 year interest free loan that rips off the environment.
3. CO_2 abatement is transportable to a more effective location.
4. Double dipping – fraud is rife. I will explain how two parties can both think they are being green, from only one actual abatement measure.

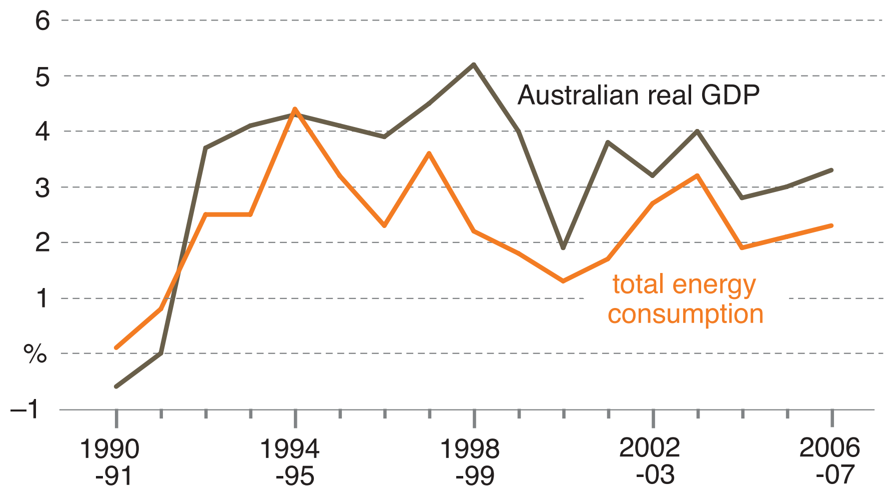

Figure 31. If you need any convincing that money and energy use are closely related, this graph should help.

7.4 The capital cost of power plants

How much did the power station to supply the electricity to your home cost? I'm referring here to your share of the value, not the complete station and I don't mean a specific power station but an average or generic power station. If your place is an average, reasonably economical house, and the power station burns fossil fuel, the answer is about \$300 – \$500 of capital equipment per household. Considering these stations last a long time, 25 – 50 years, it is a very small sum indeed. A typical fossil fuel burning and polluting 1000 MW power station costs about \$1 billion; only \$1/W. This is artificially cheap, however, because they are not paying for the damage they cause[89]. However, this book is not about building cheap fossil fuel power stations. I mention this merely as a yardstick against the costs of alternative power sources – and what we are up against to replace them.

Now let's ask the same question about a rooftop photovoltaic (PV) solar system. The gross cost, excluding any government incentives is about \$50/W, or for a very economical, grid connected house, \$18,000 to supply the electrical load[90]. The capital cost of a windfarm, is about \$7 – \$8/W in ideal locations. So one could justifiably ask the question: why are governments all over Europe and many other developed countries so keen on subsidising individual, small scale PV systems when the cost is so high? If you had to pay back the gross cost of a PV system, unsubsidised and at market rates, you could never do it. The interest on the \$18,000 exceeds the savings in electricity bills. Only a tax-payer subsidised system of rebates and feed-in tariffs based on gross electricity generated can make this personally viable.

True, a roof covered with solar panels can give a warm fuzzy feeling, but when the actual costs and returns in CO_2 abatement are assessed, there are better ways of achieving the objective. If maximising abatement is the aim, there are much more lucrative deals around.

7.5 Wind farm Co-ops

Another way of investing in renewable energy is via community wind-farms or co-ops. An example is Hepburn Wind. From the prospectus you can calculate

[89] The true cost of coal electricity would be many times the market value if the health and environmental destruction were taken into account. See http://www.greenpeace.org/raw/content /international/press/reports/cost-of-coal.pdf.

[90] To avoid confusion let me explain here that this \$18,000 is to supply only the electrical needs of a domestic residence. The \$184,000 referred to earlier was to supply *all* energy needs, both domestic and industrial, and including transport fuels etc on a per person basis.

that, pro rata, a $5000 investment is equivalent to 635 W (15 kWh/day) average. Since our house uses about 300 W (7.2 kWh/day) that's about double our electricity use, heaps better than a wimpy grid connect solar system that would only provide about half at a much greater cost.

According to the prospectus, Hepburn Co-op[91] will pay a dividend of about 7%, so it would return $350 (pre tax) per year. On a 1 kW domestic rooftop array, you can expect to save about $240 per year of post-tax income. Financially there is not much difference. However four times as much electricity is being generated by the wind farm investment of $5000.

7.6 Calculating the cost of CO_2 abatement

Apart from the capital cost of the abatement scheme, we need to calculate the amount of CO_2 emitted to manufacture that scheme.

To illustrate, let's start with the debate about the hybrid petrol/electric car. There are people who will claim that the extra technology in a hybrid car can never be justified – that it will use more energy to manufacture than it will ever save. The same argument can be heard about nuclear power, windfarms, domestic solar photo-voltaic arrays and so on. On the other hand, there will be the enthusiasts who will happily neglect all downsides and see it all as straight benefit. Obviously the answer lies somewhere in between.

To calculate the energy required to produce a hybrid car is a big job, which is beyond the scope of a lay person. It could form (and probably has) the basis of a PhD. However here's a shortcut to the answer. The idea is this: Every country has a CO_2 output which is closely linked to its GDP. Why not take that average CO_2 output per dollar of money circulating in the economy as a yardstick of calculating the CO_2 equivalent of the production of the vehicle?

At first such an approach sounds quite naive. Not all expenditure of money results in the production of the same amount of CO_2. I'm sure you can think of examples. If you buy a painting for $50,000 it has negligible impact, whilst the much targeted four-wheel-drive or SUV is at the other extreme. All true. Or is it? What happens to the $50,000 after you have parted with it? Does it go into a mattress never to be seen again? Most likely not. It doesn't matter if it goes to an artist or to a dealer, it will inevitably be put to some unknown use. Even if it just goes into the bank, the bank invests that money in some other unknown investment (for example for someone to build a mansion), resulting for the most

[91] http://www.hepburnwind.com.au/

part in further consumption. So as that money diffuses through the economy, its CO_2 impact, averaged over that economy, can be quantified by the simple dollar value.

In using this approach, not all countries are of course equal. A good list[92] is provided by Wikipedia[93]. This information can also be deduced from the graph on page 336 of SEWTHA[94]. Considering similar countries in groups, USA and Australia produce on average about 0.5 kg of CO_2/\$ of GDP – or \$2000 per tonne of CO_2. China and Russia are at about 2.4 kg of CO_2/\$ of GDP, whereas Japan, Germany, UK and New Zealand are at 0.3. Switzerland, France and Sweden do even better at 0.14, mainly through their extensive use of hydro and nuclear power. This is ignoring the fact that they, like we, are *outsourcing* some of their CO_2 emissions by buying manufactured goods from China.

You may want to consider these figures when you buy things. A cheap Chinese product may produce 20 times as much CO_2 per dollar as a Swedish or Swiss product. However, since the prices of the equivalent products are very different, you will need to take that into account.

Returning to the example of the hybrid car: I use numbers plucked from the Drive section of a Melbourne newspaper which tells me that a Honda Civic hybrid costs A\$7,000 more than a conventional Honda Civic and that the fuel consumption is 4.6 L/100 km vs 6.9 L/100 km[95]. The question is this: Does the reduction of fuel consumption from 6.9 to 4.6 L/100 km justify the extra energy that was used in manufacturing that hybrid car?

I have no way of accurately calculating the energy used in producing the myriad of components in a hybrid car. I have even less idea of what will happen to the money paid to the workers who assembled it or the sales and managerial staff of Honda. But I do have one tool at my disposal: the price. For a car manufactured in Japan, I'll assume 0.3 kg of CO_2/\$. For a price difference of \$7,000 the answer is \$7,000 x 0.3 kg of CO_2/\$ = 2100 kilograms, or about 2 tonnes of extra CO_2 to build a hybrid.

The next question should be, how much CO_2 will this car save? According to the information from the newspaper, it will save 2.3 L/100 km or, over 15,000 km, 345 L/year. However the story is more complicated. In country driving the

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92 GDP data is for the year 2004 produced by the International Monetary Fund. Carbon dioxide emissions data was collected in 2004 by the CDIAC for United Nations

93 http://en.wikipedia.org/wiki/List_of_countries_by_ratio_of_GDP_to_carbon_dioxide_emissions

94 Our numbers do not line up exactly but remember that this is a secondary effect that is being considered here.

95 Whenever quoting a figure for fuel economy, expect complaints both from people who say it is too high and too low. Please address any correspondence to the Melbourne Age.

saving is as little as 1 L/100 km whereas for city driving it is 5 L/100 km. For simplicity sake we'll stick with the average improvement of 2.3 L/100 km.

Is this worth it? Well the next step is to work out how much CO_2 the car produces. The commonly quoted figure is 2.6 kg of CO_2/L. However I do not use this figure because that is just the fuel delivered at the bowser. When exploration, production and refining are taken into account the efficiency is 0.85, so the more truthful figure is 3.05 kg of CO_2/L. By that figure the average CO_2 saved is 1052 kg or about 1 tonne per year. So CO_2-wise the payback period is 2 years; 2 extra tonnes to produce the car and 1 tonne saved per year. If the car is used exclusively for city driving the annual saving would be 750 litres or 2.3 tonnes, a CO_2 payback period of less than one year.

Now for the next question: is this good value? CO_2 offsets are pretty cheap. The going rate, if you survey the internet is about $30 per tonne. Why would you spend $7,000 more on a car to reduce your CO_2 emissions by 1 or 2 tonnes a year? Does it make sense?

The answer to this tricky question very much depends on the cost of fuel. For a mixture of country and city driving, with a saving of 2.3 L/100 km, the annual saving at a petrol price of $1.40/L will be $520. The saving over 15 years would be $7000. So over that time the extra cost of the hybrid car will have been paid for and the CO_2 saving will have cost effectively nothing[96].

Since nobody can predict it, I have plotted the cost of CO_2 abatement vs petrol price, for city, country and mixed driving over a 15 year period[97].

The idea of Figure 32 is to show how much it costs per tonne of CO_2 abatement. Depending on the conditions, CO_2 abatement could be costing a lot, or you could be saving money whilst doing it. Note that this does not mean that the more you drive the more CO_2 you save – it means that if you are going to drive anyway, you may actually save some money whilst producing less CO_2.

7.6.1 LED replacement of fluorescent lights

Another case study is our office lighting. We have approximately 100 fluorescent tubes in our office, in use for about 250 days a year at 10 hours per day. At 45 W each (there is a loss in the ballast) they use 11 MWh/year. In Victoria, at 1.4 tonne of CO_2/MWh, that amounts to 16 tonnes of CO_2/year.

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[96] I have ignored the cost of money, but I also have ignored the fact that petrol will go up in price. The calculation is approximate, to say the least. However if the cost of money tracks the cost of fuel, it may not be too bad.

[97] It remains to be seen what the actual life will be of the batteries in these cars.

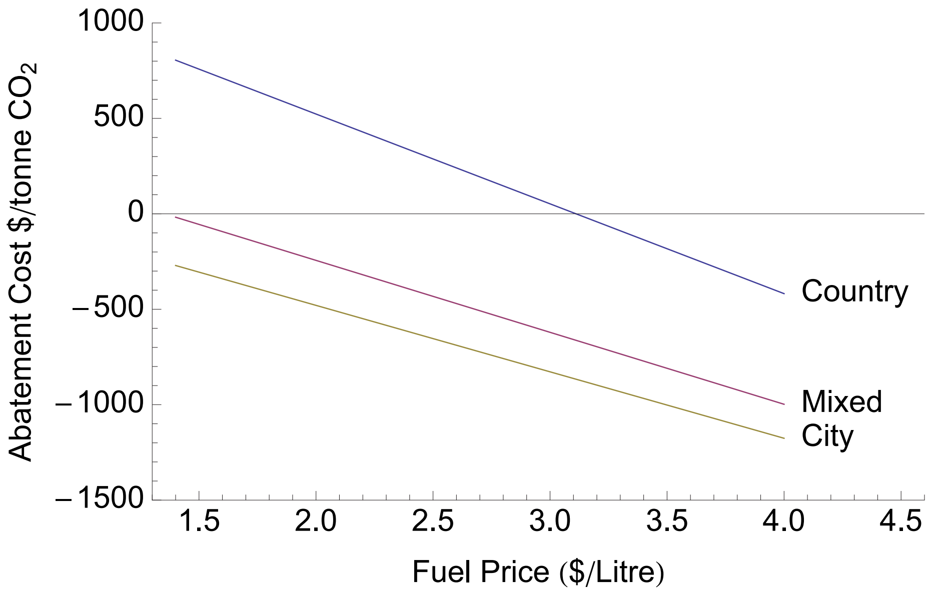

Figure 32. The apparent cost of CO_2 abatement through use of a hybrid electric car. The lines are for city, country and mixed driving. A hybrid car used exclusively for country driving is an expensive way of abating CO_2.

We have replaced these tubes with direct-fit LED arrays. These lights cost a horrifying \$90 each or \$9000 for the whole office. But they use 15 watts each instead of 45, saving 30 watts. Is this worth it? Using the carbon intensity shortcut, from the CO_2 point of view, at 0.5 kg of CO_2/\$, each LED tube represents 45 kg of CO_2 or to fit the whole office, 4.5 tonnes. The CO_2 payback time is 6 months. The payback time would be longer – 30 months – if we used the Chinese figure of 2.4 kg of CO_2/\$. The answer is somewhere in between.

Next, it is interesting to calculate the cost of CO_2 abatement through fitting these tube replacements. At the 2008 Victorian electricity price, of \$0.15/kWh, the office cost saving was \$1130/year for a capital cost of \$9000. The simplistic calculation of financial pay back period is 8 years, assuming that electricity prices track interest rates. By that time, some 87 tonnes of CO_2 abatement would have cost effectively nothing. Of course, electricity prices are likely to rise faster than interest rates, so that the payback period could be shorter.

When these tubes were fitted and some halogen downlights were replaced with compact fluorescents, the total electricity use in the office dropped from 61 to 38 kWh/day. Most of the electricity was used by lighting, and smaller proportion by laptop computers photocopiers and printer etc.

Figure 33. The endcap of an LED replacement for a fluorescent tube. These tubes are a direct plug-in replacement for a standard tube. You only have to take out the starter. They use 15 W instead of 45 W (actually 17 instead of 43 by my own measurements).

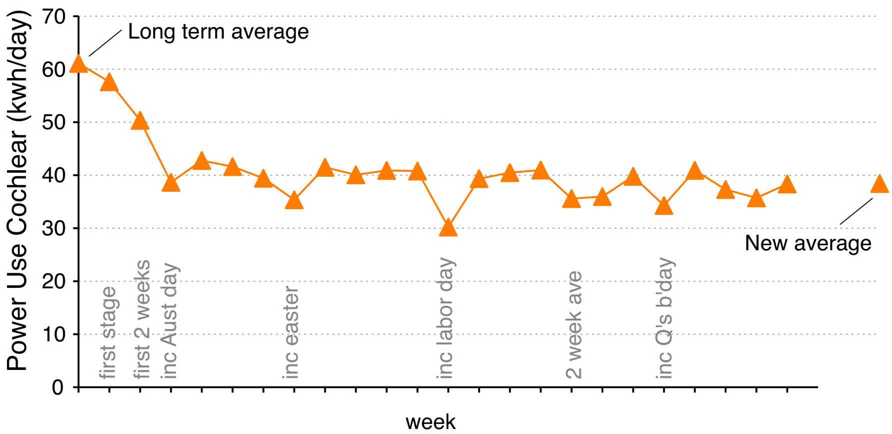

Figure 34. Electricity use after fitting LED and CFL lights in the office.

7.6.2 A tale of two solar photovoltaic arrays

It is interesting to note that two apparently similar systems, a rooftop domestic system in a capital city and a remote area power system come out very differently in terms of efficiency. Of course we cannot solve the world's energy problems by putting in more remote area power systems but this is an illustration of the calculation method[98].

[98] Here we are talking about the gross cost of the systems (to the community at large). The RECs, rebates, Feed-in-tariffs and tax deductions are left out of the discussion. They determine who is paying what part

I have to point out that this calculation was made in 2008 and that things have changed in many ways since then.

In 2008 a typical 1 kW rooftop grid connect system cost[99] about $13,000. A 1 kW system generates about 1300 kWh/year. At $0.15/kWh that's about $200 worth of electricity a year. Simplistically, assuming interest rates track electricity cost, that means a payback period of 13,000/200 = 65 years. It is not going to last that long. Let's assume 20 years. Over that time it would save $4000 of electricity and 26 tonnes of CO_2 (assuming interest rates track electricity cost and 1 kWh = 1 kg of CO_2). So the cost of 26 tonnes of CO_2 abatement is 13,000 – 4,000 = $9000. To include the cost of building the system, let's assume $13,000 x 0.5 kg/$ = 6.5 tonnes. The total CO_2 saved over 20 years is 26 – 6.5 say 20 tonnes, at a monetary cost of $9000, or $450/tonne[100]. By 2010 the situation had changed considerably. In 2010 a 1.5 kW peak system cost about $9500 gross, excluding RECs (Renewable Energy Certificates), FITs (Feed in Tariffs), rebates etc.

As a counter example I used the building of a 32 kW (peak) solar installation in the Kimberley. It is on the Mornington Wildlife Sanctuary, a property of the Australian Wildlife Conservancy. Mornington used to go through 37,000 – 50,000 L/year of diesel a year. Now they use 7,000, saving at least 30,000 L/year, which has to be trucked in. They save around $80,000 dollars a year. The gross cost of that system was about $800,000 so the payback time is 10 years. However, if it lasts 20 years, by that time they will have saved $1,600,000 in fuel. As far as CO_2 is concerned, diesel accounts for 2.9 kg of CO_2/L, but once you take into account refining and transport that's about 3.3 kg of CO_2/L, so the Australian Wildlife Conservancy will save 100 tonnes of CO_2 a year. Over 20 years it will have saved 2000 tonnes. This will not cost money, they will save $800,000, assuming diesel price tracks interest rates. Now let's look at the CO_2 penalty in building this installation. The Australian economy produces 0.5 kg of CO_2/$ of GDP. The Mornington scheme created 400 tonnes from $800,000. So

99 In 2009 this had dropped to about $9,500. In a perverse manner, the Australian government was giving rebates of $8000 plus RECs of about $1,500. The rebate was independent of the size of the system, so that it encouraged people to put in the smallest eligible system which was 1 kW. At the end of the scheme, installers were offering to put these systems in for free – good for the owner but a waste of public money.

100 A comment frequently made is that locally generated power saves on transmission line losses and infrastructure. However the infrastructure exists already and the losses are about 15%. If power is being fed in from the solar PV system, there are still transmission losses.

the CO_2 saving over those 20 years is 2000 – 400 = 1600 tonnes, for a monetary saving of $800,000 i.e. negative $500/tonne cost of abatement[101].

The reason for the difference of a positive cost of CO_2 abatement for the grid connect system and the negative cost of the solar PV outback system is a reflection of the cost of the fuels being displaced, brown coal being fed directly from a mine into a furnace by a conveyor belt vs diesel, refined and trucked into an remote area.

Don't misinterpret this. I am not saying that we can save the world from catastrophic climate change by building more solar remote area power systems. I am saying that for my dollar, I did better by supporting AWC's solar system than by putting PV panels on my roof. The benefits were:

- The Kimberley is nearly twice as sunny as Melbourne
- The Western Australian government paid for 55% of the solar system
- I could get a tax deduction for supporting the AWC but not PV on my roof (there was no domestic PV rebate at the time)

Figure 35. The 192 solar panels of the 32 kW peak power system at the Australian Wildlife Sanctuary *Mornington* in the Kimberley. The property once used 50,000 L/year of fuel and now uses 7,000 L/year.

[101] This is not quite true since the batteries will not last that long – this will probably add another 100 tonnes of CO_2 over the 20 years. This will cost say around $200,000 extra, so the total savings would be $600,000 for about 1500 tonnes so a total negative $400/tonne which is still good

Was I too glowing in my description of the benefits of Mornington's solar PV system? Possibly – I'll let you decide. And it depends on when one considered that the project actually began. The power use at Mornington reflected its cattle station origin and standard practices in that business. The generator switched off every night at 10 pm, when all the lights were switched on. When it was started at 6 am, the lights were on and remained on all day. They were nearly all incandescent. This practice was partly due to the belief that a generator does not use any more fuel if it loaded or unloaded and that a lightly-loaded generator suffers from cylinder wall glazing. This causes it to burn sump oil and need maintenance so, all in all, it was most convenient to never switch anything off. After investigation and discussion of these issues, the annualised fuel use dropped to about from 50,000 to 37,000 litres and subsequent physical efficiency measures dropped it further to around 27,000 litres. The commissioning of the solar power installation dropped the fuel use to 7,000. So what does the project save? You could say that it saves 50,000 minus 7,000 = 43,000 litres per year. At the time diesel fuel cost $1.82/L hence the saving of $80,000 per year. On the other hand the solar panels actually only generate enough power to displace 20,000 litres of fuel. As it turns out the last delivery price of diesel was only $1.23/L so that would be a mere $24,600 per year.

In calculating the cost/saving of a project such as this it is difficult to know what to include in the project. The benefits are derived not just from the equipment installed but also the knowledge acquired and behaviour modification through the increased awareness of the load and power supply. The residents are aware of the generator occasionally, which may remind them of equipment that could be switched off. The supplier of installation pointed out that the design is usually for 60% renewable energy but in the event, better than that is often achieved.

The trick of using carbon intensity to calculate CO_2 payback periods and costs of CO_2 abatement is of course very easily criticised. There are scientific methods which are more accurate but here's the catch. Consider an aluminium component. Do we know the source of the aluminium? If it is recycled, its CO_2 loading is far less than newly mined and refined aluminium. There is the question of where the electricity was generated. If it was generated in Tasmania, the CO_2 loading is small since it is mostly hydro. In Victoria it comes from the dirtiest source in the world. But now that Victoria and Tasmania are linked by a cable, does that still hold true? In fact, it is quite impossible to pin down the exact quantity of CO_2 attributable to a piece of aluminium. The dollar carbon intensity method could be the more accurate.

Finally as a CO_2 abatement strategy, let's include simply withdrawing money from the economy. This I'll call *Shred the money*. I don't mean keep the money in the bank. As I said earlier, the bank invests that money in some other unknown investment. Whilst shredding money is not the most effective way of CO_2 abatement, nor the most pleasant, it is certainly effective. This occurred or is occurring in the 2008-09 Global Financial Crisis. The CO_2 abatement will be quite noticeable. There is the danger that some countries will meet their targets, inadvertently, by this means alone providing more excuses for doing nothing.

A good example of the effect of frugality is Cuba. Don't mistake this as a plug for communism. However, as the New Scientist heading put it: *Cuba flies the lone flag for sustainability*[102]. The article explains that only Cuba provides a decent standard of living without consuming more than its fair share of resources. Although this is not voluntary, it nevertheless demonstrates that it is possible.

7.7 Efficiency, Effectiveness and Potential

To compare different CO_2 abatement measures, I need to define my terms. Cost efficiency, or just efficiency, I'll define as the cost of CO_2 abatement in dollars per tonne of CO_2 abated, spread over the duration of the project or life of the device. This efficiency includes the CO_2 cost in manufacture and also includes any cost saving the measure might bring. The efficiency number can be negative, as we have seen.

Effectiveness is not the same as efficiency and it is important to recognise the difference. Here's an example to illustrate that difference. The Mornington solar power system cost $800,000 and will save money whilst abating CO_2 emissions by 2000 tonnes. That's efficient but it's not very effective. 2000 tonnes is not much abatement for that capital outlay and the abatement will occur over 20 years. At 100 tonnes per year, that's $8000 per tonne per year. An example of the other extreme is the compact fluorescent light. These lamps cost approximately $3 and over their life (hopefully) of 6000 hours, they can save 80 x 6000 = 480 kWh which at the Australian average of 1 $kgCO_2/kWh$ comes to 480 kg or 0.5 tonnes – all for $3. Two of these lamps would provide 1 tonne of abatement at a cost of $6. So the CFL is far more *effective* than the solar power system even though it is equally efficient. This brings the discussion to the third attribute: *potential*. Neither CFLs nor remote area power systems will solve our CO_2 emissions problem. CFLs don't have the potential to do so because lighting only accounts for about 5% of total electricity use[103]. Given that much lighting is already fluorescent and that anyway electricity represents only about half

[102] *New Scientist* p. 10, 6th October 2007
[103] http://www.need.org/needpdf/infobook_activities/SecInfo/ConsS.pdf

our CO_2 emissions, the potential for CFLs to solve our problem is very limited. Likewise remote area power represents only a small fraction of total power so again the potential of this approach is limited. To really make inroads into the problem, we need measures that are efficient, effective and have large potential to abate CO_2. A mix of many measures can effectively provide this but no single measure is the answer.

Earlier in this book, I was comparing electricity generation means by using a $/W capital cost metric. However, not all energy is expended in the form of electricity and also the CO_2 produced or saved by different means varies. So rather than using the simple $/W metric, I have modified it to $/tonne$CO_2$/year. This is similar to using watts but allows a fair comparison with non-electricity based projects or devices.

7.8 Bang for buck comparison

To deal with the different methodologies, or you could say, different figures of merit, I have tabulated various schemes and devices in Table 12.

I agree that this table is difficult to use. In an attempt to simplify the presentation, I am trying a method which plots *effectiveness* on one axis and *efficiency* on another. To try to include *potential* as well, I'm using the size of the markers to indicate how much potential that CO_2 abatement measure has. So we are looking for measures that are effective, meaning that they will abate CO_2 quickly for the capital cost required. We also want them to be efficient, meaning that over their life, the cost of abatement will not be expensive and hopefully will save money. Finally we want to look for measures which have potential, meaning that they are widely applicable.

In Figure 36 I have attempted to present a comprehensive view of different measures, based on their efficiency, effectiveness and potential. For example, measures such as more efficient lighting can represent very efficient and effective measures but they only have small potential. They are represented by small dots. The comprehensive renewable power system for Australia discussed earlier has the greatest potential so it is represented by a large dot. Measures which are at the bottom left-hand corner of the diagram are both effective and efficient – i.e. a good idea. Measures at the top right-hand end of the diagram are both inefficient and ineffective. Examples are a hybrid car which is only used for country driving and a solar hotwater system on a holiday house which is only used 10% of the time.

Energy saving measure	Capital cost $/W	CO_2 payback time (years)	Effectiveness $ per tonne CO_2 saved per year	Efficiency Cost of CO_2 abatement inc. cost of energy saved
Compact fluorescent lamp (CFL)	0.05	0.003	6	-$196
LED fluorescent tube replacement	3	0.17	346	-$184
More efficient fridge	8	0.46	1005	-$25
Early replacement of heating system	1	0.05	556	-$52
Mildura power solar power	14	0.80	1651	-$37
Rooftop grid connect system	46	2.65	5929	$8
Birdsville Geothermal	7	0.40	819	-$69
Large Geothermal	3	0.17	344	-$89
CETO wave power pilot project	6	0.34	694	-$74
Portland wind farm	5	0.27	547	-$79
Hepburn Coop wind farm	9	0.49	1005	-$62
Cloncurry thermal solar	16	0.88	1834	-$30
Georgia nuclear	6	0.34	680	-$84
IRIS sealed nuclear reactor	3	0.17	343	-$89
Domestic Solar/gas hot water service	11	0.62	1289	-$147
Solar/gas HWS holiday house 10% occ.	109	6.20	17988	$602
Hybrid car, country driving	0	4.58	21956	$805
Hybrid car, city driving	0	0.92	3250	-$271
Gorgon CO2 injection project	0	0.14	281	$7
CCS Otway basin	0	0.15	305	$30
Renewable energy system for Australia	13	0.74	1535	-$42
Fairview coal bed methane	0	1.73	4169	$417
Remote area solar system complete project	133	7.61	10568	-$161
Remote area solar system solar alone	133	7.61	20305	$193
Shred money	0	0.0	2000	$2,000

Table 12. Comparison of CO_2 abatement measures including the cost of energy saved.

7.9 What makes sense?

To explain what I mean under this very general heading, here are some examples. Many dishwashers use electric heaters to heat their water. This frustrates me because I know that when we use the dishwasher on a hot sunny day the water in our solar HWS is nearly boiling yet the water is heated electrically, adding to the already high load imposed by all the air-conditioning that is operating. It would make much more sense to connect it to the solar HWS, something not recommended by the installers. However, my son did it – with no ill effects. To think of this another way, consider a household which has solar photovoltaic panels. The dishwasher uses about 1 kWh/day or about 40 watts on average. Nearly all of that power goes into heating water. At $50 per average watt, that's about $2000 worth of solar panels required to supply the dishwasher's heater. It would certainly make more sense to reconnect the dishwasher to a hot water source.

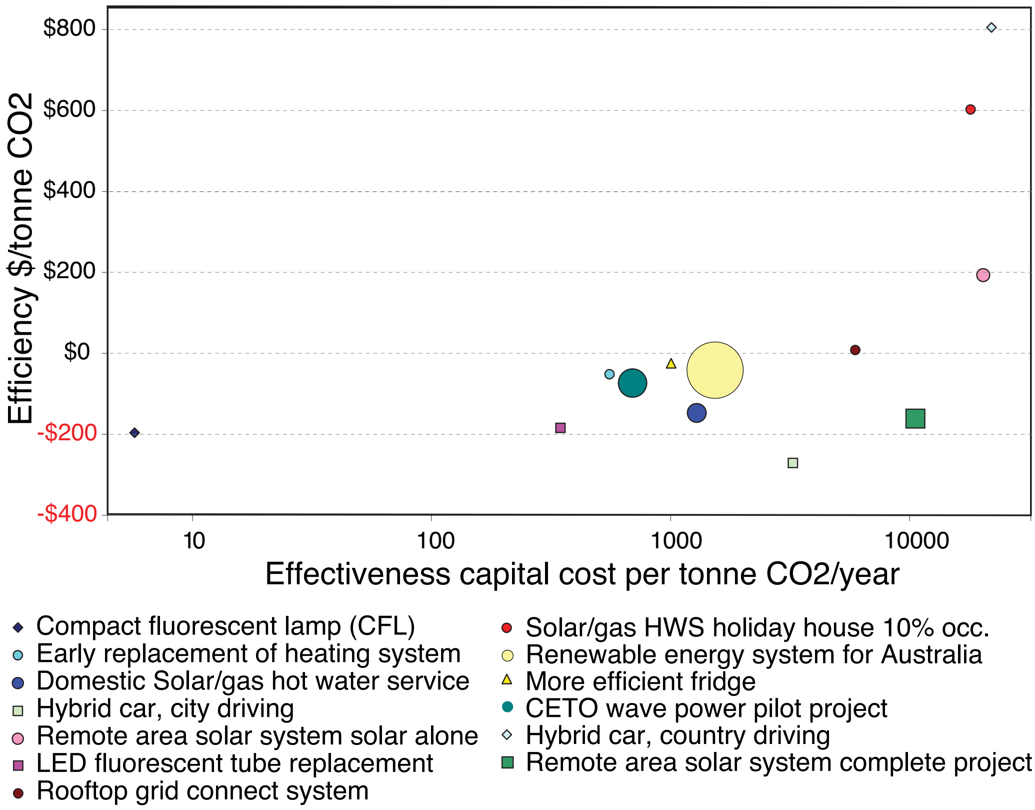

Figure 36. Diagram showing Effectiveness, on the horizontal axis, in tonnes of CO_2/year per $ of capital cost and Efficiency on the vertical axis showing $/tonne of CO_2 abated over the life of the project, This number can be negative, if money is actually saved by abating CO_2. The diagram also attempts to depict Potential, by the size of the mark for each particular CO_2 abatement measure.

When our household changed from a fully electric to a fully gas stove and oven, our daily electricity use dropped by 3 kWh/day or about 120 watts on average. To supply that from solar PV would take $6000.

Recently we have heard bleating from people who have had solar PV and have had their meters changed and no longer qualify for off-peak electricity for water heating. My question would be: why are they using electricity to heat water?

The only situation in which you might do this is in an area where gas is not available, or an area where solar provides nearly all the hot water and requires only minimal boosting by electricity.

Of course you don't have to have solar PV for these arguments to apply.

The motive for many people to install a solar PV system may not be environmental but financial. The dense web of RECs, FITs and rebates distorts the market to the point that this can be financially beneficial to the individual but not to the community as a whole.

Another motive for people to take up solar PV may be the perception of autonomy. It is a well-hidden fact that the grid-connected solar PV system is not at all independent of the grid in the case of a power failure. If the grid goes down, it simply shuts off. Having no energy storage and no way of matching the supply to the demand, it cannot work without the grid.

8 Transporting negative CO_2

To maximise bang for the buck of CO_2 abatement, you do not have to place the abatement scheme on your house or even in your local community. The scheme may be far more effective elsewhere.

To explain the concept of transporting negative CO_2, I shall use some examples. A friend expressed the desire to go green and how good it would be to have solar panels on her house. Unfortunately, she told me, her roof was quite unsuited to solar. I said *your son has a big roof facing north, why not put it on his roof?* But *I want to go green!* she replied. But here's the point: does the atmosphere know what roof the panels are on? If your intention is to be green, the obvious tactic is to put the panels on the most suitable roof available; who owns the roof is not relevant. Of course there is the minor matter of whose electricity bill gets the benefit, but that's an accounting issue. To illustrate in a different way, I will mention another friend's household in British Columbia which uses 240 kWh/day (in contrast to our house 7 kWh/day). Most of the electricity is used by a very inefficient heat pump to heat the house. I was told however that that was OK because all the electricity in British Columbia is hydro. But just across the border, in Alberta, the power is 85% coal generated. So a more judicious use of power in BC could mean that power could be exported to Alberta, cutting total emissions of Canada overall. A high *bang for buck* scheme would be to give the family a more efficient heating system. The abatement would come at $10/tonne CO_2 even though BC has hydro-electricity.

8.1 Carbon offsetting

It is usual in considering the CO_2 produced by driving to consider only the fuel used. There are carbon offsetting companies that offer CO_2 offsets such as planting trees. In fact the CO_2 due to cars is about three times as much as that due to the fuel burned in the engine, taking into account the principle mentioned earlier that CO_2 actually produced is proportional to the dollars spent. Here are some figures from the automobile club, the RACV, magazine for a medium sized car travelling 15,000 km a year.

- 20 c/km fuel cost
- 50 c/km other costs

- 15,000 km/year – 1,500 litres
- multiply by 3.05 to get 4,600 kg of CO_2 (includes drilling, refining, transport)
- Car costs $0.5/km in non-fuel costs (RACV figure)
- Non-fuel cost $7,500/year
- CO_2 = 0.5 x 7,500 = 3750 kg
- Total annual CO_2: 8.4 tonnes
- Typical offsetting company calculator: 4 tonnes

From these figures, it is not unreasonable to suggest that the actual CO_2 contribution of a car is approximately double that produced by burning the fuel alone.

Have you ever wondered why carbon offsetting is so cheap? I certainly have. While stumping around trying to raise money for the solar system for the Australian Wildlife Conservancy I was thinking: Why are we doing this? For only $1000 a year we could offset the 80 tonnes of CO_2 a year put into the atmosphere by AWC's diesel generator. I think I have it figured out.

Say you lend me $100. After a while you come back and say *what about my $100?* I reply *OK, here's $10 – just put it in the bank and in 50 years it'll be worth more than $100.*

Whilst a tree will remove a tonne of CO_2 over its lifetime, isn't that the same as the $10 for 50 years in the bank as a substitute for a $100 repayment? The global warming caused by the CO_2 you generated this year will never be fully compensated by gradually removing that CO_2 over the next 50 years – it is doing the damage now.

A tree will remove a tonne of CO_2 over its lifetime. Figure 37 shows a graph to explain what I mean.

Figure 37 uses figures from Greenfleet[104] who for $40 will plant 17 trees to offset the CO_2 produced by a typical car in a year. The offset is for fuel alone, not the associated CO_2 costs. I have nothing against Greenfleet and I subscribe to them myself. I am just making the point here that by planting 17 trees each year, after 20 years your car will have produced 70 tonnes more CO_2 than your trees will have absorbed. In 45 years you will break even. I have to emphasise that I am using notional figures here[105] – and every plantation is different but is this *loan* acceptable?

What's my point here? We are being offered carbon offsets these days for all sorts of things. For example, it is very easy to just click on a box, offset your

104 http://www.greenfleet.com.au/

105 Assuming that the tree has its maximum uptake of CO_2 at 35 years and lasts about 80 years.

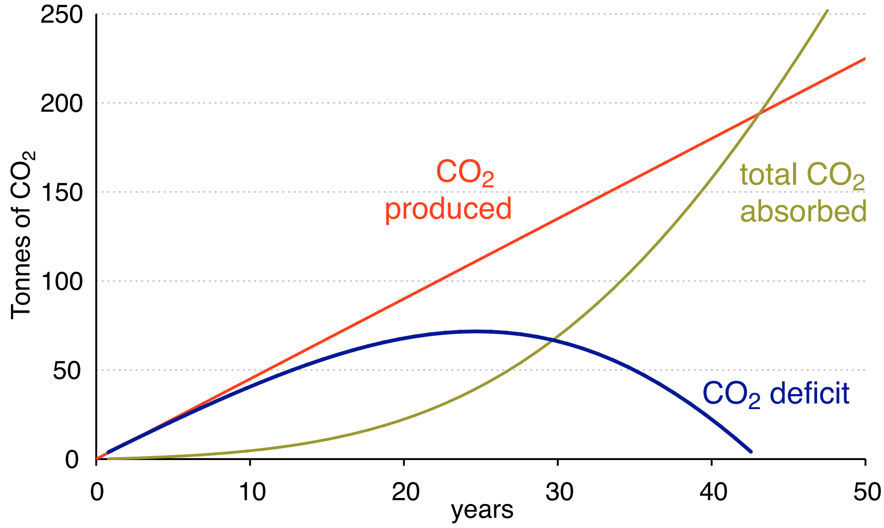

Figure 37. Cumulative CO_2 produced by a car and absorbed by planting 17 trees every year

air travel and fly off with a clear conscience. I see a danger in this. In fact the airlines are encouraging people to fly more just by offering it. Planting trees is a good thing but don't feel you're off the hook that easily. Personally I think a more immediate approach is necessary.

My suggestion is that you would have to double the recommendation to account for the car or plane that is using the fuel and then multiply by another X times – a total of 2X to break even on CO_2. But how much is X? It is beyond the scope of this treatise to calculate it – just think how willing you would be to give someone a 50 year interest free loan.

8.2 Biomass – sequestration

SEWTHA[106] shows that all accessible fossil fuels together contain 1600 Gt of carbon and far more – 3000 Gt – of carbon is contained in soils. Considering that we are in the process of converting all of the fossil fuel into CO_2 over maybe 200 – 300 years, the potential for tucking some of it away in soil seems quite significant.

Dr Christine Jones[107] a groundcover and soils ecologist and the founder of the Australian Soil Carbon Accreditation scheme is working on crops which improve the carbon content of the soil, in contrast to growing crops specifically to convert

[106] p.241, SEWTHA
[107] http://renewablesoil.com/pdf/Dr-Christine-Jones-CV.pdf

them to charcoal (biochar – as proposed by James Lovelock) to be buried. Dr Jones makes the surprising statement:[108].

> *"It would require only a 0.5% increase in soil carbon on 2% of agricultural land to sequester all Australia's emissions of carbon dioxide. That is, the annual emissions from all industrial, urban and transport sources could be sequestered in farmland soils if incentive was provided to landholders for this to happen"*

This statement needs careful interpretation[109]; firstly it is important to realise that agricultural land is very different to arable land. Australia is deemed to be 60% agricultural but only 6% arable. Agricultural land includes grazing land, some of it semi-desert which might support one cow per square kilometre. Secondly you need to realise that 0.5% increase in soil carbon is not the same as 0.5% increase in carbon in the soil. The soil carbon percentage might be say 5% so an increase of that figure by 0.5% would be a 10% increase in the carbon in the soil – from 5% to 5.5 %. As a result the statement above is a factor of about 200 different to what you might assume. Having got over these points, let's look at the statement again which could read: it would require a 10% increase in carbon in the soil on 20% of arable land to sequester all Australia's emissions of carbon dioxide. Then the question would be how often could you do this? One would assume that you couldn't increase the percentage of carbon in the soil by 10% year-on-year.

In Jones's paper *Our soils our future* she says

> *"On average, 7 tonnes of topsoil is lost for every tonne of grain produced. This situation has worsened in recent years due to an increased incidence of erosion on unprotected topsoils, coupled with declining yields. The most meaningful indicator for the health of the land, and the long-term wealth of a nation, is whether soil is being formed or lost. If soil is being lost, so too is the economic and ecological foundation on which production and conservation are based. In addition to the loss of soil itself, there has been a reduction of between 50% and 80% in the organic carbon content of surface soils in Australia since European settlement."*

She claims:

> *"By adopting regenerative soil-building practices, it is practical, possible and profitable for broadacre cropping and grazing enterprises to record*

108 http://www.amazingcarbon.com/PDF/JONES-OurSoilsOurFuture(8July08).pdf

109 A 0.5% increase in soil carbon across only 2% of agricultural land would sequester

a net sequestration of carbon in the order of 25 tonnes of CO_2 per tonne of product sold (after emissions accounted for).”

Assuming that each person consumes about 1 kg of food per day and taking into account that some of the produce is fed to animals and some is wasted, maybe 3 times as much produce has to be grown to make that 1 kg. That would be 3 kg per person per day, or about 1 tonne of product per person per year. If the statement above is correct, that could sequester the 20 tonnes of CO_2 for which Australians are responsible.

Can this be verified? I’m not convinced yet. I consulted agricultural professor at the University of Melbourne, Bill Malcolm. Unfortunately regeneration of soil carbon by agricultural methods has problems. He quoted research from CSIRO that shows that yes – it can be done, but for every tonne of carbon tied up 850 kg of nitrogen is also tied up and significant amounts of phosphorus and sulphur. This means that the soil either loses productivity, or you need to add these elements in - which is very expensive and fertilisers use a lot of energy to produce. If that is not bad enough, N_2O is produced in the process of building up soil carbon. N_2O is a potent greenhouse gas. His conclusion was that it was a non-starter.

Putting biochar into the soil is being looked into to see if it has the same deleterious effects but the jury is still out[110].

8.3 A personal strategy

We have discussed a number of tactics – ranging from hybrid cars and LEDs to a complete renewable power system for Australia. However the range of options available to the householder is limited. Once you have reduced your flying, driving etc, insulated your house, what next? Here’s the problem as I see it. Per person, we use about 200 kWh/day – that’s about 8000 W of gross power and about 100 kWh/day/person or 4000 W/person of end-use power. Let’s look at the most visible, most discussed and one of the most expensive renewable energy devices available to the general public. That’s the domestic rooftop grid connected photovoltaic system. A 1 kW array in Melbourne or Sydney will produce about 160 watts average. Assuming a household of four people, that’s about 40 W/person or 1 kWh/day/person – about 1% of total end-use energy use. So what to do?

[110] Transport is a major issue as costs of moving biochar more than 25 km means that it all falls over (at what CO_2 price? 1 tonne of CO_2 is sequestered by 270 kg of C. Is the cost of transporting this 25km prohibitive compared to say $30 for that tonne of CO_2?)

I think the answer is to try to think beyond our own domain. We need to think about other possibilities such as our workplace and the community. In my case it was the Australian Wildlife Conservancy solar power system, our workplace lighting and the Hepburn Community Wind farm. Each of these projects saves more than I could have achieved in our own house. In fact, together they achieved more than we could have by moving into a tent, turning vegetarian and never driving or flying again. *It is important to keep in mind that only between a third and a quarter of our energy use is under our personal control*.

To me, the best way of leveraging the use of renewable energy is to find good *bang for buck* projects and technologies and show those in control that they can actually save money whilst saving energy. There is little enough money around for these projects, so don't waste it on stuff which is poor value.

8.4 Rebates and Renewable Energy Certificates

Often governments offer rebates to install solar systems, both hot water and photovoltaic. Until recently, the federal government was offering a fixed $8000 rebate for solar grid connect PV systems. This scheme was very popular and encouraged people to put in the smallest eligible system, thus maximising the proportion that the rebate would cover. Eventually the systems were offered for free. The bonanza came to an end when the government ran out of money for the scheme. It was replaced by a new scheme which generates the money from Renewable Energy Certificates (RECs) rather than taxes. This is an arrangement where power companies are able to buy *green* energy from the public. Each REC is supposed to be equivalent to 1 MWh of green power.

The government sponsored scam, is that to enable the domestic rooftop industry to continue, initially they would issue 5 times as many RECs as the solar system was deemed to generate over the next 15 years. The resulting income from the RECs is meant to provide the replacement for the rebate which was coming from the taxpayer. The major flaw is that these phantom RECs can now be sold to gullible *green* electricity buyers.

The decline of the REC market has also had the consequence that financing for some planned renewable power projects has become more expensive due to a reduction in the value of RECs that could be sold for it, putting some of these projects in jeopardy.

The issue of RECs which don't represent their true renewable energy component goes further. RECs are issued for the installation of solar hot water heaters on the assumption that they replace electric heaters. However the greenhouse gas emissions of existing gas heaters are about one sixth lower than electric heaters. This is because inherently gas has about half the emissions of coal, which accounts for a factor of 2 and because electricity generation is about 30% efficient. So replacing a gas water heater does not reduce emissions by the value of the RECs, but only by a fraction of that. Secondly, there is no stipulation that the solar water heater must be in use to generate the RECs. It could be on a holiday house (I have one on mine) and the deemed saving is only available when the house is in use, maybe a tenth of the time. So again the RECs are fictional (I didn't sell mine). The justification used by the government for these schemes is that they stimulate the solar industry, never mind the deception. If anybody else were playing this game it would be illegal.

Leaving the phantom RECs aside, another question is whether, by selling their RECs, people are in fact selling their *greenness* to whoever is buying green energy. Of course the panels are on your roof, but nevertheless, both of you can't be green. For you to remain *green*, you have to hold the RECs, not sell them.

If you want to buy *green* electricity, the safest plan is to buy wind power, which in general cannot be bought from the public. The electricity companies have to buy it from wind farms or generate it themselves.

Several Australian state governments are now also offering net Feed-In-Tariffs, (FITs) in which the electricity can theoretically be sold back to the power utility at a much higher price than they normally pay. This sounds good until you realise that the net FIT is paid only on the excess over your own consumption and that furthermore, systems which are large enough to provide an excess, that is systems over 2 kW peak, are excluded from the deal (because the customer might benefit).

There are however also Gross Feed-In-Tariffs offered in the ACT and now also in NSW. The question of gross vs net feed-in-tariffs is as follows: Gross tariffs pay you for all the electricity you generate, regardless of how much you use. Net tariffs pay you only for the excess you generate over your own use. The benefit of the gross tariff system is that it is easy to calculate how much power will be generated over the coming years and how much money that will earn and thus what the payback period is. The rates for buying the electricity are usually on a contract over a given period and so there is minimal risk in the decision. Also, feed-in purchase rates can be as high as $0.60/kWh which is about 4 times the usage rate, making the pay-back period of a grid PV system about 15 years which is shorter than the 20 year lifespan. A final advantage is that system sizes can now be as large as 10 kW (peak) installations, providing a substantial financial gain after the system is paid off. The disadvantage of the gross FIT is it does not encourage energy saving measures. You get paid the higher rate for your electricity regardless of how much of it you use yourself.

With the net FIT, the financial return is almost impossible to calculate. If the net were calculated on a long term basis there will be no surplus for a system of a size which would qualify. On the other hand, if the metering is every half an hour, there will be times on a sunny day when the fridge is not running and nothing else is being used. All of the solar is going into the grid. So it all depends on the metering and the load patterns. It is virtually impossible to calculate what the payback period would be.

The system which would be fair and would encourage low electricity use would be a long-term net FIT based system which allows large systems. People do know what their long term electricity use is and by allowing a large enough system to provide a net input to the grid, economy would be encouraged and the return would be predictable. This is not a scheme which appears to be under discussion.

8.5 Personal cost or gross cost?

A tricky decision is whether to cost your CO_2 abatement measures by the price you yourself pay, or the total cost. All alternative energy measures are surrounded by a dense network of rebates and subsidies. Whether to consider societal cost or personal cost is a decision we have to make ourselves.

In addition, you may want to try to include the market cost of CO_2[111]. At present in Australia the cost of CO_2 is about $50/tonne, based on the cost of RECs and CO_2 average[112] of our electricity generating system. You may want to include this in the value of energy saved, if and when a carbon trading scheme is implemented.

[111] One unit of carbon = 44/12 = 3.67 units of CO_2, a factor often confused. Oxygen has an atomic weight of 16 and Carbon, 12. So CO_2 is 12 + 2 x 16 = 44

[112] 1 tonne of CO_2/MWh or 1 kg of CO_2/kWh

9 Efficiency and waste

9.1 Fridges

I was struck by David MacKay's measurement of his fridge (p. 50 SEWTHA) drawing only 18 W. My son who also lives in Cambridge has a similar fridge which uses 25 W. That's fine David's fridge is a high efficiency German one. For both, the low power surprised me because our fridge in Melbourne uses about 90 W. These UK fridges are about half the size of a modest Australian fridge (187 L vs 420 L). Scaling the 25 W power consumption by the square root of the size comes to 37 W. Since our fridge is about 10 years old, I checked the market and found that current 420 L fridges have an energy rating of 440 kWh/year, about 50 W. More efficient fridges are available in other countries[113].

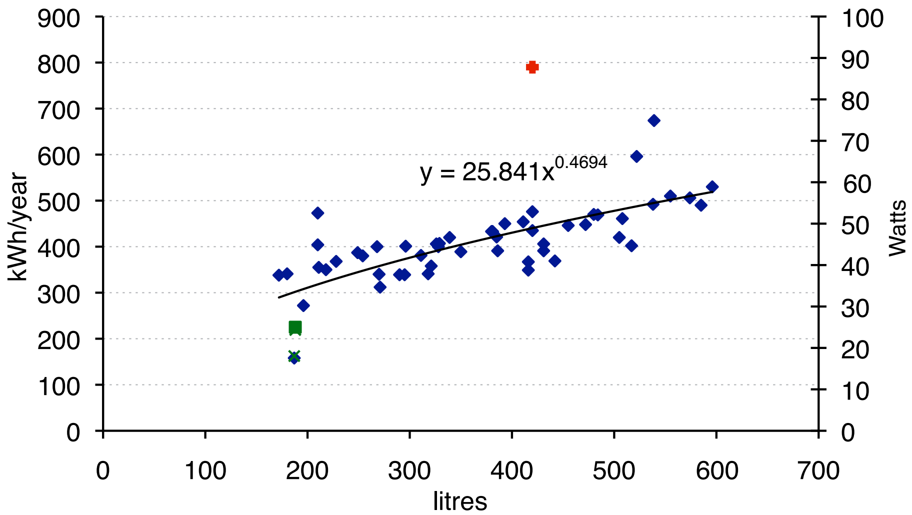

Figure 38. Current Australian fridges compared with a 10 year old Australian fridge (red dot) and a small UK fridge (green square). The dot below that is David MacKay's fridge.

You can see why I was surprised at David's figures. The fridge uses about a quarter of the power in our house. However the benefit of replacing it early is only modest. If we replace it say 5 years early, at a pro-rata cost of \$320 (average life of a fridge is 15 years, cost \$960) the CO_2 abatement using the *bang for buck* approach is \$36 per tonne of CO_2. The new fridge would save about 40 W.

[113] A friend in China tells me that 200 L fridges there are in the 18 W to 25 W range.

As far as cost is concerned, there did not appear to be any correlation with efficiency. Using the example of a 400 L fridge and making minor corrections[114] to prices and wattage of fridges of around that size showed that price was unrelated to efficiency.

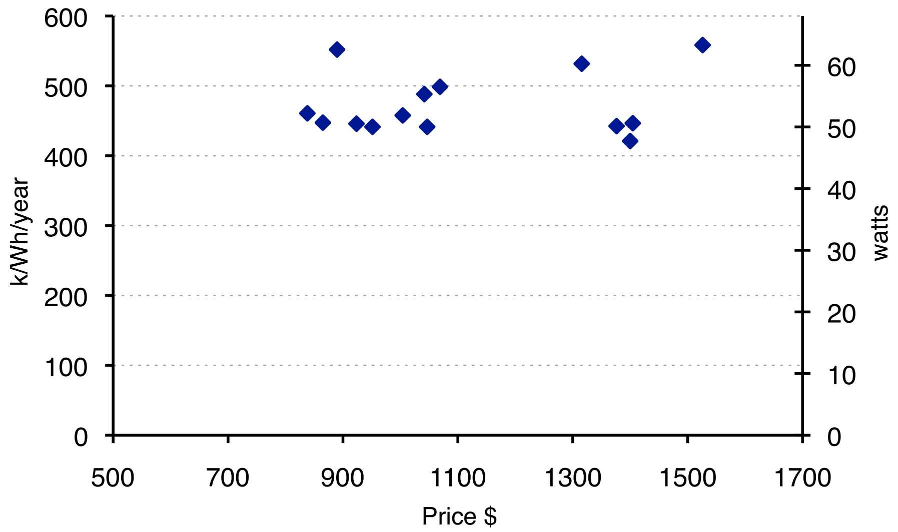

Figure 39. Cost vs power consumption of fridges around 400 L. There appears to be no correlation.

Returning to the question as to why David's fridge and my son's fridge, both in Cambridge are so much lower power than the Australian figures could be because, at least during the summer months, Australian kitchens are a good bit warmer than UK kitchens. The difference is perhaps not unexpected.

9.2 Ducted heating system

If you have done all the things which have become very familiar, like using low energy lights, insulating the ceiling and installing solar water heating, you have to move on to other measures. These might include insulating the walls, and double glazed windows, all rather expensive and difficult operations. Here's something you may not have thought about. In a place like Melbourne, the biggest single user of domestic energy is the heating system. Here is a graph of the gas use in our house over the period 1985 to 2009. We have gas fired, air ducted central heating.

[114] I adjusted the watts by using a power of 2/3 function to reflect the increase in area and volume. For price I used a linear function.

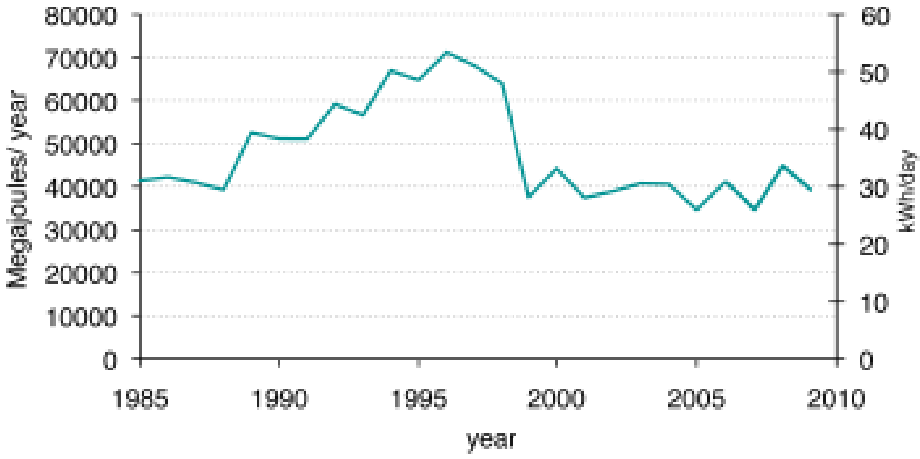

Figure 40. Gas usage in our house, before and after the heating system was replaced. The gas use started to climb from around 1988 and then dropped abruptly in 1999.

The heating system we had, was installed in about 1979 (off the graph). You can see that up to about 1988 our gas use was about 40,000 MJ/year or 30 Wh/day, averaged over the whole year. However over the years 1989 to 1999 there was a steady increase in our gas consumption. Repeated service calls did not reverse the trend. By 1999 our gas use was up to 70,000 MJ/year. In that year we replaced our heating system and you can see the dramatic return to our previous consumption.

When we had the heating system replaced, I had the ducts changed, since they were in a poor state too. Although I will never know how much of the increase in gas use was due to the ducts and how much due to the heater itself, I did attempt to find the best source of ducts for the new system. I was disappointed in how badly this part of the system was characterised. The heaters on offer competed on the basis of efficiency (between 78% and 90%) but when it came to ducts, the installers were only dimly aware that these could differ. Ducts were just ducts. They thought I was pesky to ask what they were intending to use.

When I finally did get specifications of various ducts and calculated the expected heat loss of the best on offer, it came to 1.5 kW (while the heater was actually running – not average). I estimated that the heater ran for about 480 hours per year (actually running) so the annual losses would be 2 kWh/day. However investigation much later showed that this theoretical calculation was not supported by measurements. For more information see a paper by Fricker, Fricker and Johnson[115]. Their data suggests that the real losses from the ducts would be about double this – 3 kW while running , or annually 4 kWh/day. This did

115 http://www.concertinafoilbatts.com/

not include any leakage from the somewhat makeshift and dubious looking duct couplers which were used. These couplers and Y junctions, although having a small surface area, were completely uninsulated and bound up with what else – duct tape! This tends to lose its stickiness in time, especially when subjected to heat. This is a work in progress. If it sounds as though I might be splitting hairs here, look again at the graph in Figure 40. The savings (or lack of losses) can be substantial. Consider – you may shop around for the best heater, which is about 90% efficient. For a 22 kW system, that means, 2 kW is lost. Now consider the ducts, which could be losing 3 kW. The total efficiency is then only 80%. It would seem there is a lot of potential saving here.

Returning to the issue of whether it was a good idea to replace the heating system at 20 years, rather than hang on for, say, another 5 years we can use the *bang for buck* approach. The new system cost $4000 or about $200 per year of capital cost. By replacing it 5 years earlier, it cost us an extra $1000 but saved $1500 in gas. The extra CO_2 produced in its earlier replacement was about 0.5 tonne but it saved 10 tonnes in emissions. So we saved 9.5 tonnes of emissions at the same time as saving about $500. The total *cost* of CO_2 abatement was therefore negative, about – $50/tonne, a very approximate calculation, since we are only guessing about how long the old system would really have lasted or how much gas we really saved.

Incidentally, our current usage of 40,000 MJ/year is not too impressive. Now that only two people live in the house it's 15 kWh/day/person.

9.3 Water heating

Water heating in our house is now a negligible user of gas since we have gas boosted solar hot water. In Figure 41 I have plotted the primary energy use in our household for heating water and the house heating. The electricity figure has been multiplied by 3 to reflect the energy loss in electricity generation. The graph depicts primary energy, whereas the gas use is the form of primary energy already, including losses in the ducts and heater. The right hand axis is in kWh/d and the left in MJ/year but they are on compatible scales. They compare *apples with apples*. As you can see from the primary energy standpoint, the water heating was similar to the house heating. Now with gas boosted solar water heating, gas use by the booster is lost in the *noise*, i.e. there is no discernible difference in overall gas used. Why am I telling you this? Because when our solar hot water service was electrically boosted with off-peak electricity, it used

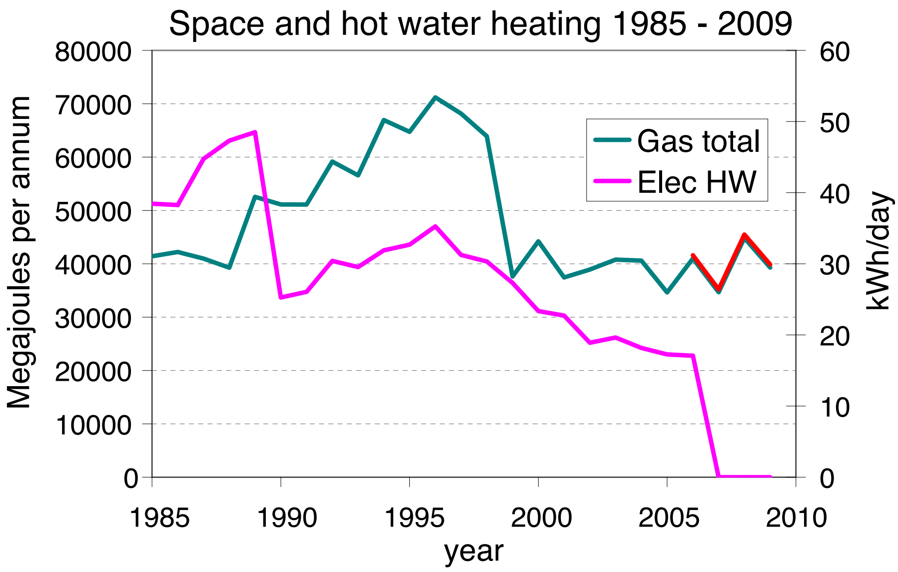

Figure 41. History of our gas use, showing the demise of the old system and its replacement. The red trace shows the gas use since the introduction of a gas booster for the solar hot water heater in 2006. It made no difference! The sharp drop in electricity use for hot water in 1989 shows the transition to electricity boosted solar water heating. The final drop is when we got rid of the electric boosting.

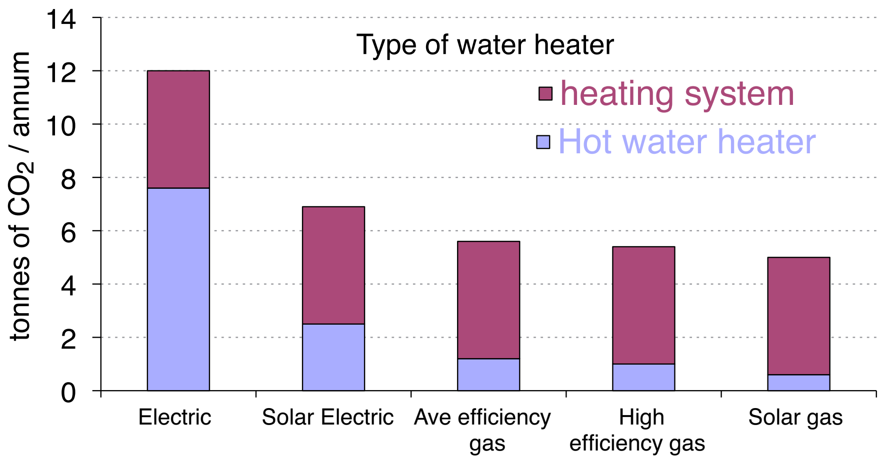

Figure 42. Comparison of CO_2 emissions from various domestic hot water heaters and gas space heating systems in Melbourne. The biggest benefit is obtained by just getting rid of electric water heating. Note that if you already have a gas water heater, the gains in efficiency might be swamped by an inefficient central heating system.

as much primary energy as our central heating system. Switching to gas boosting eliminated this. It halved our electricity use, whilst insignificantly increasing our gas usage.

How does this translate to CO_2 emissions? We saw in Figure 40 that our gas usage was as high as 70,000 MJ/year. At 63 g/MJ, that's 4.4 tonnes of CO_2/year. We reduced it to 40,000 MJ/year by changing the heating system, so reducing the CO_2 to 2.5 tonnes of CO_2/year, a reduction of nearly 2 tonnes of CO_2/year. Now consider, if we had had a normal gas hot water heater, and changed that to solar; we would have dropped our CO_2 load from about 1.2 tonnes to 0.6 tonnes, a reduction of only about 0.6 tonnes. As far as CO_2 is concerned, Figure 42 compares the typical impact of gas space heating vs a range of water heaters. Electric water heating dominates over space heating and electrically boosted solar is better but not the answer (in Melbourne). An average efficiency gas HWS is still better whilst a high efficiency one better still. The gas boosted solar hot water is the final touch.

What about running costs? Whilst, it is a good idea to change to gas boosted solar water heating, don't be too surprised if you don't see the difference on your gas bill, especially if you have a particularly inefficient heating system. Here's a calculation: just say you had something like our previous poor heating system and decided to keep it but replace a conventional gas water heater with a solar one. You could have been using 70,000 MJ/year plus 19,000 for hot water or 89,000 total. Say that using solar you dropped that to 70,000 plus 9,000 = 79,000 MJ/year . that's only a 10% decrease. If at the same time the price of gas went up by 10% (it went up by 8%), the monetary billing amount may not have noticeably changed. If the heating system was becoming increasingly inefficient as ours had, you would not have seen any effect at all.

In summary, if you want to dramatically lower your energy use, look at the central heating system first. And certainly if you have electric water heating, get rid of that. Electric water heating in dishwashers is another culprit and so are all electric stoves. Solar water heating is valuable but may not be the highest priority. Solar photovoltaic systems would be the lowest, only after you have attended to the others.

You will note that I have not mentioned the gas used by cooking. I have neglected this. Figure 43 shows why.

This figure shows that during the summer months, the gas use is insignificant (1.4% of the monthly average) compared to the rest of the year. I have written in more detail about this and other domestic energy use issues in my articles in the CSIRO's ECOS magazine[116].

[116] http://www.ecosmagazine.com/act=view_file&file_id=EC138p16.pdf
http://www.ecosmagazine.com/act=view_file&file_id=EC139p32.pdf
http://www.ecosmagazine.com/act=view_file&file_id=EC140p28.pdf

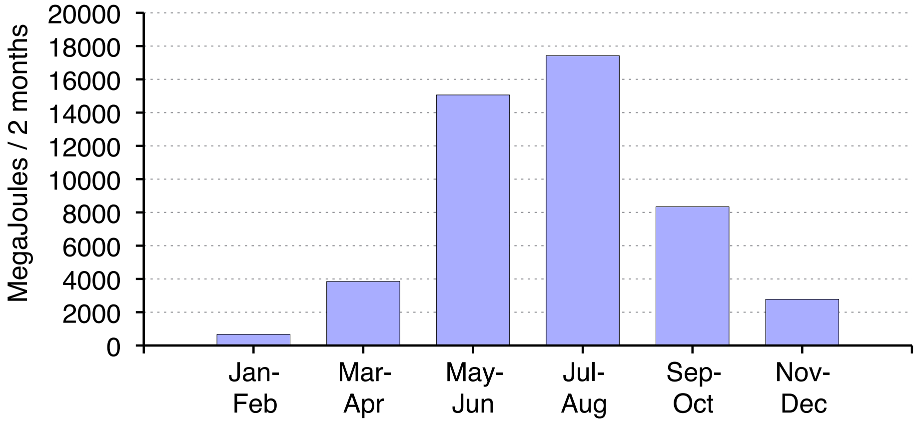

Figure 43. Gas use over the year. Note that the cooking use (Jan – Feb) is insignificant compared to heating.

9.4 Floor Insulation

In regard to domestic energy conservation, ceiling insulation is number one. Double glazing is considered too, but less frequently, on account of the cost, although retrofits are possible. But do you hear of floor insulation? Hardly ever. Partly that's because it is generally believed that floors don't lose much heat. Everyone knows that heat rises. That's true but it doesn't mean that the floor can be ignored. If you have already a well insulated ceiling, additional insulation there may not make as much difference as insulating the floor. Few companies offer floor insulation but one that does claims that for a moderately well insulated house, some 20% of the heat losses are through an uninsulated suspended timber floor.

I ran our house through software for the energy rating of houses using the CSIRO AccuRate *engine*. Comparing the cases with and without floor insulation of R3, the annual saving was 8000 MJ equating to 250 watts annual average or about 6 kWh/day.

Is this good bang-for-buck? With R3 insulation under this house, we would save 8000 x 1.37/100 = $109 per year. The price of this insulation, installed, would be about $6000. The saving in greenhouse gas emissions would be 8000 x 0.063 = 500 kg/y or about half a tonne of CO_2 per year.

Assuming this is a 25 year *project*, over the 25 years it would save $2725, or cost $3275. It would save 12.5 tonnes of CO_2 but the $6000 price could be estimated to create (at $2000/tonne) an additional 3 tonnes of CO_2 . So the CO_2 saving would be 9.5 tonnes for a financial cost of $3275 giving a bang-for-buck efficiency of $345/tonne of CO_2 abated. At a capital cost of $6000, the effectiveness would be 6000/0.5 = $12,000 capital cost per tonne of CO_2/year.

These two measures put it in the top righthand corner of Figure 36. This doesn't make it particularly good bang-for-buck but slightly better than a solar hot water service on a holiday house. However if you have done all the other things that are feasible on a pre-existing house, it might be the next best thing. When building a new house, it would certainly be good idea, since the cost of floor insulation, whether it is under a timber floor or a concrete slab, is so much easier and the duration of the *project* is maybe 70 years rather than 25 years. Some time well before that, it is likely that burning gas just to heat houses will no longer be possible.

9.5 The CSIRO AccuRate software

I discovered the CSIRO AccuRate software after I had first done my calculations of heat loss from our house using a simplistic approach, i.e. using the R values of the surfaces, their areas and the degree days for our location. I did this in much the same way as David MacKay did in Section 21 of his book SEWTHA: Smarter heating and in Appendix E: Heating II. In these sections the U values (the reciprocal of the R values) are given for various building materials. The concept of heating and cooling degree-days is discussed. However there is much more to it than that, and this is taken into account in the AccuRate software. The program includes effects of convection, shading, solar gain and very importantly, the thermal mass of the building materials. It matters too whether the mass is inside the house or on the outside since internal thermal mass surrounded by insulation produces a smoothing effect in temperature, allowing daytime solar gain to keep the house warm at night. Insulated thermal mass also keeps the house from rising to high temperatures in summer. The frame materials, double glazing and glass coatings are all modelled as well as various types of drapes and blinds. All this is supported by the local climate data, drawn from a database.

The beauty of this software, which is generally used to establish the star rating of houses to meet building regulations, is not so much the star rating feature but the ability to tinker with the house (or prospective house) to optimise the thermal performance. The program is available in its CSIRO version but two other vendors[117] have added their own user interfaces to the program to make it more user friendly. Detailed performance information is given[118] apart from the simple star rating. It was this software which illustrated the significant difference between the simplistic calculations of heat loss through the floor based on temperature

[117] BERS and FirstRate5
[118] BERS and AccuRate

differences and R values versus the more detailed approach. In this case the difference was a factor of two higher for the heat loss through the floor but in other cases the reverse may apply.

9.6 Domestic heating and cooling statistics

The following information[119] is from the Australian Bureau of Statistics

9.6.1 Heating and cooling

Electricity was used for home heating in over half of all NSW households, split equally between reverse cycle air conditioning and other forms of electric heating. One in four households used gas heating and one in ten used wood heating, mostly outside Sydney.

Air-conditioning was used to cool homes in half of NSW households. Outside of Sydney, 30% of households used fans and less than 5% used evaporative cooling.

9.6.2 Hot water systems

Off-peak electricity was used for hot water systems by over 40% of households in NSW. Usage was higher in households outside of Sydney at 60% compared to one third of households in Sydney. Over half of all households in separate houses used off-peak electricity, compared to one in six households (16%) in flats, units and apartments. This should not be interpreted as meaning only 16% of flats used electricity. My interpretation is that if they used electricity, it was based on the general tariff.

Gas hot water systems were used by one quarter of NSW households, with usage higher in Sydney (at one third) and lower outside Sydney at 15%.

Solar energy was used for hot water systems by less than 3% of households in NSW. There was a higher uptake in areas outside Sydney at 4%, compared to only 2% of Sydney households.

One startling thing about these statistics is that only one quarter of NSW households used gas or solar, the rest being apparently electric. A typical electric hot water heater uses about 6000 kWh/year or 16 kWh/d, 670 W. In terms of primary energy, that's about 55 kWh/d/household, almost all of it unnecessary

[119] 10 May 2007 Domestic water and energy use NSW http://www.abs.gov.au/AUSSTATS/abs@.nsf /mediareleasesbyReleaseDate/E6E28532AF3FE2F5CA2572D60081B288?OpenDocument

since gas boosted solar water heating uses a tenth of this, or less in many areas. These water heaters, for NSW alone, which has about a third of Australia's population, represent about 1 GW of electrical end-use power. This compares with the average total electricity generation of 25 GW. Australia-wide, electric water heating is about 10% of unnecessary load.

I tried to estimate the air-conditioning load by looking at the monthly statistics of electricity use. Figure 44 shows that there are two peaks, in winter and in summer. In between there are dips when little or no heating or air-conditioning is required. From this graph it can be roughly deduced that the air-conditioning load is about 2.5 GW in summer. In the calculation I subtracted the dip from the summer maximum for each state separately and added these differences together. This was because the autumn/spring dips do not coincide in the states so the total does not give the best indication of the air-conditioning load. Using the same method, I estimated the winter heating load which was also about 2.5 GW. This rough estimation does not consider that many office buildings require cooling even in winter because of large glass areas and high internal heat generation. It does not take into account that on some days the heating will be operating on the shady side of the building whilst the air-conditioning is operating on the sunny side. There is generally no attempt made to simply shift the excess heat from the sunny side to the shady side.

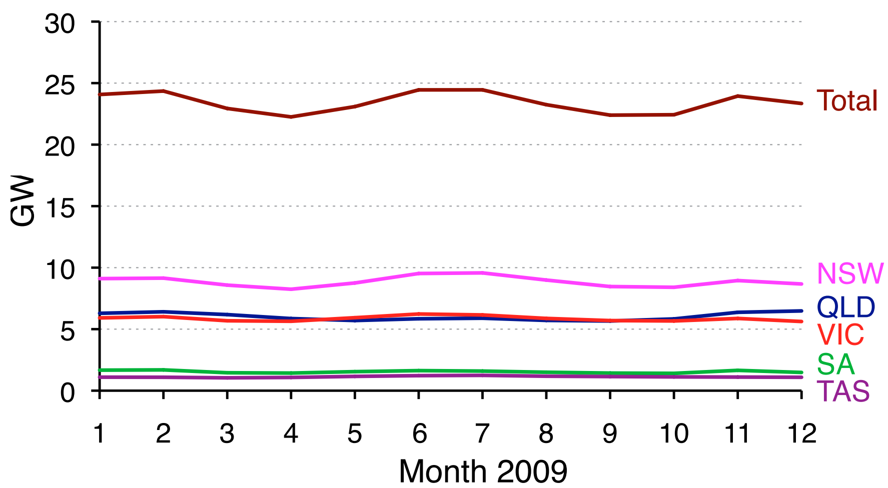

Figure 44. Monthly statistics of electricity use in Eastern Australian states. There are dips in autumn and spring when little heating or air-conditioning is required. The peak summer load is about 2.5 GW above these dips. No data available for WA.

Australia's heating, hot water and cooling statistics as supplied by electricity and gas look something like this:

- Hot water: 5 kWh/day/person (UK 12 kWh/day/person)
- Heating: 20 kWh/day/person (UK 24 kWh/day/person)
- Cooling: 9 kWh/day/person (UK 0.5 kWh/day/person)
- Refrigeration: 1 kWh/day/person (UK 0.5 kWh/day/person)

Compared to the UK figures (p. 53 SEWTHA), we use far less to heat water (maybe surprising but UK water heaters are particularly badly insulated). We use almost as much heating our houses, but our houses are several times the size of UK houses. For cooling we use 18 times as much energy – no surprise there. For refrigeration we use twice as much, because we have bigger and less efficient fridges. In total we use about 35 kWh/day/person compared to the UK figure of 37 kWh/day/person

9.7 Solar air conditioning

The big advantage of solar air-conditioning is that the peak cooling load matches the solar input.

In general, air-conditioning can be achieved in a number of different ways.

Conventional compressor-type air-conditioners, use a cycle involving compressing a gas, allowing the heat to dissipate in one place and then allowing the gas to expand removing the heat from the surroundings in another place. This is the process used in most, but not all fridges.

Cooling can also be achieved by direct evaporation of a fluid, such as water. The cooling is effectively using the unwanted heat to evaporate water. The downside is that the water adds to the humidity and thus some of the benefit of lower temperature is lost.

Another form of cooling called absorption refrigeration uses heat to produce cold. In former times gas and kerosene refrigerators used this principle[120]. Ammonia is introduced into the evaporator, causing the refrigerant to evaporate, taking energy from the surroundings. The process involves the mixing of the gas with butane and this mixture is dissolved in water. The ammonia solution flows to a heat exchanger where a heat source drives it from the water as a gas again and it returns to the evaporator. This principle is adaptable to solar thermal systems, particularly concentrating tubes which can achieve the temperatures required.

Other forms of solar air conditioning involve using desiccants to draw the humidity and hence some of the heat from the air. Solar thermal energy is then

120 This refrigerator was invented by Albert Einstein and Leo Szilard who conceived the nuclear chain reaction.

used to dry out the desiccant. These systems are called adsorption[121] chillers and the desiccant is typically silica gel.

Solar air-conditioners are being actively developed in China[122]. A useful paper comparing seven installations is referred to here. The cooling system is mostly using absorption and evacuated tubes and heat pipes. One system, in Freiburg uses adsorption. The absorption systems have a coefficient of performance (COP) of 0.7, which is considered to be very low. However when I compared these systems to a conventional air-conditioner with a COP of 3, driven from photovoltaic panels, I found that the effective equivalent PV efficiency would need to be 17% to get this level of performance. So the absorption system turns out to be very good. No costings are given but the systems are impressive. However, at present no domestic sized air-conditioners are being trialled; the systems were in the range 36 kW – 560 kW cooling capacity. The Fraunhofer-Institut für Solare Energiesysteme ISE, in Freiburg Germany is trialling many different systems including smaller sizes.

The CSIRO is making progress on solar cooling[123] in a system that uses a dry absorbent material heated by solar collectors. However, additionally, cooling is possible without sunlight by being coupled to conventional solar hot water heaters. It is not based on the absorption refrigerator principle. ANU is working on the same problem, developing a hybrid thermal system capable of solar air conditioning in summer, solar space heating in winter and solar water heating all year round using commercially available collectors[124]. The ANU system is based on an ejector jet pump principle.

9.8 Waste reduction

How often have you had an appliance fail, sometimes for a trivial reason? The all too frequent solution is to replace it rather than fix it.

An obvious way to reduce waste of goods to landfill would be to improve the repair process. However spare parts are often too expensive or not available. One way to reverse this would be to have 'appliance wreckers' in the same way as car wreckers.

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[121] Adsorption is distinct from absorption. Adsorption is where something sticks to the surface of a body rather than being absorbed by it.

[122] Comparison of Seven Solar Air-Conditioning Systems Installed in Different Countries, He Zinian, Beijing Solar Energy Research Institute Li Wei, Wang Ling Beijing Sunda Solar Energy Technology Co., Proceedings of ISES World Congress 2007, Springer.

[123] http://www.heliosray.com/msg.php?id=64

[124] http://solar-thermal.anu.edu.au/low_temp/solarac/index.php

By way of illustration, our dishwasher broke down. The repairman said it was the controller which cost $340 and $540 by the time it was installed. I visualised our dishwasher on the tip with a dud controller, next to one with a good controller but a dud pump. As it was, I repaired the controller – the part cost 87 cents – but that's not what I am advocating. If these goods, rather than going to the tip, went to a depot where the good parts could be removed and reused, a lot of waste could be avoided. But before I actually fixed the controller, I found that many dishwashers shared that controller, but there was nowhere where I could get a used one.

This facility, which is extensively used in the car industry is not available for household appliances.

9.9 Waste management

Burning gas from landfill sites and burning of waste is treated on page 42 onward of SEWTHA. I will add to that only that there are ways of treating waste which are more environmentally friendly than this. An example is the Global Renewables[125] process used in Sydney[126].

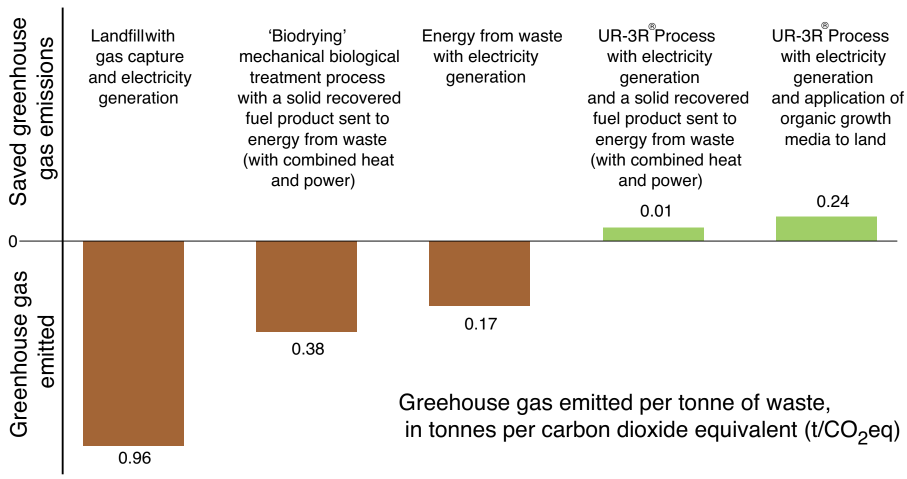

Figure 45. Global Renewables process for saving CO_2 emissions by electricity generation and application of organic growth media to land.

[125] http://www.globalrenewables.eu/ur3r-process/description

[126] Carbon Footprint of Global Renewables' UR-3R™ process and Competing Alternatives, Jan 2008, prepared by Eunomia Research and Consulting.

The graph shows that although burning waste from landfill is effective, it still produces greenhouse gases. The company claims the process can actually sequester carbon whilst generating electricity from waste. From their website they are:

- **Reducing** waste generation through community education and recognition of the full life cycle cost of waste management
- **Reducing** greenhouse gas and leachate emissions by processing the putrescible portion of the waste stream
- **Recovering** valuable recyclables from the non-putrescible portion of the waste stream
- **Recycling** the organic portion of the putrescible waste stream into renewable energy and high quality organic growth media (OGM), thereby reducing greenhouse gas emissions and leachate, and helping to close the carbon cycle.

The Eastern Creek UR-3R™ facility in Sydney integrates these technologies to provide a total solution for waste management.

9.10 Desalination

A highly controversial project in Victoria is the desalination plant to bolster Melbourne's dwindling water supplies. The three supplies considered were: a pipeline from the north, using recycled water and building a desalination plant. Of these three, two are going ahead or are already completed. The pipeline, which was meant to bring water from the rivers in the north was justified on the grounds that the infrastructure in the north will be improved to reduce the significant water lost through evaporation and leakage. However little water has become available due to the ongoing drought and the fact that the calculations were based on *average* rainfall rather than the rainfall of recent years. In the meantime, some[127] 92 GL of almost pure (to meet EPA requirements) treated water is being pumped out to sea each year. By 2012 it will be pure enough so that if mixed in dams would reach potable standard. However the government's stance on this is *The Government does not support the drinking of recycled water*.

How much power does the desalination plant use? In a report[128] Victorian Desalination Project Assessment Under Environment Effects Act 1978 January 2009,

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[127] http://www.environmetrics.net.au/docs/Stateline\%20Victoria.pdf

[128] http://www.dpi.vic.gov.au/CA256F310024B628/0/DD995AED61193C74CA2575380077C830/$File/Final+Assessment+-+Victorian+Desalination+Project.pdf

the plant will produce 150 GL/year of clean water. The electricity use of this plant, including pumping is about 92 MW average or about 23 W/person, or 0.7 kWh/day/Melbournian. That's not very much compared to our 4000 W overall end use consumption but on the other hand it is almost as much per person as a household can obtain from a 1000 W peak solar photovoltaic system. To supply the electricity for this plant, every household in Melbourne would need to have a 1000 W solar PV system. You can interpret that either way. On one hand it is a large chunk of our domestic electricity use but on the other hand it is a trivial proportion of our total energy use. This illustrates once more that our domestic electricity use is only a very small part of our total energy use.

As far as greenhouse gases are concerned, the plant will produce about 1 million tonnes of CO_2/year or about a quarter of a tonne per Melbournian, compared to 20 tonnes average per person per year.

It is planned that the CO_2 emissions of the desalination plant will be offset by the purchase of RECs from accredited sources.

Whilst the plant, per Melbournian, is a relatively small contributor to our emissions, it is another example of how we are heading in the wrong direction. The government may say that the power will come from renewable sources but without the desalination plant we could have made a gain with those resources, rather than staying where we were.

9.10.1 Multiple Effect Distillation

Desalination of water can be done by distillation which is generally an energy intensive method. However a process called Multiple Effect Distillation (MED)[129] capitalises on the effect that water boils at lower temperatures when the pressure is reduced. By using a number of successive stages and using the heat given up by condensation of previous stages, the efficiency can be significantly improved. The beauty of this system is that the maximum temperature required is of the order of 70 degrees, making it suitable for use of waste heat from conventional power stations and/or solar power. By using waste heat an energy use of 1 kWh/kL is possible, about a fifth of that required for reverse osmosis. One might ask why we did not we didn't take the opportunity to displace some coal fired power by combined-cycle gas electricity generation and use the waste heat from that to desalinate water. Indeed, why aren't we doing that with recycled water, which is far easier to treat than seawater? Being distilled water it would not really be drinking treated sewerage.

[129] http://www.sidem-desalination.com/en/process/MED/Process/

9.11 Burning fuel like there's no tomorrow

If we are to encourage the population to save energy, it would be a good start to set a good example. Instead we see overt displays of wanton waste of energy for totally frivolous reasons, as seen in the flames at the Crown Casino. The amount of gas used is a well kept secret. It doesn't really matter; it conveys the impression that really there isn't a problem. Our gas will last forever. Climate change? Climate what?

Figure 46. Flames at the Crown Casino Melbourne. Six or so huge flames whoosh every hour between dusk and midnight every night. Each hour this happens not just once, but many times.

9.12 Heating the great outdoors

Australia led the world in anti smoking measures. For years smoking in restaurants has been banned and it's now illegal to smoke even in pubs. That's great. A repercussion of this is that eating places have moved outside. That's OK but when the weather is not so warm, we solve the problem by heating the outdoors. In a busy restaurant area in Melbourne, in one block, I counted some 40 heaters, with ratings of about 40 MJ/hour, or about 10 kW each. That's about 0.4 MW to heat the street. Most outdoor heaters are gas but some are electric which is worse by a factor of six.

9.13 A domestic central heating, cogeneration heat pump.

Here's an idea combining two technologies. Heat pumps are *good*, because they provide 3 times more heat than the electricity they use. This is the Coefficient of Performance (COP). On the other hand, only one third of the fuel burned in a fossil fuel power station ends up as electricity at your house. Burning gas directly is *good* because most of the energy, say about 80% ends up in your house. However, why not combine the two?

1. Gas Boiler alone
   - Heat into building 0.8
2. Power station plus heat pump
   - COP = 3, power station efficiency 0.33
   - Heat into building = 0.33 x 3 = 1
3. Local gas fired, direct drive heat pump
   - Engine efficiency = 0.35
   - COP = 4 (this higher value is used because of the high temperature heat source)
   - Heat into building = 0.35 x 4 = 1.4
   - Waste heat from engine = 0.65
   - Total heat into building = 2.05

Such a system, whilst not using renewable energy goes a step further towards using non-renewable energy as efficiently as possible. The total energy into the building is about twice the level that can be obtained by burning gas directly or using heat-pumps driven by electricity from a fossil fuel source.

9.14 Electric cars

Some electric car enthusiasts describe them as zero carbon. The usual reply to that would be – yes but what about the pollution produced at the power station? And the reply to that is – but I'm going to power my car from renewable energy. Let's look at the figures in the context of Australia.

To use the same figures as our earlier example of a hybrid car, the CO_2/km emitted is 4.6 (L/100 km) x 3.05 (kg of CO_2/L) /100 = 0.14 kg or 140 g of CO_2/km.

What about a realistic electric car? I say realistic because it is common to compare a four door family sedan with a two-seater miniature car[130]. A comparable car uses about 200 – 300 watt-hours/km. Let's take the Australian average

[130] A comparison of electric and petrol cars is well covered in http://www.paulchefurka.ca/Electric\%20Cars\%20and\%20CO2.html

electricity generation CO_2 production of 1 kg of CO_2/kWh. I am assuming an overall charging efficiency of 85%, including the fact that you don't get all of the electricity out of a battery that you put in, and that the chargers themselves are not 100% efficient. So a grid charged electric car, used in Australia produces between 230 g – 350 g of CO_2/km, or let's say about twice as much as a hybrid.

But – the argument can run – *I'm going to provide the electricity from renewable energy*. Fine – but in our current situation you can do even better by driving a hybrid and putting that renewable energy into the grid, displacing 1 kg of CO_2/kWh.

Haven't I been saying that we will have to electrify transport to go to renewable energy. Yes, we will. But it would be putting the cart before the horse to go electric now. Until we have lowered the grid-wide CO_2/kWh to half of its current level, it would be counterproductive. I stressed the grid-wide (almost country-wide, or national) because your personally generated CO_2/kWh is not the relevant figure. If peak oil or oil independence is the issue, yes we could go to electric cars earlier, but at the expense of CO_2 emissions.

The answer to the question as to when, environmentally, it starts to make sense to use electricity to power cars depends on the source of the electricity. It can be summarised in a chart such as Figure 47.

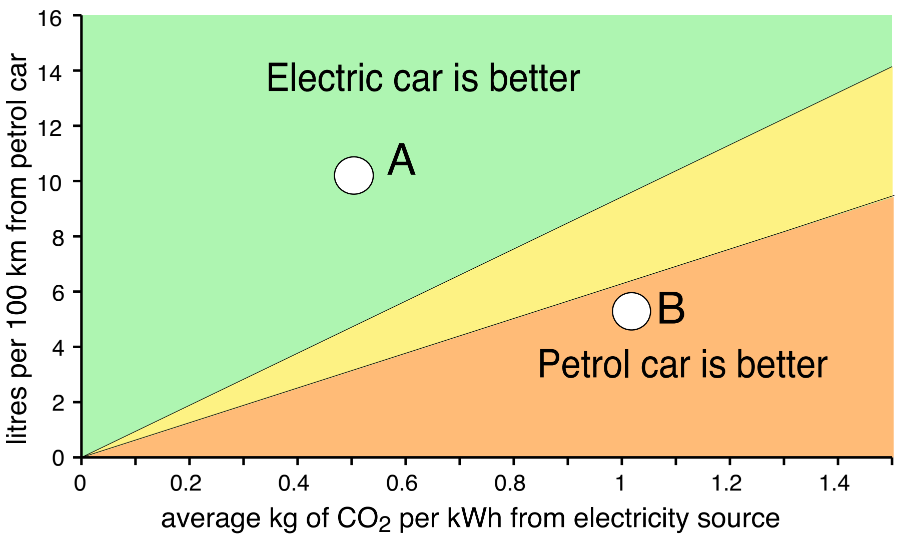

Figure 47. Chart showing when the replacement of liquid fuel power cars by electricity is worthwhile. Point A shows that replacing a petrol car with an economy of 10 L/100 km in a country with an average of 0.5 kg of CO_2/kWh is advantageous. In a country with an average of 1 kg/kWh, using a car with a fuel economy of 5 L/100 km (point B) is better than an electric car.

10 Market forces

It could be argued that when there is a carbon market in operation, society will automatically choose the wisest technologies for greenhouse gas abatement. However for companies to invest there must be security of return. A variable carbon price means that planning is very difficult and there is a long delay in gaining sufficient confidence for work to begin.

I propose an integrated utility organisation that would cover Electricity, Gas, Water, Transport and Efficiency measures. This organisation would use public money on whatever measures are most effective in greenhouse gas abatement. This organisation would operate as the old fashioned government utilities did.

To achieve the abatement, all utilities should be modelled in one major integrated computer program, which would characterise the generators, water providers, public and private transport etc., in a similar way to the climate models. Then changes could be made to the input conditions to determine the effectiveness and cost efficiency of any measure. For example, if a railway is to be built, a desalination plant, wind farm or geothermal power station, the net cost/benefit could be assessed including the repercussions on other utilities and people's behaviour.

11 Putting it all together

After exploring the options available in Australia, let's see if we could supply all our needs from sustainable energy. I seem to have swapped between the terms sustainable and renewable, so we should get this clear first. Renewable means we could keep using it for as long as we are around. The best example is solar power. Sustainable means that we are using up something but we could keep doing it for the foreseeable future. In the case of coal in Australia, if we didn't export any and used it all for ourselves, we could keep doing that for hundreds of years. This isn't the answer that most readers of this book would find satisfactory. So we have to add another requirement to satisfy the readers: very low or zero addtional atmospheric carbon. The object is to come up with a strategy to enable us to live comfortably for a very long time without ruining the planet or running out of something we need and can't replace. Geothermal power from hot rocks falls into a grey area; it is not replaceable but could last a long time.

Business as usual	End-use kWh/day/person	$kgCO_2$/kWh (thermal) chem.[131]	$kgCO_2$/ kWh(elec)	tCO_2/person/year
Coal electricity generation	20.9		1.1	8.4
Metallurgical coal	16.0	0.3		1.8
Gas electricity generation	5.5		0.75	1.5
Gas heating	30.0	0.19		2.1
Oil	70.4	0.25		6.4
Total	**143**			**20**

Table 13. Broad-brush approach to end-use power and CO_2 produced at present. The table shows how much end-use power is used from various sources and how much CO_2 is produced by that use. Columns 3 and 4 show the relevant conversion factors. The overall effect is that 0.38 $kgCO_2$/kWh is produced. This is much lower that the figure of 1.1 $kgCO_2$/kWh when the end use power is in the form of electricity and much higher than 0.19 $kgCO_2$/kWh when the end-use is heat derived from burning gas directly where the heat is required

We have seen that if we used a combination of solar, wind, geothermal, hydro and possibly some wave power we could feasibly and economically cover our

[131] p. 335 SEWTHA.

electricity needs. Let's look at how we could cover all our energy needs in a sustainable, zero carbon fashion.

In Table 13, I use a very broad brush approach to our existing energy use, splitting it into coal, gas and oil. I split coal into electricity generation and metallurgical uses. I split gas into electricity generation and other, mainly heating.

In Table 13, I have listed end-use energy, which is really what we want, rather than primary energy, which is required to provide the end-use energy. I have also listed the CO_2 produced in utilising each form of energy. Two further columns give the conversions from that form of energy to CO_2 produced. The total CO_2 produced comes to 20 tonnes CO_2/year/person.

In this exercise, I will go through the various possibilities we have explored and assign some percentage of utilisation of those ideas. I will use them in proportions which will reduce the CO_2 produced to zero and calculate the impact that those measures have on the need for electricity produced from renewable sources.

	Renewable/ sustainable tactic	percentage of potential	CO_2 benefit tCO_2/person/year	Addition to electricity generation kWh/day/person	Addition to electricity generation GW
1	Convert all coal electricity generation to renewables	100%	8.4	20.9	19.1
2	Convert transport fleet to electricity	50%	3.2	3.8	3.4
3	Upgrade gas electricity generation to combined cycle	100%	0.6	0.0	0.0
4	Convert gas heating to heat pump	63%	1.3	6.3	5.8
5	Biofuel from CO_2	0.04%	2.7		
6	Biofuel from sugar cane	10%	0.1		
7	Biofuel from wood plants	2%	0.1		
8	Biochar on percentage of arable land	5%	1.6		
9	Soil carbon percent of Jones's claim	10%	2		
	Total		**20.0**	**30.9**	**28.4**

Table 14. Various renewable or sustainable approaches that could be used to get the emitted CO_2 to zero. The table includes their impacts on electricity generation.

Table 14 works like this:

- In row 1, we replace all coal fired power with electricity from renewable/sustainable resources as described in Sections 2.1-2.9. The CO_2 benefit is 8.4 tonnes of CO_2/year/person. The renewable power required is 19.1 GW.
- In row 2, we convert a certain proportion (say 50%) of the oil fuelled transport fleet, to electricity. This displaces a further 3.8 tonnes of CO_2/year/person, but adds 3.4 GW to the renewable energy electricity demand.
- In row 3 we upgrade gas fired electricity generators to combined cycle generators that produce only 0.45 kg of CO_2/kWh instead of 0.75 kg.
- In Figure 29 we saw that some 19 kWh/day/person is used for heating, this being the difference between summer and winter gas use. In row 4 we assume that 19 of the 30 kWh/day/person of gas use is replaceable by heat pumps[132]. That's 63% and it has an impact on the electricity system. The coefficient of performance (COP) is assumed to be 3.
- Row 5 assumes that 0.04% of the country is given over to producing biofuels from CO_2 feedstock produced by the remaining combined cycle gas fired power station CO_2 and the metallurgical uses of coal – a total of 2.7 of CO_2/year/person.
- Row 6 assumes that 10% of the land used to grow sugar cane is devoted to growing biofuels.
- Row 7 assumes that 2% of arable land in arid areas is used for biofuels from woody plants.
- Row 8 assumes that biochar techniques are used on 5% of arable land. This is not incompatible with farming.
- Row 9 assumes that 10% of arable land, or 1% of agricultural land is used to grow perennial grasses as described by Christine Jones, to increase the soil carbon.

These assumptions are wild stabs but illustrate that a zero carbon, renewable /sustainable outcome is possible. I have not even begun to consider that the objective here would be much more easily met by using aggressive conservation and efficiency measures. I have deliberately left them out to demonstrate that we could even without these *austerity measures* achieve our objective, though this would not be the most economical way.

In Table 14 I have included biofuels from sugar cane even though they appear to contribute very little. They are in by way of illustration that this might not be a promising avenue to pursue. I have left out carbon capture and storage because

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[132] David MacKay, p. 98 SEWTHA, does not consider earth heat pumps in densely populated areas to be strictly renewable, but in Australia air sourced heat pumps are quite practical.

unlike all the other tactics I have mentioned, they do not appear to have any potential at present, even by the government's own assessment.

11.1 Other studies like this

Whilst writing this book, I did not pay particular attention to other studies relating to sustainable energy for Australia. My focus was initially to compare Australia with the UK based *Sustainable Energy – without the hot air* (SEWTHA). Then my book evolved into a more or less autonomous sustainable energy plan for Australia. Later I found that there were at least two significant efforts along the same lines. The first of these is by Beyond Zero Emissions (BZE)[133]. BZE is an Australian-based, not-for-profit climate change campaign centre founded by Matthew Wright and Adrian Whitehead. This group has formulated a plan that has the same objectives as this book but its focus in primarily on using solar thermal systems, backed by the use of waste material burned in the solar power stations when there is insufficient solar input. A wind power component is included. The plan aims to provide Australia with 100% renewable energy within 10 years at a cost of around $400 billion. That's very close to my independent assessment using seawater pumped storage. For transport, partial electrification and use of biofuels is advocated.

Another study, which although not specifically Australian, is that by Derek Abbott of the School of Electrical & Electronic Engineering at the University of Adelaide, South Australia. His paper[134] Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs? focuses wholly on solar power as an energy source. It systematically analyses most other sources and discards them. The storage medium and fuel for transport is hydrogen. Hydrogen is pretty much dismissed by David MacKay (page of 128 SEWTHA) who says: *I think hydrogen is a hyped-up bandwagon. I'll be delighted to be proved wrong but I don't see how hydrogen is going to help us with our energy problems*. On the other hand Derek Abbott thinks it is the only sensible medium to use for storage and transport. Naturally the question arises as to how to produce hydrogen using solar energy. His *final option* is alkaline electrolysis, which is current commercial technology, using ceramic microporous separators and an aqueous KOH or NaOH electrolyte. The indications are that using existing technology, efficiencies between 60 and 70 % are achievable[135]. Abbott particularly excludes processes that

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133 http://beyondzeroemissions.org/

134 http://www.physorg.com/news170326193.html (for a summary of paper published in the Proceedings of the IEEE, Jan 2010, vol 98, No. 1)

135 http://www.hydrogen.energy.gov/pdfs/review07/pdp_16_bourgeois.pd

use exotic materials or platinum, which could be a limiting factor if required on a large scale. Although the efficiency of hydrogen storage is not quite as high as pumped storage, it has the significant advantage that it can be used as a transport fuel directly. Abbott deals in detail with the safety and practicality of hydrogen as a transport fuel and claims that existing vehicles could use it with minimal modification. Currently 20% of Berlin's busses run on hydrogen. He dismisses electric vehicles on the grounds of the burden that chemicals for batteries would place on our resources and has concerns of the high levels of toxic waste. As far as hydrogen storage is concerned, Abbott advocates the use of underground storage as has been done by ICI for a number of years without problem. For transport applications, double-walled fuel tanks of composite aluminium-glass fibre have been successfully demonstrated. He dismisses the inherent energy loss in liquefying the hydrogen on the grounds that the potential of solar collection of energy is so great that it can withstand some inefficiency. As far as cost is concerned, the existing process can produce hydrogen at 9 cents/kWh[136], equivalent in energy terms to 90 cents/litre of petrol.

Whether we use pumped hydro, molten salt or hydrogen storage and which mix of wind, solar, wave and geothermal power we use, the conclusion is the same. Given the will, we could supply all our energy needs in a sustainable and mostly renewable way. We could do this at a price we could afford. Possibly the best solution will be a combination of these approaches.

[136] Based on an electricity price of 4 cents/kWh. For more information of the price sensitivity see the above footnote

A Appendix

A.1 Bang for Buck Calculations

Efficiency (Cost of CO_2 *abatement) = A/B where:*
A = Capital cost of system – Money saved over life of system
B = CO_2 *saved over life of system – Embodied* CO_2 *of system*

Embodied CO_2 *of system = cost of system /* CO_2 *intensity*

Effectiveness of CO_2 *abatement = Capital cost of system /* CO_2 *saved per year*

CO_2 *intensity in \$/tonne for particular country*

CO_2 *saved over life of system =* CO_2 *saved per year x life of system.*

CO_2 *saved per year = renewable MWh generated or saved per year x tonne* CO_2/MWh

Australian average tonne CO_2/MWh = 1.0

This is the method of comparison I used in Table 12 and Figure 36.

A.2 Cost of money, electricity and fuel

How valid are my *bang for buck calculations*? Have I not forgotten the cost of money? What about the increase in electricity or fuel prices? Figure 48 shows how this affects the calculations.

The dotted line shows the simple assumptions I made in my *bang for buck calculations*. This was: no interest, no increase in fuel or electricity prices. The four curved lines show the case for an interest rate of 3% and, importantly, the excess increase of electricity and fuel prices over interest; this ranges from the tracking of the two, to a 3% higher increase of fuel over interest. The difference between no interest with no increase vs. tracking gave the same result – 19 years. The assumption of fuel prices outrunning interest by 3% per year only changed the payback period to 15 years.

Although interest and fuel price increases do of course affect payback periods, the interesting thing here is that the simplified assumptions gave a payback period of 20 years as did the fuel-price-tracking-interest assumption.

I did these calculations on the basis of an interest rate of 3% but the outcome does not substantially change if you increase it to say 6%.

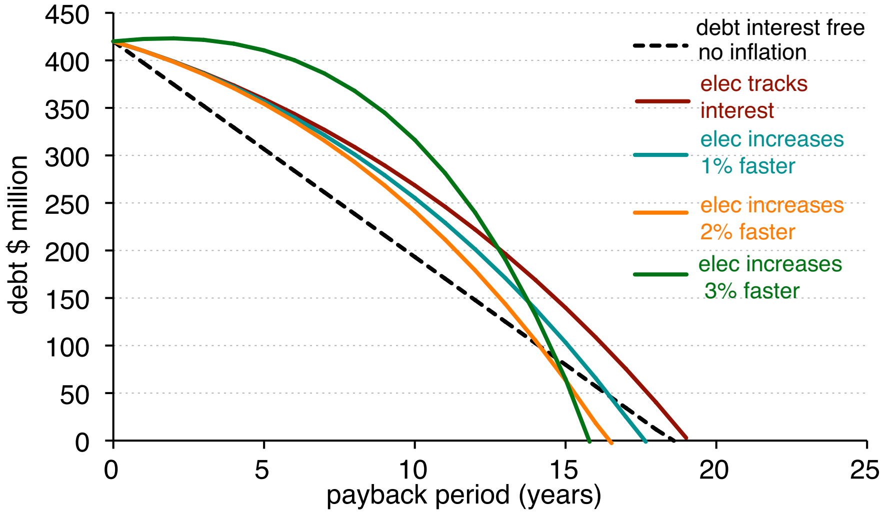


Figure 48. How interest and the rise of electricity price over the interest rate affect the payback period. This graph is for the Mildura solar concentrating PV station. The green line which initially increases the debt is the case for an interest rate of 6%

In the *bang for buck* calculations, I did not attach as much importance to the actual figures, which are going to be variable, as to the ranking. We don't have a crystal ball to see what the prices or interest rates will be in future. However the ranking will stay essentially the same.

So how do fuel prices increase compared to the CPI?

Typical costs of electricity, unleaded petrol and gas in Australia vs CPI are plotted in Figure 49 – Figure 51

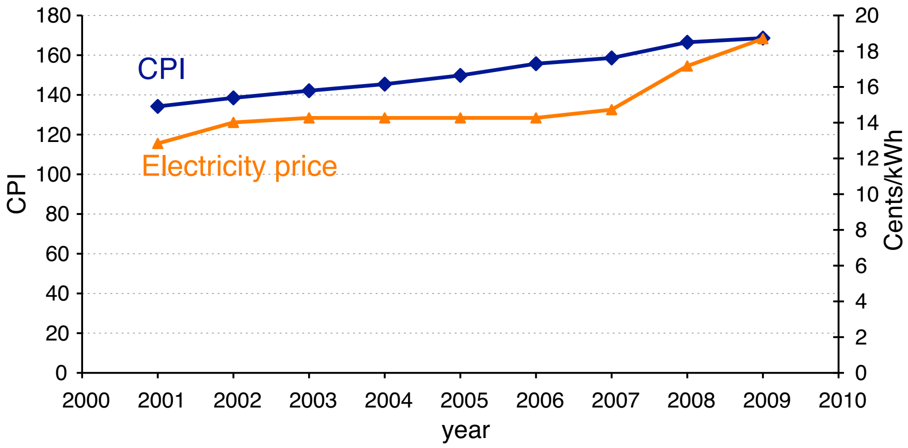


Figure 49. retail price of electricity in Melbourne between 2001 and 2009.

The graphs show a steady rise of CPI but in the meantime the interest rates have varied between 6.75% in 2007 and 3.25% in 2009. The margin above inflation required (called the *Real* interest rate) is about 2.5%. Nicholas Stern rather controversially put this at zero. Most infrastructure investment seems to require 2% – 3% above inflation.

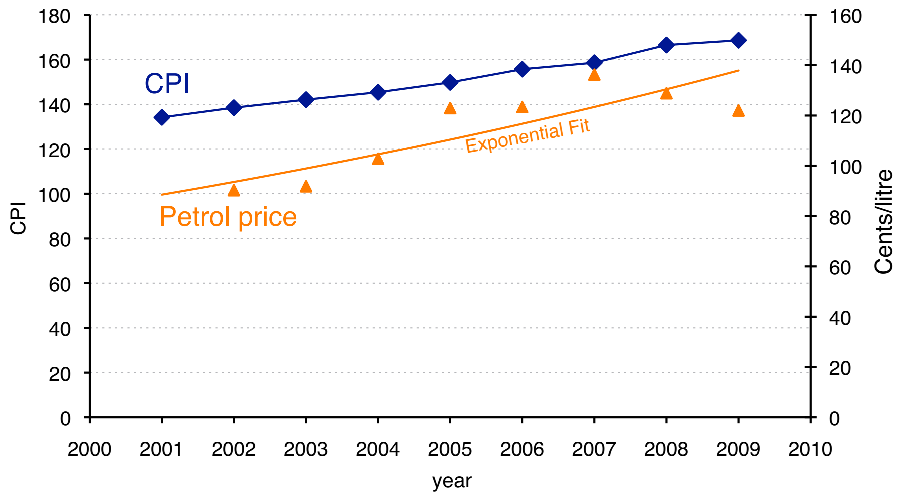


Figure 50. Average unleaded petrol price across Australia compared to CPI.

In my calculations, I have assumed that electricity and fuel prices track interest rates, both being approximately 2% above inflation.

Whilst there is always plenty of bleating in the newspapers about the increases in prices of petrol, electricity and gas, in fact, over the years 2001 – 2009, the average annual energy price increase in Australia has been 1.9% when taking into account the inflation rate of 2.9%.

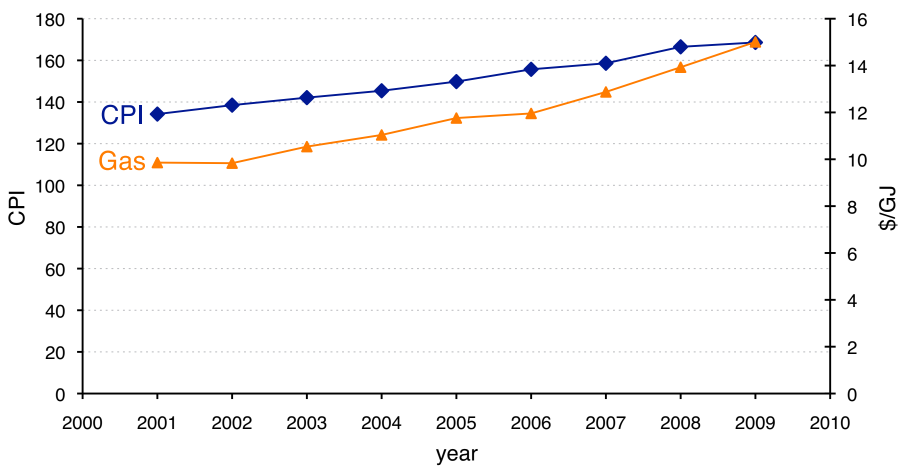


Figure 51. Natural gas price increase vs CPI in Melbourne from my own gas bills.

	% increase 2001 – 2009	Raw % annual increase	CPI adjusted % increase
Inflation	26	2.9	
Interest	52	5.4	2.5
Electricity	46	4.8	1.9
Petrol	38	4.1	1.2
Natural Gas	52	5.4	2.5
Average energy increase		**4.8**	**1.9**

Table 15. How energy price increases track inflation and interest rates. In this table, the annual increase is such that actual prices match the 2009 figure.

In compiling Table 15 I was forced to decide whether to calculate the price increases per year to match the end points of the data set (i.e. the total increase would match the real increase by 2009) or whether to fit an exponential curve to the data and base the annual increase on that. This second method, in Table 16, has the advantage that the 2009 point is in no way special, all points are equally important.

	Raw % annual increase	CPI adjusted % increase
Inflation	3.0	
Interest	5.6	2.7
Electricity	3.7	0.8
Petrol	5.7	2.8
Natural Gas	5.5	2.6
Average energy increase	**5.0**	**2.1**

Table 16. How energy price increases track inflation and interest rates. In this table, the annual increase is based on an exponential curve fitted to the data.

Regardless of the method used, it can be seen that the assumption that energy prices roughly track interest rates is, at least in these cases, not far off the mark.

A.3 Hybrid solar power – case study

The solar PV system shown in Figure 35 was analysed using Homer: the NREL program for optimising renewable energy power systems

A.3.1 Payback period for complete system

There are a number of ways in which the payback period can be calculated. One way is to treat the load reduction and solar power systems separately. In this method, the return on investment of a power system is examined as a separate exercise after load reduction has been carried out. However in a more holistic approach, the load reduction is costed together with the solar system and the payback of the system as a whole is calculated...

The assumptions in 2006 were:

- The cost of diesel fuel is \$1.50 and rises by 10% per year
- The interest rate is 10%
- The *loan* is repaid from the difference between *business as usual* and the diesel cost after the system is operating, including the attendant rises in fuel cost (if these assumptions are made, the *loan* would be repaid within 7 years as shown below).

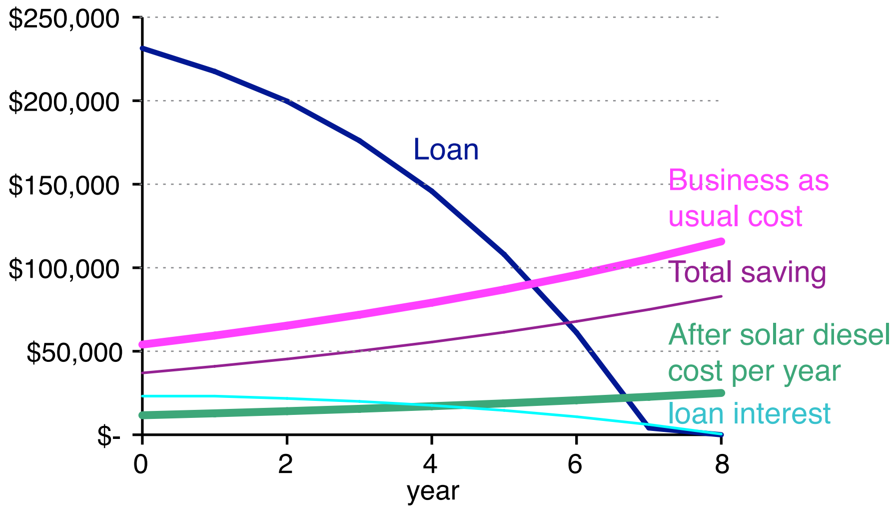


Figure 52. The Australian Wildlife Conservancy property Mornington in the Kimberley solar system payback period. The loan is reduced by the difference between the business as usual cost and the savings.

It is also important to calculate what would happen if the cost of fuel did not rise as expected. If it is assumed that this rises only 3% per year, the payback period only extends by 1 year.

A.3.2 Optimisation of the system

The NREL program Homer is used to assess various combinations of batteries, power sources such as solar or wind, diesel backup generators, angles of panels and many other components. In this case study, I'm investigating the use of 60, 90 and 120 batteries and using 18, 24, 32 and 40 kW of panels. The objective is to calculate the most cost effective system over a 25 year period. Battery wear out costs and other maintenance costs are included in the calculation. The part of the screen in which the system is arranged is shown in Figure 53.

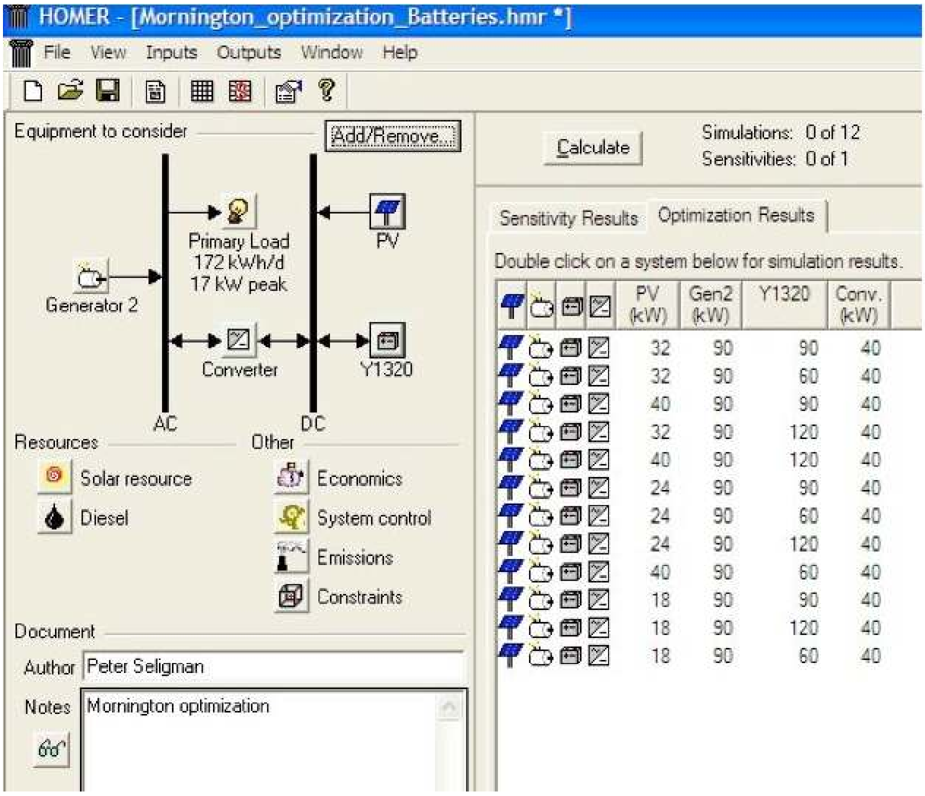


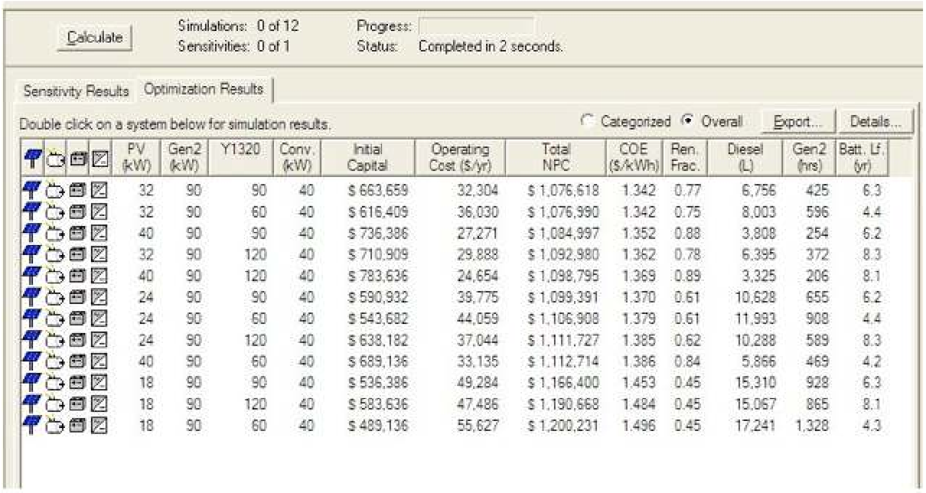
Figure 53. Homer screen showing components to be analysed. The batteries are Yuasa Y1320

In the optimisation, the combination of 90 batteries and a 32 kW array results in the cheapest electricity and the use of about 6700 L/year of fuel. Using only 60 batteries increases the fuel use to about 8000 L/year. Using a 40 kW array reduces fuel use but the cost of electricity is marginally higher.

This case study is to illustrate that on a countrywide scale, a similar approach could be used.

A.3.3 Collector angle

It is normal practice in installing solar PV panels, if they are not 2 axis tracking, or adjustable, to place them at the latitude angle. In this way, for half of the year the sun will be slightly higher than optimum angle and for the other half, it will be too low. The energy collected will be, to a rough approximation, optimised.



PV (kW)	Gen2 (kW)	Y1320	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen2 (hrs)	Batt. Lf. (yr)
32	90	90	40	$ 663,659	32,304	$ 1,076,618	1.342	0.77	6,756	425	6.3
32	90	60	40	$ 616,409	36,030	$ 1,076,990	1.342	0.75	8,003	596	4.4
40	90	90	40	$ 736,386	27,271	$ 1,084,997	1.352	0.88	3,808	254	6.2
32	90	120	40	$ 710,909	29,888	$ 1,092,980	1.362	0.78	6,395	372	8.3
40	90	120	40	$ 783,636	24,654	$ 1,098,795	1.369	0.89	3,325	206	8.1
24	90	90	40	$ 590,932	39,775	$ 1,099,391	1.370	0.61	10,628	655	6.2
24	90	60	40	$ 543,682	44,059	$ 1,106,908	1.379	0.61	11,993	908	4.4
24	90	120	40	$ 638,182	37,044	$ 1,111,727	1.385	0.62	10,288	589	8.3
40	90	60	40	$ 689,136	33,135	$ 1,112,714	1.386	0.84	5,866	469	4.2
18	90	90	40	$ 536,386	49,284	$ 1,166,400	1.453	0.45	15,310	928	6.3
18	90	120	40	$ 583,636	47,486	$ 1,190,668	1.484	0.45	15,067	865	8.1
18	90	60	40	$ 489,136	55,627	$ 1,200,231	1.496	0.45	17,241	1,328	4.3

Figure 54. Part of the Homer screen in which the results are displayed. Four different sizes of PV arrays and three sizes of battery are compared in all combinations.

However if the load pattern is such that more electricity is required at certain times of the year, this may not be the best angle. The graph in Figure 55 shows that for Mornington the best angle was 30°, although the latitude is 17°. This is because the tourist season when the load is high, is in winter, the dry season.

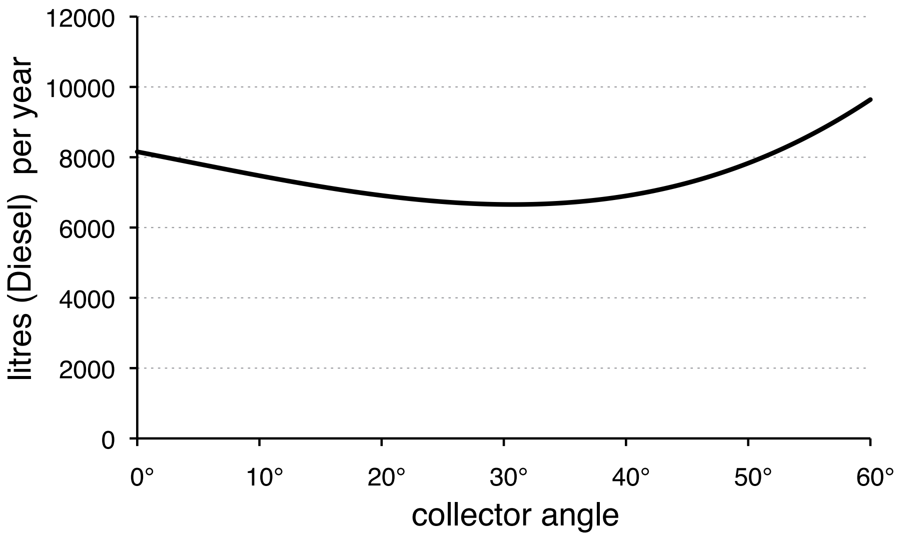


Figure 55. Optimisation of collector angle for solar PV system in the Kimberley. The latitude of this installation is 17° but the optimal collector angle is steeper than this to match the load pattern.

A.4 Effectiveness of energy saving measures

The graph in Figure 56 shows the benefit of individual energy conservation measures. The x-axis is simply the efficiency measures ranked in order of payback period, from shortest to longest.

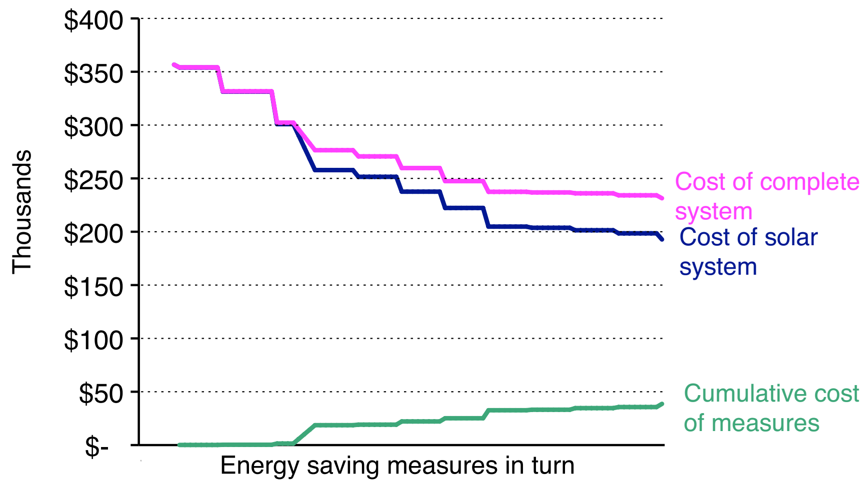


Figure 56. Cost effectiveness of energy saving measures at Mornington. At first the gains come cheaply but then there is a law of diminishing returns.

It is useful to calculate the critical payback period at which the capital cost will start to increase. This is when the cost of the measure taken is more expensive than the solar cells (and rest of the system) it avoids. It typically is about 54 months.

Payback (critical) = Q x C / F x 1.37 months

Where:

Q = solar fraction (proportion of the load to be provided by solar averaged over the year)

C = cost of solar power per watt including the balance of the system (about $31)

F = fuel cost in $/kWh

If the question is asked why P(crit.) = 0 when the solar fraction Q = 0, it is because this calculation relates to capital cost of the system only, not running costs. If there is no solar system to reduce in size by reducing the load, any energy saving measure just adds to the capital costs. Of course it still reduces the running cost.

A.5 Energy use data sources

A.5.1 Total Energy

From Australian Bureau of Agricultural and Resource Economics (ABARE), Table A1 Australian energy supply and disposal:

5773 PJ/year = 5773 x 10^{15} (J) / 22x10^{6} (people) / 3.6 x 10^{6} (J/kWh) / 365 (days/year) = 200 kWh/day/person

http://www.abare.gov.au/publications_html/data/data/data.html

http://www.environment.gov.au/soe/2006/publications/summary/pubs/summary.pdf

http://www.esaa.com.au

A.5.2 Transport including road rail water and air

All travel :1387 PJ/year = 48 kWh/day/person

Air travel: 226 PJ/year = 7.8 kWh/day/person

All travel, excluding Air travel: = 40 kWh/day/person

http://www.environment.gov.au/soe/2006/publications/drs/indicator/327/index.html

A.5.3 Electricity

Total principal electricity generation in 2006 – 07 was 226,600 GWh, comprising 56.7% from black coal, 24.5% from brown coal, 12.2% from natural gas, 6.1% from hydro, and 0.6% from oil and other fuels. Consumption by sector:

- Residential – 27.8%
- Commercial – 22.4%
- Metals – 18.1%
- Aluminium smelting – 11.6%
- Manufacturing – 9.2%
- Mining – 9.1%
- Transport and storage – 1.0%
- Agriculture – 0.8%.

A.5.4 Natural gas

Australia had a total of 143,000 PJ of proved and contingent natural gas reserves at December 2005.

Total natural gas production in Australia in 2006 – 07 was 2089 PJ.

Primary natural gas consumption was 1115 PJ comprising:

- Electricity generation – 35.0%
- Manufacturing – 32.9%
- Mining – 14.1%
- Residential – 11.3%
- Commercial – 3.6%
- Transport and storage – 3.1%
- Agriculture – <0.05%

The ESAA annual statistical data publication, *Electricity Gas Australia*, includes a comprehensive list of power stations in Australia that states the plant and fuel type and total capacity, amongst other things. This information can also be obtained from ABARE.

A.5.5 Proportion of private vs total energy use

It is easy to fall into the trap of thinking that individual energy use is the main use of energy and that if everybody looked after their own needs, we would have solved the problem. But how much of our country's energy use is attributable directly to individuals? How much it would change the energy use if one individual simply leaves? Some things would change instantaneously and others wouldn't. I'm thinking that what would change instantaneously is *private* and what would change only slowly and infinitesimally is *public*. So for instance, the food electricity and petrol the individual consumes would change, but the freeways, hospitals and schools wouldn't. But *private* also includes stuff people buy and use outside those categories.

It is clear that it is difficult to get an accurate assessment of proportion of *private* use but Table 17 is an attempt.

I have taken the figures from ABARE for a number of categories to assess private use. Where I have been unable to obtain data, I have assumed 50% private. That was for air travel and construction. Then I have added all the private use together and reconciled that as a proportion of the total. This is how the figures turn out.

	Private	Public	Total	% private
Electricity primary energy	604	2080	2686	23%
Natural gas (non electricity generation)	136	732	868	16%
Food and Beverage	198	0	198	100%
Ground transport	546	1125	1671	33%
Air travel	113	113	226	50%
Construction	13	13	26	50%
Total	**1613**	**4062**	**5675**	**23%**

Table 17. Proportion of energy used by the private sector as a proportion of total energy use. The figures are in PJ/year.

It appears that private use of energy is about a quarter of total energy use.

A.6 Technology and companies

A.6.1 Electricity generating projects

http://www.abareconomics.com/publications_html/data/data/data.html#engHIST

A.6.2 Energy Storage

Electricity Storage Association:

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

A.6.3 Seawater pumped storage

An excellent paper on a seawater pumped storage pilot plant was published in the Hitachi Review[137] in 1998. The Yanbaru installation[138] on Okinawa, Japan, 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%.

137 http://www.hitachi.com/rev/1998/revoct98/r4_108.pdf

138 Office in Kunigami Village, Okinawa but the facility is on the East coast of Okinawa. At 25°4' N 128°16' E.

Figure 57. 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.

Figure 58. Pumped seawater storage plant as seen in 2009

From the Japan commission on Large dams website[139] 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:

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

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

"

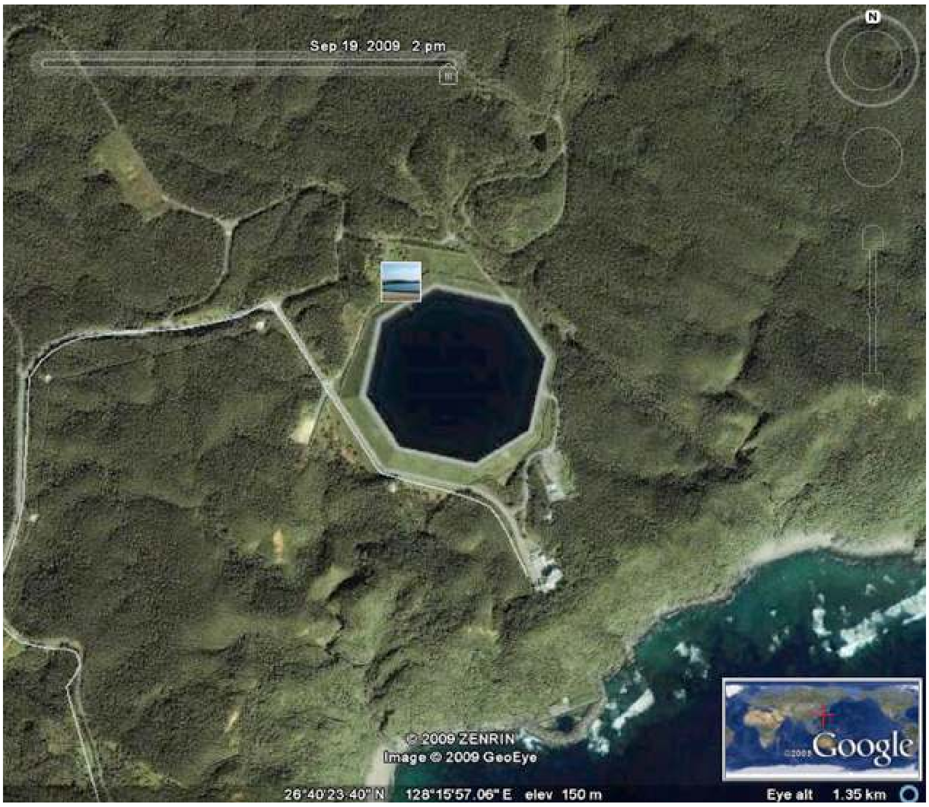


Figure 59. Okinawa seawater pumped storage facility as seen from Google Earth

A.6.4 Isentropic heat storage

A very promising technology is being developed by a Cambridge UK company called Isentropic. This company is developing a method of energy storage using two containers of gravel. Gravel is a very good heat exchanger, having a large surface area for a given volume. It also has a large thermal mass. The idea is that using the energy to be stored, a reversible heat pump, pumps the heat from one gravel filled tank to another. Air is used as the heat transfer medium. The cold tank is pumped down to -150 °C whilst the hot tank is raised to +500 °C. Then to recover the energy this temperature differential is used in a heat engine to drive a generator to produce electricity. It is claimed:

> *"In order to regenerate the electricity, the cycle is simply reversed. The temperature difference is used to run the Isentropic machine as a heat engine. The round trip efficiency is over 72% - 80%. Because gravel is such a cheap and readily available material, the cost per kWh can be kept very low - $55/*kWh *- and $10/*kWh *at scale."*

$10/kWh is the cost of the pumped seawater storage as discussed earlier. A 200 GWh store would cost about $ 20 billion.

A number of questions immediately spring to mind. What single device is both a heat pump and a heat engine? Is the quoted efficiency of this storage possible?

As far as the theoretical efficiency of this process is concerned, the maximum efficiency the heat engine part of the process can have is the Carnot efficiency which is $(T_h - T_c)/T_h$ where T_c is the temperature of the cold body and T_h is the temperature of the hot body, both in absolute units (K, add 273 to °C). The Carnot efficiency is 84%, which is not attainable in practice.

As far as the heat pump issue is concerned, what is the maximum coefficient of performance (COP) that can be obtained? For heating, the maximum COP is $T_h/(T_h - T_c)$. That would give a COP = 1.19, ie. 19% more heat is shifted as is used by the machine that is shifting it.

It should come as no surprise that 0.84 * 1.19 = 1, indeed the algebra can give us that and the actual temperatures don't matter. When the temperature difference is high, the heat engine will be very efficient but the heat pump inefficient. When the temperature difference is small, the situation is reversed. The theoretical maximum round-trip efficiency remains at 1. So the-round trip efficiency of 72 - 80 % is not theoretically impossible, it's just that the practical losses must be no greater than 28 % to meet the claim. Is this likely? What miraculous machine can operate both as a heat pump and a heat engine and has an efficiency within 72 - 80 % of the theoretical maximum?

I posed this question to David MacKay. He replied

> *"I know Isentropic. I think their work is very exciting and I am trying to help them get support"*

This is high praise indeed from David because when I asked him about claims of in the following announcement[140]:

> *"Cambridge, MA Joule Biotechnologies today revealed details of a process that it says can make 20,000 gallons of biofuel per acre per year"*

David replied:

> *"there's too much snake oil per square meter!"*

And this claim is only 20 % of the theoretical maximum.

A.7 Exporting renewable energy

The discussion on this cliff-top seawater pumped storage drew the following response from Prof. Mike Sandiford, Director of the Melbourne Energy Institute, University of Melbourne:

> *"I have been reflecting on the idea you briefly mentioned about using the height of the Nullarbor Plain (about 70 m) as a natural renewable storage opportunity (through pumping sea water). It occurs to me an even better place for such storage would be along the western coastline between Kalbarri and Shark Bay (about 800 kms north of Perth). The Zuytdorp Cliffs are up to 250 m high, have the best wind resource in the country, and have deserts close by with the best solar resources in the country. It seems this might be one of the world's best renewable locations!*
>
> *The location also fits well with the ELEXI[141] concept I have been discussing with Dr Shivkumar from the IBM research labs in India (which of course is very similar to DESERTEC's concept), and so allows the possibility to think about supplying southern Asia with a reliable supply from Australian renewables. The potential to marry these two ideas is quite exciting and is something that I am sure Shivkumar will also be interested in. The Zuytdorp Cliffs are one of the most extraordinary parts of the Australian coastline – almost 300 kms of inaccessible sea cliff, blasted constantly by the dry westerly winds blowing across the Indian Ocean. They are most famous for the wrecks of Dutch ships that overshot the northward turn to Batavia, and inadvertently wrecked themselves at the foot of the cliffs. The Zuytdorp was one such ship, wrecked in 1711."*

[140] http://www.technologyreview.com/business/23073/

[141] http://energy.unimelb.edu.au/index.php?mact=News,cntnt01,detail,0&cntnt01articleid=24&cntnt01origid=16&cntnt01returnid=27

Although this area is about as far from the major population centres of Australia as you can get, the idea is to export electricity to other countries via our Asian neighbours. For example, Melbourne is 3200 km away whilst Jakarta is 2100 km. The population of greater Jakarta is 23 million, greater than the population of Australia. The population of Indonesia is 240 million.

A.7.1 Biodiesel from Algae

PetroAlgae[142] claims it can cost-effectively replace fossil fuel based diesel on a massive scale:

> *"Through a modular, flexible design construction, PetroAlgae enables a near-continuous growing and harvesting process of a wide variety of micro-crops suited to local climates, ensuring maximum growth rates. Micro-crops are the world's only truly scalable, sustainable and carbon-neutral petroleum alternative.*
>
> *Micro-crops produce yields 25x to 100x more productive than macro-crops such as corn, soy and sugar cane that are used to produce ethanol and biodiesel. Micro-crops can be grown on non-arable land, removing competition with the food supply, a significant issue facing macro-crops. Micro-crop fuels are carbon-neutral, consuming nearly double their own weight in CO_2. The PetroAlgae system recycles 98 percent of the water used to grow micro-crops, a significant environmental benefit over both macro-crops and petroleum, which requires vast amounts of water in the drilling and extraction process."*

Another company – a tiny startup called WM MOSS JR Corporation[143], claims that it is about to go into production with a process producing 30,000 gal/acre/year, equivalent to 32 W/m^2 which is spectacularly high. A further statement in their promotion literature mentions 100,000 gallons of oil per acre each year. That would be over 100 W/m^2.

A.7.2 Biofuel calculations

Here are some calculations based on a reviewed journal paper[144] in the *International journal of Molecular Sciences*. The paper was provided by WM MOSS JR Corporation.

142 http://www.petroalgae.com/index.php
143 http://www.wmmossjr.com/
144 Biomass Production Potential of a Wastewater Alga Chlorella vulgaris under Elevated Levels of CO_2 and Temperature Senthil Chinnasamy, Balasubramanian Ramakrishnan, Ashish Bhatnagar and Keshav C. Das Int. J. Mol. Sci 2009, 10.

Under Section 4: Conclusions, it is stated that approximately 120 ton CO_2/ha/year may be fixed by algae at 6% CO_2 concentration.

Let's convert the 120 ton of CO_2 to fuel terms. One litre of diesel produces 2.9 kg of CO_2 when it is burned. Assuming *ton* means 1000 kg, that's 120,000 / 2.9 = 41,000 litres of fuel. Converting this to the antiquated US system, 11,000 gallons which is 11,000/2.5 = 4,500 gal/acre/year.

The article is based on the extrapolation of 47 μmol m^{-2} s^{-1} photon density. It is stated

> *"Since natural sunlight provides four times more photon density than the experimental conditions, it is expected that 120 ton of CO_2 may be fixed..."*

Elsewhere in the article[145], it states

> *"A 12 h light/dark cycle was maintained for all experiments where the irradiance was 47 μmol photons/m^{2}s (during the light cycle)."*

I'm surprised that 4 x 4 fluorescent tubes are thought to be equivalent to broad sunlight. Let's check the assumed sunlight level.

Plant physiology uses a different measure of irradiance to the W/m^2 we have used before. This is because photosynthesis is only sensitive to certain wavelengths. The average wavelength of light in photosynthetically active radiation (PAR) is 510 nanometers (nm). We need to look at the intensity of radiation at these wavelengths. Full sunshine is 2000 μmol m^{-2} s^{-1} photon density. We were trying to establish whether 4 x 47 μmol m^{-2} s^{-1} photon density for 12 hours per day represents normal conditions. In south-eastern Australia 1000 W/m^2 translates into about 160 W/m^2 , taking into account night-time, sun angle and cloud. That is about one sixth of the peak normal radiation.

So the 120 ton CO_2/ha/year figure in the paper is based on 4 x 47 x 0.5 = 94 μmol m^{-2} s^{-1} photon density whereas we can expect about 2000/6 = 333 μmol m^{-2} s^{-1}. There seems to be some disparity here. If I am correct in my assumptions and calculations, the process would be capable of producing 4,500 x (333 / 94) = 16,000 gal/acre/year.

Let's consider the various claims ranging between 30,000 and 100,000 gal/acre/year. What is the efficiency of conversion and the theoretical limit?

Broad sunlight has 2000 μmol m^{-2}s^{-1} photon density.

We convert this as follows:

[145] In Section 5.3: Experimental CO_2 chamber setup

The energy of a single photon in joules is $e = hc/\lambda$, where h is Planck's constant (6.63 x 10^{-34} J s), c is the speed of light (3 x 10^{17} nm s^{-1}), and λ is wavelength in nm. One mol is 6.022 x 10^{23}. One watt (W) is one Js^{-1}. The answer comes to 468 Jm^{-2} s^{-1} = W/m^2. This compares with 1000 W/m^2 for the full spectrum. So let's conclude that 47% of the spectrum is useful for photosynthesis.

In the sunniest places on the planet 1000 W/m^2 translates into about 250 W/m^2 , taking into account night-time, sun angle and cloud. So 47% of that is about 118 W/m^2. What's that in gal/acre/year?

W/m^2	118
kWh/m^2/year	1030
L/year/m^2	103
gal/year/m^2	28
gal/year/ha	278,270
gal/acre/year	111,308

So about 110,000 gal/acre/year is the theoretical limit, if all the incoming radiation of photosynthetic frequencies were converted to into fuel energy. Note that energy has to come from somewhere, and it's not from the CO_2 and it's not from the water. The process involves converting radiant energy into chemical energy by converting CO_2 and H_2O to hydrocarbons C_XH_Y, assuming there are no other inputs.

Here's another question: if the process works well at 6% CO_2 going in – what is the CO_2 level going out? This is an important point because if we use this process as an alternative to sequestering CO_2, we want to make sure that a good proportion of the CO_2 is being removed. It would not make sense if large quantities of CO_2 at 6% concentration would be necessary, resulting in similar quantities of CO_2 at 5% exiting the process.

Biofuel	gal/acre/year	gal/ha/ year	L/ha/ year	kWh/m^2/ year	W/m^2	Area (km^2)
Petro Algae, air only	4,700	11,750	43,475	43	5.0	9,845
CO_2 supplement	6,000	15,000	55,500	56	6.3	7,712
WM Moss 6% CO_2	30,000	75,000	277,500	278	31.7	1,542

Table 18. Various claims of the amount of biodiesel that can be produced from algae.

So my assessment is that 30,000 gal/acre/year is quite a stretch and 100,000 gal/acre/year is deep in snake oil territory.

A.7.3 Joule Biotechnologies

I thought it was worth checking what Joule Biotechnologies[146] (first mentioned in connection with snake oil) were up to 9 months later. Their process

> *"produces clean, infrastructure-compatible fuels directly from sunlight and waste CO2 in a single-step, continuous process that requires no costly biomass intermediates, processing or dependency on precious natural resources. We combine breakthroughs in genome engineering, bioprocessing and hardware engineering to form an integrated, commercial-ready solution with unprecedented scale and productivity. First generation biofuels have known drawbacks, such as the reliance on agricultural land, fresh water and food crops for feedstocks, as well as high product costs, limited productivity and scale. Newer cellulosic and algal biomass-derived fuels address some of these concerns, but they still require costly, multi-step production to reach end product, and their productivities are limited. Joule's transformative Helioculture technology directly converts waste CO2 into ethanol and hydrocarbons, requiring no raw material feedstocks, biomass harvesting or processing. The efficiencies and scalability of our Direct-to-Product process will allow Joule to deliver direct solar fuels at high productivity levels and competitive costs."*

Joule Biotechnologies are currently producing 6,000 gal/acre/year of ethanol. This is equivalent to 6.3 W/m^2. It's in the same ball-park as solar electrcity generation but given that electricity used in cars is about 5 times as efficient as petrol (or ethanol), it is not so impressive. However the commercial target is 25,000 gal/acre/year of ethanol and 15,000 gal/acre/year of diesel. This would make it attractive if the price were right. The process appears to use a medium circulating through panels which look much like photovoltaic panels.

A.8 Carbon Capture and storage projects in Australia

A.8.1 Callide Oxyfuel

An international oxyfuel demonstration project in Central Queensland

The Callide Oxyfuel Project will demonstrate carbon capture using oxyfuel combustion, combined with carbon storage.

[146] http://www.jouleunlimited.com/

The Oxyfuel boiler is scheduled to be operational in the Callide A power plant by 2011. The plant, which has been out of service since 2001, is currently undergoing a complete overhaul.

The project team is assessing potential carbon storage sites to the west of the power plant and planned to select the final location in 2009. The carbon dioxide will be transported in road tankers.

The project is headed by CS Energy Ltd in conjunction with an international team of partners, including IHI Corporation (Japan), J-Power (Japan), Mitsui & Company (Japan) Schlumberger Oilfields Australia and Xstrata Coal.

The Australian Coal Association, and the Commonwealth, Queensland and Japanese governments are providing major financial support for the Callide Oxyfuel Project, and it is a flagship project for the Asia-Pacific Partnership on Clean Development and Climate.

A.8.2 CO_2CRC

The CO_2CRC (the Cooperative Research Centre for Greenhouse Gas Technologies) Otway Project is Australia's most advanced carbon dioxide storage project. Launched in April 2008, the project involves the extraction, compression and transport and storage of 100,000 tonnes of naturally occurring CO_2. The CO_2 is being stored in a depleted natural gas reservoir two kilometres below the earth's surface.

A key project feature is its world-leading CO_2 monitoring program. Designed, developed and implemented by CO_2CRC researchers from Australia, New Zealand, the USA and Canada, this comprehensive monitoring program will contribute to the development of new monitoring technologies for safe CO_2 storage. In April 2009, CO_2CRC Chief Executive, Dr Peter Cook, reported an important project milestone.

> *"The CO_2CRC Otway Project has safely and securely stored 50,000 tonnes of CO_2 in south-western Victoria, twelve months since injection began. More importantly, sampling of deep underground fluid and gas, as well as soil, groundwater and atmospheric monitoring, are showing that the CO_2 and the rocks in which it is stored are behaving as researchers have predicted."*

The promising results have opened the door for researchers to expand the project into new and important areas, and gain a better understanding of carbon storage. The project is funded by the members of the CO_2CRC Pilot Project Ltd, the

Australian Commonwealth and Victorian governments, the Australian Coal Association and other partners.

A.8.3 Munmorah PCC (Post Combustion Capture)

Developing carbon capture technologies on the NSW Central Coast

CSIRO's Energy Transformed Flagship is working with Delta Electricity to test post-combustion capture at a pilot plant they have built at the Munmorah Power Station.

The Flagship's goal is to provide proof of the post-combustion concept, evaluation of various CO_2 absorbents, assistance in the scale up to demonstration and commercial plants, and provide the science underpinnings for future policy options for CO_2 capture.

It is hoped the Munmorah project will provide the foundation for a $150 million post-combustion capture and storage demonstration project in NSW, planned for operation by 2013, capturing up to 100,000 tonnes of CO_2 each year.

A.8.4 ZeroGen project

Through a staged deployment program, the project will first develop a demonstration-scale 120 MW (gross) IGCC (Integrated Generation and Carbon Capture) power plant with CCS. The facility is due to begin operations in late 2012 and will capture up to 75% of CO_2. Some of the CO_2 will be transported by road tankers for partial sequestration (carbon storage) in deep underground reservoirs in the Northern Denison Trough, approximately 220km west of the plant.

To facilitate more rapid uptake of the technology at commercial scale, ZeroGen will concurrently develop a large-scale 450 MW (gross) IGCC power plant with CCS. Due for deployment in 2017, the facility will be one of the first of its kind in the world and will capture up to 90% of CO_2. Its location will be at a site in Queensland to be determined by a feasibility study. ZeroGen Pty Ltd is currently supported by the Queensland Government and the coal industry's COAL21 Fund.

A.8.5 Using CO_2 to extract Geothermal energy

http://www.technologyreview.com/energy/23953/

A.9 Other data

A.9.1 Refrigerator testing

Electricity consumption is measured[147] at specified internal compartment target temperatures (as specified for its Group) while operating at an ambient temperature of 32°C. During the test, the freezer compartment does not contain test packages and any automatic defrost mechanism is allowed to operate. Energy use is measured over a whole number of defrost cycles and there are separate procedures for adaptive defrost systems (where time between defrosts exceeds 24 hours). There are no door openings in the test procedure. All tests are undertaken with a power supply at 230 V and 50 Hz.

Using data provided by Choice magazine (Nov. 2007) which tested fridges, a comparison of claimed and measured power consumption (Figure 60) shows that the ratings are fairly realistic. The average measured power was only 1% higher than claimed although in one case the measured value was 32% above the claimed value.

Since the test standard does not include opening the fridge, I calculated the likely effect of this. For a 400 L fridge, let's assume that when you open the door and leave it open, all the air in the fridge falls out and is replaced by 25 °air at 100% humidity. This air then has to get cooled to say 5 °.

- The heat content of the air for 20 °differential is 2.8 watt hours
- Cooling the moisture is 0.09 watt hours
- Condensing to water: 6.4 watt hours
- Freezing the water: 0.86 watt hours, since when it goes past the heat exchanger it will get frozen.
- Total energy used: 9.3 watt hours.

Say you open the fridge 10 times in 24 hours, that averages out at 3.9 watts. If the coefficient of performance of the fridge is 3, that would make it only 1 W extra power used in opening the fridge, or about 9 kWh/year (2% or so of the fridge's total energy use).

[147] http://www.energyrating.gov.au/rf4.html

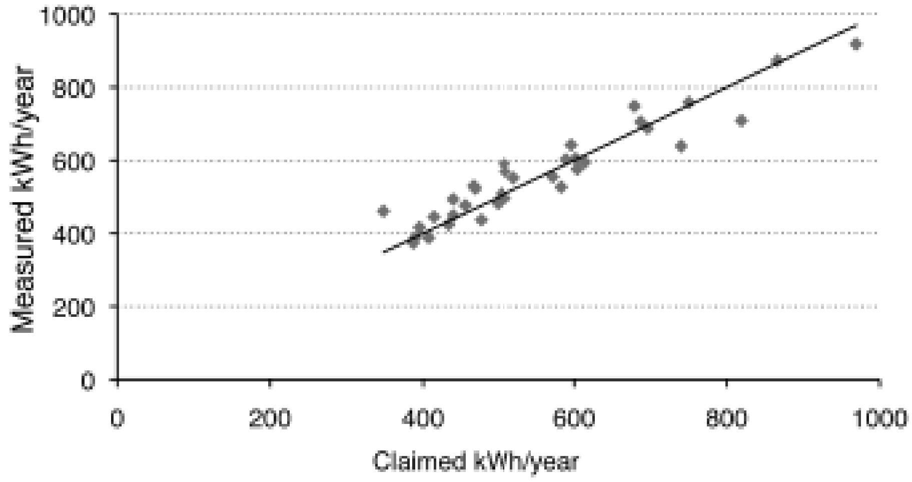


Figure 60. Some fridges, as measured used more power than claimed whilst others less. No test-retest data is available. The black line is measured = claimed.

A.10 Conversions and useful data

The Watt is a measure of power, not energy. It is the rate of use of energy.

1 W (watt) = 1 joule/second.

40 W is the power of a medium sized incandescent light globe which if left on all day, uses 1 kWh of electricity (well 24 x 40 = 960 Wh actually, which is 0.96 kWh)

100 W is the power of largish domestic incandescent light globe.

1000 W is the approximate power of an electric bar heater.

1000 Wh = 1 kWh equivalent to a bar heater running for 1 hour.

1 kWh (kilowatt-hour) = 3.6 MJ (Megajoules)

1 kWh of electricity produced from:

- brown coal produces 1.4 kg of CO_2;
- black coal produces 1.1 kg of CO_2;
- natural gas using gas turbine produces 0.75 kg of CO_2;
- natural gas using combined cycle produces 0.45 kg of CO_2.

1 litre of:

- petrol contains 10 kWh or 36 MJ of energy;
- diesel contains 11 kWh or 39 MJ of energy;
- LPG contains 7 kWh or 25 MJ of energy.

When burned, 1 litre of:

- petrol produces 2.6 kg of CO_2;
- diesel fuel produces 2.9 kg of CO_2;
- LPG produces 1.7 kg of CO_2.

Natural gas when burned produces:

- 63 grams of CO_2 per MJ or 0.23 kg of CO_2 /kWh (of heat – not electricity). Therefore 16,000 MJ of gas produces 1 tonne of CO_2.

Tonne of oil equivalent (TOE):

- Unit representing energy generated by burning one metric tonne (1000 kilograms or 2205 pounds) or 7.4 barrels of oil,
- equivalent to the energy obtained from 1270 cubic meters of natural gas
- 1.4 metric tonnes of coal is 41.87 GJ (gigajoules), 39.68 million Btu (British Thermal Units), or 11.63 MWh (megawatt-hours).

A.11 Notes

1. All values are typical. Fuels vary in their chemical composition and hence calorific value. Coal varies particularly in water content.
2. With the same fuel, the CO_2 produced from 1 kWh of electricity generation depends on the efficiency (basically age) of the power station.
3. Transmission and ancillary services of electric power generation use about 16% of the power generated. This is heavily dependent on location and equipment used.
4. Whilst diesel vehicles use fewer litres of fuel per kilometre, the fuel produces more CO_2 per litre. Conversely LPG vehicles use more litres per km but the fuel produces less CO_2. Petrol falls between the two. We will leave it to the reader to work out which is best overall, since this is an issue which may produce heated discussion!
5. A factor often not considered is the energy and pollution caused in extracting, transporting and refining fuels. Again this varies widely, and can be a reason why different proponents can come to opposite conclusions.
6. Carbon and CO_2 are often confused. One unit of carbon produces 44/12 = 3.67 units of CO_2. Oxygen has an atomic weight of 16 and Carbon, 12. So CO_2 is 12 + 2 x 16 = 44. When comparing data, be careful to check which is being quoted.

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About the Author

Peter Seligman, was born in the UK of Czech parents in 1944 and emigrated to Australia via Czechoslovakia in 1948. He studied engineering at RMIT and then Monash University. In 1966 he worked on a private project to develop a land navigation device which was built, demonstrated and was the subject of a patent application. His final year project in Electrical Engineering was the design and construction of a Braille digital multimeter for a blind engineer. This was followed by an "oscilloscope" for the blind. Peter received his B. Eng (elec) at Monash 1968 and PhD in 1973. His thesis topic was "Auditory Pattern Transmission". From 1973 - 1979 he worked for the Westinghouse Brake and Signal Company on fail safe electronics and the computer control of railway systems. He was also involved in the design of photovoltaic solar energy systems for railway signalling in remote locations. A private project was the development of a trenching machine to insulate earth for heat storage for solar heating systems. A working machine was demonstrated. This was the subject of a provisional patent.

Dr Seligman was a key member of the team that developed the Melbourne/ Cochlear multiple-channel cochlear implant. He worked in the field for 30 years and was particularly responsible for the development and improvement of speech processors. He designed the first portable Speech Processor for the University of Melbourne device. He joined Cochlear Ltd (Nucleus) in 1983 and was instrumental in speech processor miniaturisation and signal processing. He holds over 20 patents in the Cochlear Implant field.

In 2009 Dr Seligman was awarded a Doctor of Engineering (*honoris causa*) by the University of Melbourne for his contribution to the field of cochlear implant signal processing. Since his retirement from Cochlear Ltd in 2009, he has been able to devote more of his time to the area of sustainable energy and conservation, a field in which he has been active for 35 years.

Dr Seligman is an associate of the Melbourne Energy Institute and Professor with the University of Melbourne.