RENEWABLE ENERGY – CANNOT SUSTAIN AN ENERGY-INTENSIVE SOCIETY.

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It is commonly assumed that greenhouse gas and energy problems can be solved by switching from fossil fuel sources of energy to renewables. However little attention has been given to exploring the limits to renewable energy. The main problems are to do with the magnitude of the supply tasks that would be set and the difficulties that would be encountered integrating large amounts of intermittent renewable energy into supply systems. This paper argues that wind, photovoltaic, solar thermal and biomass sources, along with nuclear energy and geo-sequestration of carbon could not be combined to provide sufficient energy to sustain affluent societies while keeping greenhouse gas emissions below safe levels. The case is strongest with respect to liquid fuels and transport. Brief reference is made to the reasons why a "hydrogen economy" is not likely to be achieved.

This paper is updated from time to time, to summarise and improve on the discussions in Renewable Energy Cannot Sustain a Consumer Society, T. Trainer, Springer, 2007.

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(Early 2000s figures are used for the $(A)/$(US) exchange rate and for the price of coal.)

Awareness of the need to reduce use of fossil fuels and of the possibility that petroleum supply is close to peaking is rapidly is increasing. However it would be difficult to find a more unquestioned assumption than that it will be possible to substitute renewable energy sources for fossil fuels without threatening the fundamental commitment of consumer societies to high "living standards" and economic growth.

The argument that this assumption is seriously mistaken is detailed in Renewable Energy Cannot Sustain A Consumer Society (Trainer 2007a.) There has been little critical discussion of limits to renewable energy. There seems to have been only been one book previously published on the topic, Hayden's The Solar Fraud, (2004). There is a strong inclination to assume that we can move from fossil fuels to renewables without any need to question affluent living standards and economic growth. Unfortunately people working on renewable energy technologies tend not to throw critical light on the difficulties and limits. They typically make enthusiastic claims regarding the potential of their systems.

The concern in Renewable Energy Cannot Sustain A Consumer Society was to summarise and interpret accessible evidence as an early step in an overdue process which might in time arrive at confident conclusions. Some of the book's analyses are not very satisfactory, mostly because of the difficulty of accessing information. Commercial operators possessing key information often will not make it public, often ventures are experimental with obscure implications for long term viability, and at times conclusions derive from modelling studies with uncertain assumptions rather than field experience, etc. The book is therefore not offered as having settled many issues but rather as an attempt to assess the implications of the evidence that it has been possible to access, so that subsequent studies can build on these mostly tentative impressions. The present paper summarises some of the book's themes, but adds evidence and argument that have come to hand since the publication of the book. It offers more sound analyses of some themes, especially solar thermal.

Because there has been little study of the limits of renewable energy little or no critical literature has been available for incorporation into the discussion of topics such as the capacity to solve the greenhouse problem. The highly influential Stern Review (2006) and the IPCC Third Working Group Reports (Barker, et al., 2007) have therefore made naïve and highly challengeable optimistic assumptions about the potential of renewable energy because they have made no reference to the factors which indicate that renewables cannot solve the greenhouse problem. (For a critical analysis of the Stern Review see Trainer 2007b, and of the IPCC see Trainer 2008. A similar criticism of Garnaut has been made, Trainer 2008.) Their conclusions regarding mitigation have relied solely on a large economic modelling literature which assumes without examination that renewables can be scaled up sufficiently. As a result it can be argued that their general and universally accepted conclusions, i.e., that the greenhouse problem can be solved and that it can be solved at negligible cost, are invalid and are leading to fundamentally mistaken policies and actions.

It must be stressed that the argument in this paper does not question the analyses the discussions of climate science in either source. Nor does it argue against renewable energy sources; we must move to full dependence on them as soon as possible... but we cannot run an consumer-capitalist society on them.)

It is necessary to divide a discussion of renewable energy potential into two parts, one to do with electricity and the other to do with liquid fuels. Liquid fuels set the biggest problem.

LIQUID FUELS

There is a strong case that biomass cannot meet more than a very small fraction of the global demand for liquid fuels (i.e., oil plus gas.) Any very large scale scenario will have to be via ethanol produced from woody biomass. There is far too little forestry waste, oil crop potential, or corn/wheat input material for biodiesel or ethanol production on the necessary scale. (Hydrogen will be considered below.)

The view among the main researchers and agencies tends to be that in future it will be possible to produce about 7 GJ of ethanol from each tonne of woody biomass. (Derived from Fulton, 2004. See also Hoehenstein and Wright, 1994.) In addition 1 GJ/t of electricity might be generated from the lignin residue, if it can be dried satisfactorily. However some authorities doubt that ethanol from cellulose will become economically viable. (See Augenstein and Benenmann, 2007.) The 7 GJ figure is an estimate of net yield, i.e., the amount after all energy costs of production have been paid, but it does not take into account the energy content of possible co-products, so the figure for output of liquid/gaseous fuel might be somewhat lower. It should be kept in mind that estimates of ethanol yield from biomass vary considerably (Mardon, personal communication) and that as there is as yet no commercial plant operating, confident conclusions are not possible.

Australians use about 128 GJ of liquids (oil plus gas) per capita per year, so to provide this via ethanol would require 16.3 tonnes of biomass each year. Biomass can be produced at 20 t/ha/y, and more than 35 t/ha/y as sugar cane (dry weight), but only in special conditions. Very large scale biomass energy will have to come from such very large areas that the average yield will be far below these figures. World forest growth is c. 3 t/ha/y. It will be assumed that for very large scale biomass production the yield will be 7 t/ha/y. This would mean each Australian would need 2.6 ha of land growing biomass to provide for their liquid and gas consumption (in the form of ethanol net, not primary energy.) To provide the 9+ billion people we will probably have on earth by 2060 we would therefore need <u>24 billion ha of biomass plantations.</u>

However, <u>the world's total land area is only 13 billion ha</u>, and the total forest, cropland and pasture adds to only about 8 billion ha, just about all heavily overused already. Therefore the above assumptions can be varied considerably without it becoming possible to show how all people could rise to anywhere near the present rich world liquid fuel consumption derived from biomass.

Stern implicitly assumes (Fig. 9.4) that by 2050 biomass will yield 110 EJ. This is a doubtful assumption because it would require 850 million ha, equal to more than half the present area of cropland. Shared among 9 billion people this biomass would provide ethanol equivalent to 4 GJ per person p. a., when the present Australian transport fuel consumption is 60 GJ/person, and increasing at 2% p. a. t/ha this

There are many reasons why the potential for biomass production is likely to decline in future years, including increased pressure on land for food and building materials as energy-intensive materials become more expensive, and especially the effects of the greenhouse problem. For instance the water resources of the Murray-Darling river system in Australia are likely to be greatly reduced this century.

There would therefore seem to be little chance that biomass could provide more than a quite small proportion of world transport fuel demand.

ELECTRICITY

Many sources could contribute some renewable electricity but the most likely three are wind, photovoltaic solar and solar thermal. Several other technologies are valuable and/or promising (briefly referred to below) but it is not clear that they are likely to contribute significantly to very large scale electricity production.

WIND

An examination of wind maps indicates that the annual quantity of wind energy that is available in the US and SE Australia could well be considerably greater than demand. The European situation seems different; Trieb (undated, p. 48), a strong believer in the potential of renewables, says total onshore plus offshore potential is about 4 EJ, around half present electricity demand. On land usually only a small fraction of the suitable area can be given to wind farms, for reasons such as prior uses. This is especially so in densely populated Europe where the fraction could be under 10%. In off-shore regions this is not such a significant problem but off-shore potential is less clear because much depends on the water depth limit assumed. The maximum water depth for windmills at present is around 18 metres. Mills might eventually be mounted on floating platforms but the cost and the movement make this unlikely.

If wind was to provide a large fraction of electricity then demand many times the present wind farm area would be needed. For instance Stern's assumed wind contribution, 62 EJ, by 2050 would be about 80 times the early 2000s contribution. (Installed wind capacity is increasing rapidly, confusing comparisons.) However this is a misleadingly low target. If wind was to provide one-third of the 4500 EJ that would be needed to provide 9 billion people with the per capita electricity use Australians are heading for by 2050, the multiple would be about 2000 times the dearly 2000s wind contribution. Even a 10-fold increase for Europe would require use of very distant regions, such as Morocco and Siberia, along with a possibly15% loss in transmission, embodied energy costs of transmission plant, and/or use of less than ideal sites. So far only the best sites have been used, within convenient distance of demand, and the associated average global capacity is only .23. (IPCC, 2007, Section 4.3.3.3.)

The variability problem.

The major limitation with most renewables is not to do with quantity but concerns their intermittency or variability. The typical pattern of output from a wind system rises and falls markedly much of the time and sometimes there is little or no wind. Australian modelling by Poldy (2008) shows that electricity supply from a large integrated system would more or less rise and fall by a factor of 2 every day. In the past it has been generally thought that because of its intermittency wind might be able to contribute up to 25% of demand, but there is reason to think that the figure will be lower. The Germans, with far more wind mills than any other country, and the Danes with the world's highest ratio of wind output to electricity consumption, experience difficulties at times even though wind is supplying only about 5% of national demand. (See Sharman, 2005, E.On. Netz, 2004, 2005. Denmark's output is equivalent to c.18% of the demand from its very small population, but most of this is not used locally and can be conveniently exported to large neighbouring countries with hydro storage capacity or large demand.) Sharman (2005) reports that even in Denmark in 2003 the average output of the wind system was about 17% of its peak capacity and was down to around 5% for months at a time. The E.On Netz (2004) report for Germany also says that in 2003 system capacity was 16%, and around 5% for months. They stress that 2003 was a good wind year.

The magnitude of the integration problem is made clear in a recent study by Oswald Consulting (2006) modelling what the performance if a system spanning the whole of the UK would be. They found that output could plunge from 85% of peak capacity to 10% in 10 hours. It would not be possible to "ramp up" coal or nuclear capacity to fill the gap that quickly if wind constituted a large proportion of generating capacity. In any case the jagged wind supply distribution would require constant variation in output from other generators and this is not good for their efficiency or wear and tear. (Gas turbines can vary more easily, but gas resources are about as limited as oil, and fossil fuel use must be greatly reduced; see below.)

Davey and Coppin (2003) carried out a valuable study of what the situation would be if an integrated wind system aggregated output from mills across 1,500 km of south east Australia. Its findings align with those of Oswald. Coppin points out that this region has better wind resource than Europe in general. Linking mills in all parts of the region would reduce variability of electricity supply considerably, but it would remain large. Calms would affect the whole area for days at a time. Their Figure 3 indicates that the aggregated system would be generating at under 26% of capacity about 30% of the time, and for 20% of the time it would be under 20% of capacity. Clearly a very large wind system would have to be backed up by some other large and highly reliable supply system, and that system would be called on to do a lot of generating.

The study of the wind energy potential of a system spanning the whole of Ireland (Coelingh, 1999) yields a plot (Fig. 7) similar to that from Davey and Coppin. For instance, output would be under 20% of capacity 40% of the time, under 8% 20% of the time, and under 4% 10% of the time.

Because the wind sometimes does not blow at all, in a system in which wind provided a large fraction of demand there would have to be almost as much back-up capacity from other sources as there is wind generating capacity. E. On Netz has emphasised this problem with respect to the German experience. The Oswald study showed that in Britain, possibly the best wind region in the inhabited world, and in January which is about the best month of the year for European wind energy, there would be about three times during the month when wind energy fell almost to zero. So if we built many wind farms we would have to build almost as many coal, gas or nuclear power stations to turn to from time to time. (The problem would be offset in so far as solar sources were contributing at these times of need, but this is not a strong prospect in Europe in winter.)

This means that renewable sources tend to be <u>alternative</u> rather than <u>additive</u>. Therefore it is not a matter of having each renewable source carrying a fraction of the load all the time. If we build one unit of wind power and one unit of PV power we would not necessarily have two more units of renewable energy capacity; sometimes we would have no more, e.g., on calm nights. This means we might have to build two or even four separate systems (wind, PV, solar thermal and coal/nuclear) each capable of meeting much or all of the demand on its own, with the equivalent of one to three sitting idle much or all of the time. This would obviously be very expensive, and still would not eliminate times when total renewable input was well below demand.

In addition electricity distribution grids would have to be reinforced and extended to cope with the new task of enabling large amounts of power to be sent from whatever region had high winds at that time. Centralised coal or nuclear powered systems do not have this problem.

One aspect of the variability problem is the seasonal difference in wind strength. Czisch (2004, Fig. 5.) shows that in February Europe gets almost 5 times as much wind energy (not mean speed; energy is proportion to speed cubed) as in May, so if we built a system big enough to meet demand in February it would only do 20% of the job in May. The difference is evident in the above winter and summer capacity figures for Denmark and Germany.

There are schemes for connecting vast intercontinental regions into the one wind energy system, e.g., from Morocco to the Sahara and Kazakhstan. (Czisch and Ernst, 2003.) This would considerably reduce the variation problem because when the winds were low in Western Europe they would probably be high in some of the other regions. The important point however is that even though wind speed correlations across such distances could be zero and some wind would usually be blowing somewhere, there would still be many times when the average wind across the whole system was low, and that means the wind system as a whole would not be producing much. The studies by Davey and Coppin, Oswald and Coelingh referred to above show this. "Synoptic" weather patterns often apply to large regions. As Hayden (2004, p. 150) says, "There are times when the wind is calm <u>everywhere</u>."

If we assume that the wind is always good in Morocco, or Kazakhstan or Siberia or Western Europe, then if we are to have a system that always reliably meets demand from one or other of these regions, we would have to build four entire systems each big enough to meet demand. We would also have to build several costly 4,000-5,000 km transmission lines to Europe (losing perhaps 15% of energy generated.)

Note that most of these regions are well to the East of Europe so it will be night time there when European demand is highest, during the day. Winds tend to be low at night.

Costs.

Wind farm costs are usually quoted as c. \$(US)1000/kW, but this is misleading. Firstly the recent cost of some Australian systems has been up to \$(A)2,400/kW(e). (Trainer 2007, Chapter 2.) More importantly these figures are for <u>peak</u> output. Average capacity at a good site can be well above 35%+ of peak output but the global average is .23 (IPCC,2007, Section 4.3.3.2). Again the German <u>system</u> in 2003 averaged less than half this figure. (We should focus on the performance of the system, not of individual mills; the system involves other factors and losses.) If we take the recent Australian cost and a system with 25% capacity, about the European average, then the capital cost of wind-generated electricity would be more than 2 times that for a coal fired station plus fuel for its lifetime (early 2000s price.) To this would have to be added thecost of revisions to the grids and the almost 100% duplication of wind plant with back up coal or nuclear plant if wind was to be a large component of the total system.

The limit to wind's contribution -- about 25%?

The following analysis indicates that even in a good region wind could not contribute more than about 25% of average demand.

Let us assume a system with an average demand of X GW and in which X GW of peak wind capacity has been built. Taking the UK average wind system capacity, about .25 over a year, the wind system would generate on average about .25 X GW, leaving .75 X GW to be generated by coal or nuclear sources. (This is to simplify; other renewable sources could take some of the load.) We would have cut coal use significantly but carbon release would remain far greater than safe greenhouse limits (below), and we would still need X GW of coal or nuclear capacity to call on when there was no wind. Our electricity generation system's capital cost would be X GW of coal/nuclear plus X GW of wind capacity. We would have doubled system capital cost to cut greenhouse emissions by about 25%.

If we now explore having twice as much wind capacity, 2X GW, the wind system would <u>generate</u> on average about .5 of demand, but much of this could not be used because when winds were strong the 2X GW peak capacity wind system would be generating twice the X GW required. Wind would therefore be contributing perhaps .3 or .4 of demand, still leaving an unacceptable level of coal use, while total system capital costs would be X GW of coal/nuclear plus 2X GW of wind.

It is evident from the graphs from Oswald et al., Coelingh, and Davey and Coppin that no matter how much wind capacity we added there would still be several times a month even in the best wind time of the year when more or less the whole X GW needed would have to come from coal or nuclear plant, and that we could cut carbon emissions to the very low required level only if we had perhaps 5X GW of wind capacity and dumped most of the energy it generated (or stored it very inefficiently as hydrogen.) Clearly the gains from "over-sizing" the wind system would be savagely offset by the rise in total system capital costs, and it would not pay to have much more than X GW (peak) of wind plant, meaning plant capable of delivering on average about .25 of demand (or whatever the average wind system capacity fell to in view of the need to use very large areas.)

The same logic would apply to other renewables and to their combination. The situation is complicated somewhat by the capacity to store some energy in dams, although hydroelectric generating capacity is small, and by the capacity of solar thermal plant to store heat (below).

PHOTOVOLTAIC SOLAR.

The main problem with PV electricity is not its high cost but that it too is an intermittent source and its possible contribution to a wholly renewable energy system is therefore limited without the capacity for very large scale electricity storage. Even in the best regions PV provides no energy for up to 15 hours on a hot and clear summer day. It is valuable when it can feed surpluses from house roofs etc., into a grid running on coal or nuclear power, while households draw power from that grid at night. However this is possible only when much coal or nuclear capacity is functioning as a giant "battery" PV can send surpluses into, and there is obviously a limit to the size of such a PV system.

Very large scale use of PV systems would set difficult integration problems. Output from the whole system would go from 0% to 100% of capacity in an hour or two on a summer morning. At night another system about as big as the PV system would be needed to substitute for it, as was seen above regarding wind systems. The above discussion of wind energy indicates that the PV system would be limited to providing perhaps .15 of demand, by the capital cost and energy dumping problems encountered if systems are over-sized (taking into account the probable winter capacity factor for tilted fixed modules.)

SOLAR THERMAL ELECTRICITY

The major drawback for renewable energy is the inability to store electricity from intermittent sources. Solar thermal technologies are especially valuable because they can store heat and use it to generate electricity when it is needed. Some believe this capacity will be the key to enable renewable energy sources to meet all electricity needs. (E.g., Trieb, undated, Czisch, 2004.)

Solar thermal systems are best suited to the hottest regions and it is not clear how far into the mid latitudes they can be effective, apart from via very long transmission lines. They seem to be especially doubtful in winter, even in the best locations. (For a more detailed discussion of solar thermal's limits and potential see Trainer, 2008.) Trough systems will be considered first, then dishes.

The winter electrical output for the US SEGS VI trough system is reported at about 20% of summer output. (NREL, personal communication.) Modelling for Central Australia, possibly the best solar thermal location in the world, by Odeh, Behnia and Morrison (2003) produces a ratio closer to 1/8.

The SEGS VI plant with its north-south troughs was not designed to maximise winter performance. Arranging the troughs on an east-west axis, as distinct from the usual north-south axis, would raise the winter/summer ratio for energy entering a trough. ("Polar axis" alignment of troughs enables maximum energy yield, but is not feasible for large scale power generation.) However even in good solar thermal regions the performance of east-west troughs in winter (and summer) is relatively low, compared with the summer and annual average performance of north-south troughs. This is evident in Figure 1 from Odeh, Behmia and Morrison. Summer thermal energy collection (not electrical output) entering a NS trough at Alice Springs would be 780 MJ/m/month, whereas in winter from and EW trough it would be 430 MJ/m/month, or 4 kWh/m/day.

The radiation data given by RREDC (undated), Meteonorm and ASRDHB, 2005, point to the same general conclusion. These sources indicate that Alice Springs is a better location than Egypt, receiving possibly 50% more solar energy per metre in winter. It also seems to be a little better than the SW US. Thus if solar thermal technologies are problematic in winter at Alice Springs they are not likely to be viable in the US or for Europe.

A critical problem for solar thermal systems is what proportion of collected heat is above the threshold level required for generation of sufficient steam pressure. In regions where radiation is low to moderate, considerable heat energy could be collected without enabling generation of a significant amount of electricity. For SEGS VI radiation appears to have to reach 700 W/m (DNI or direct normal irradiation, not global radiation) before generation becomes moderate, and at 500 W/m it is only about 33% of maximum. (NREL, undated, Jones, et al., 2003, Figs. 5 and 14.)

ASRDHB data show that for Alice Springs in winter the intensity of DNI per square metre entering an east-west trough averages only 408 W/m, over a 12 hour period. It is over 700 W/m for about 7 hours. Fig 3 from Odeh, Behnia and Morrison shows that at Alice Springs 26% of DNI received over a year is under 500 W/m and 18% under 350 W/m.

More direct evidence comes from the SEGS VI record. Hayden (2004, p. 190 .) reports that the 2.3 million square metres of collectors average 77 MW over a year, which corresponds to a continuous flow of 33 W/m. The above evidence is that winter performance is about 30% of the average performance, which is a solar to electricity efficiency of 10.7%. This suggests that the winter figure would be c. 13 W/m.

From this very low gross output a number of factors must be deducted, the main two being the energy required to build and run the plant. The latter energy losses, mostly for pumping fluid through the absorber, are given by Sargent and Lundy (2003, Section 4 – 3) at 17% p.a., although they estimate that in future the figure will be under 10%).

The embodied energy cost, i.e,, the amount of energy needed to build the power plant, is reported by Dey and Lenzen at c. 4% of gross output for a plant of normal size in normal conditions. However a plant capable of delivering 1000 MW in winter would have to be 2.5 times as large as one capable of this output as an annual average, so its embodied energy cost would be that much higher. (It would then generate much more than 1000 MW in summer and the ratio of embodied cost to total output would remain c. 4%, but a problem would then be that summer output would be far in excess of demand. On problems in storing such a surplus as hydrogen see below.)

The embodied energy cost analysis of solar thermal systems must also take into account the energy cost of building and maintaining the long distance transmission lines, e.g., from North Africa to North West Europe and of transforming from DC to AC power. The lines might add one-third to power plant dollar cost. (Czisch, 2004.)

The loss of energy from solar thermal storage is low but has been estimated by Sargent and Lundy as .9%.

Finally, the loss of energy in the very long distance transmission has to be taken into account, e.g., from Egypt to NW Europe. This is likely to be 15% of gross output.

Some of these numbers are uncertain but when combined they indicate that the total energy loss might be 35% of the meagre gross output, meaning that a net delivered amount well under 10 W/m might reach users. If so plant capable of delivering 1000 MW in winter would need 100+ million square metres of collection area. At the estimated SEGS cost of $800/m (Trainer 2008) the plant would cost $80 billion.

More confident data on trough performance in winter would be desirable here, but on Hayden's account they would not seem to be viable.

Dollar costs.

Sargent and Lundy (2003) put the capital cost of solar thermal plant at $(US)4,589/kW ($(A6,556) for the "near term future" (including heat storage, which reduces required generator capacity and cost, by enabling the generation rate to be levelled out.) NREL say the 2003 equivalent price of the SEGS plant is $(US)7,700. These figures are to be compared with $(A)3,700 million for coal plant plus fuel (early 2000s price) over plant lifetime. These figures are for peak outputs and the average output from a coal plant is c. .8 of peak whereas for a solar thermal plant it is around .25 of peak capacity (in the best locations). Thus capital cost per gross kW delivered on average (as distinct from peak) from solar thermal plant would be over 7.5 times as great as for coal including fuel. (See Trainer, 2007, Chapter 3.) Transmission lines from the Sahara to Europe under the Mediterranean Sea would probably add more than 33% of generating plant capital costs. (Czisch, 2001, 2004) indicating a multiple of 10. Note that these figures are not for plant large enough to deliver well in winter and for SEGS VI this factor might multiply by a further 2.5. Note also that dish costs are at presently much higher than trough costs.

Again future materials, energy and construction costs are likely to be far higher than at present so these figures are not very meaningful guides to future viability.

Water pre-heating.

A solar thermal plant near Sydney, NSW, some 34 degrees south, has been constructed to pre-heat water for a coal-fired power station. (Mills, Le Lievre and Morrison, 2000.) This is sometimes taken to show that solar thermal systems are viable in the mid latitudes. However this system delivers heat at about half the temperature required in coal-fired power stations, and therefore does not have to concentrate solar radiation intensely. The absorber is about 1 metre wide and therefore reflectors can be wide with little curvature. Thus the capital cost is quite low. These features indicate that this plant is not a good guide to the effectiveness or cost of solar thermal plant at this latitude that would generate electricity without augmenting fossil fuel power generation. In a world that did not exceed safe greenhouse limits there could be few if any fossil fuel plants. Also the performance of the system falls markedly in winter as the above discussion would lead one to expect.

Dishes.

Dishes would collect more energy in winter because they can be pointed directly at the sun, but there are two significant drawbacks. Their dollar costs are reported as being 2 – 4.5 times those of troughs (Sandia, undated), although costs will surely fall considerably with further development and mass production.

The data I have been able to access indicates somewhat surprisingly low but useful winter output from dish–Stirling devices. Some US dishes seem to have an average 24 hour flow equivalent of around 20 - 30 W/m (Davenport, 2008.) An output plot for the Mod dish-Stirling device shows that the January average flow (averaged over 24 hours) was c. 18 W/m, and for December, 22 W/m. Commonly published power curves show that at 700W/m output falls to around half peak output.

However this is not very relevant to our problem. If solar thermal systems are to provide electricity 24 hours a day, and also to solve the general intermittency problem set by other renewables, then heat must be stored. This means that the efficiencies will be much lower than those represented in the literature on dishes, which almost entirely deals with dish-Stirling systems. Dishes are not well suited to heat collection.

Trough systems transfer heat long distances to the power block mostly through the absorber pipes, which are heated as they collect radiation (nevertheless 4% is lost, according to Sargent and Lundy, 2003). With a dish system this would not be so and either very long pipe distances would have to be insulated and would still lose much heat energy or many small generators would have to be located close to groups of dishes. (The equivalent of a 1000 MW plant in winter would involve tens of thousands of big dishes; below.) For these reasons the European and US dish developers I have contacted regard the use of dishes to collect heat as not being viable. (Personal communications.)

Kenaff's pioneering work at White Cliffs, Australia on dish-steam generation achieved 9.1% annual solar to electricity efficiency. The ANU Big Dish has a 13.9% efficiency, which it is expected can rise to 19% in future. (Note that this is a measure at a point in time under ideal conditions, not a measure of recorded annual average output; which would be considerably lower, e.g., because of dust build up and warm up delay after cloud, etc.) I do not have figures on the winter performance of either system. If we assume 5 kWh/m/d radiation, the White

Cliffs 15% loss of heat between collector and engine room, the 19% heat to electricity generation efficiency Lovegrove expects, and an 8% energy cost for pumping (the trough figure), then output might correspond to a gross 31 W/m flow. However this assumes 1000 /m radiation and in winter radiation barely rises above 700 W/m, which for dish-Stirling generators cuts output in half. Again Kenaff's evidence is that steam generation is significantly affected by lower DNI. (See Trainer 2008 for more detail.) The derivation does not take into account heat storage issues. Very important is the fact that the White Cliffs system involved only 14 rather small dishes and thus a very short distance for heat to be moved to the engine room, and the Big Dish is a single unit close to its steam generator. For the equivalent of a 1000 MW plant very long distances would be involved (or many small power blocks.). Thus it is not possible with this information to estimate a net winter output after heat storage, but it would seem likely to be significantly below 30 W/m.

The heat storage strategy using dishes which looks most viable is that being developed by the ANU group, involving the use of ammonia dissociation as a means of heat storage (Lovegrove et al, 2004). This is being built into a commercial plant at Wyhalla, South Australia. It is estimated that half the energy entering the dish might be available for generating after storage by this means., and that electrical output after storage might be 90% of direct output without storage. (Wizard Power personal communications.)

The designers cannot predict performance confidently at this stage (personal communications), and understandably will not make the technical information they do have available to the general public. It would seem from above that if Big Dish efficiency can be raised to 19% then after storage 17% could be achieved. Gross winter output in Central Australia then might correspond to the region of 35 W/m continuous 24 hour flow. (At present Big Dish efficiency the figure would be 26 W/m/.)

Several factors would reduce this gross figure, including the effect of warm up delays after the passage of cloud, operating energy costs, emergy embodied in the dish and the long trans mission lines, energy losses in those lines, and especially the embodied energy cost of the ammonia processing plant (including the reactors in the dishes which dissociate the ammonia, and the one in the power block that recombines it.). The emergy implications of the ammonia processing plant are difficult to assess, and could be problematic. The attempt sketched in Trainer 2008 suggests supply from a 1000 MW plant, taking the most favourable of the estimates for storage volume received (17 litres per kg of ammonia, and 4 MJ/kg), might require some 2,800 km of one metre diameter gas pipe, the intended containment vessel.

Also a concern is the fact that big dishes (Whyalla will use 500 square metre dishes) involve disproportionately higher materials and energy costs for structures, foundations and drive equipment, in view of the higher wind stresses they will have to cope with. An estimate based on the materials in the ANU Big Dish indicates an embodied energy cost three times that of troughs, i.e., in the region of 13% of plant lifetime output. (Trainer 2008.) However the developers believe other advantages of big dishes outweigh these factors, although I do not know whether this is only a dollar cost calculation or one focused on embodied energy costs. There is a high probability that in future the cost of materials and construction will be far higher than they are now.

These figures suggest that a solar thermal ammonia storage system will be capable of low but significant/useful output in winter. From above, net energy delivered to distant users would seem likely to correspond to around 20+ W/m. However it is not clear that the very large numbers that would be required could be afforded. On the above estimates a plant capable of delivering 1000 MW in winter would have to include up to 50,000 big dishes each of 400 square metres. These would probably have to be spread over an 11+km x 11+ km area. Just to connect the dishes to the power block would probably require some 2,800 km of pipe, although it would not have to be insulated. This seems to be about the length needed for storage above, but easily overlooked is the need for the same length of pipe to carry the recombined ammonia back to the dishes from the power block. Having many small plants rather than one big 1000 MW plant would not alter the overall ratio of pipe length to kW output. The total 5,600 km of steel pipe capable of taking 15mPa pressure might weigh 280,000 tonnes and have an embodied energy cost of 11.2 PJ. This is around 45% of the annual output of a 1000 MW power station (assuming .8 capacity), so the embodied energy cost of the pipe alone might add 2.2% of lifetime output to the total embodied energy cost figure.

Also of concern is the fact that if net delivered output corresponded to a say 25 W/m flow in winter, then it would take 46 metres of dish collection area to sustain one person at the Australian average electricity consumption rate, meaning that the ANU Big Dish would provide for only 8+ people.

Direct hydrogen production.

It is possible to produce hydrogen by splitting water at high temperature, around 800 degrees, and a practical application of solar thermal to this strategy is being discussed. (Taylor, Davenport and T-Raissi, 2008) A theoretical 40% solar to hydrogen efficiency is thought to be achievable. If this becomes viable it would probably be the best option, although it would involve the usual problems in large scale handling of hydrogen. These include pipe embrittlement, leaks, and the very low energy density meaning either very large storage volumes and/or high compression. Especially problematic are the energy losses in long distance transport. Bossell estimates that to pipe hydrogen from North Africa to Western Europe could require more than half the energy despatched from Africa. Ideal solar thermal sites are a long way from demand.

A system designed to deliver 1000 MW after storage would need a 1000 MW hydrogen-fuelled power station in addition to the dish system which generated the 1000MW supply of hydrogen to run it, indicating high capital and embodied costs. The efficiencies of the various steps (e.g., .4 for hydrogen production, .8 for handling/transport, .4 for fuel cell generation) suggest an overall gross solar to wheels/use efficiency of 13%, from which the embodied and operating costs of materials-expensive hydrogen handling plant would have to be deducted. It is therefore not clear that this path would be more viable than the others considered above.

The intermittency problem.

The heat storage capacity of solar thermal systems overcomes some of the intermittency problems that trouble wind and PV systems, such as the occurrence of night time. The standard provision will be 12 hour storage enabling continuous 24 hour electricity delivery. However examination of climate data reveals that even at the best sites sequences of 4 or more days without sunshine are not unusual. The best US sites often have 2 runs of 4 consecutive days of cloud in a winter month. (Davenport, 2008)

If 1000 MW(e) output was to be provided for four cloudy day from stored heat, some 290,000MWh of heat would have to be stored. Storage cost has been estimated at $(A)10/kWh(th) meaning that the required storage plant would cost more than $8 billion, or around twice the cost of a coal-fired plant plus fuel. However this refers to trough technology and it is likely that for the ammonia process costs would be higher.

Again we would be faced with the prospect of very high capital costs for a large amount of plant that would not be used most of the time, and would still be insufficient occasionally. There would also be the question of whether there would be enough solar radiation in winter to meet daily demand and also recharge a large storage sufficiently to cope with the next run off 4 cloudy days.

The climate evidence given in Trainer 2008 seems to leave no doubt that solar thermal systems even at the best locations would suffer a significant intermittency problem, despite their capacity to store energy.

Another problem is that if solar thermal plants are to help buffer the intermittency of inputs from other renewable sources then a major cost saving often claimed for solar thermal systems would not be available. The ability to store heat from peak mid day collection and generate with it at a much lower constant rate, perhaps .2 of peak capacity, means that much smaller and cheaper generators can be used, perhaps one fifth of the capacity that would be needed to use heat energy at the mid day rate of collection. The power block can make up around half of a solar thermal system's cost so the saving in capital costs, energy costs and operations and management is considerable. However if the solar thermal component of a renewable supply system must at times plug gaps left by variable wind and sun, then there will be times when it must meet almost all demand and so its individual stations must often be cable of generating at much greater than average rate.

There would also be a problem regarding the need for solar thermal plant to rapidly ramp up to high levels of output, in order to meet most of the demand when sun and wind energies fall suddenly. Thermal generators can't be brought up to full output quickly. This evidence seems to mean that there is no chance that the capacity of solar thermal systems to store energy could overcome the problem of gaps left by combining the output from the other renewable energy sources, as some have hoped.

Solar thermal conclusions?

The climate data seems to show that despite their storage capacity solar thermal systems would suffer a significant intermittency problem and in winter would either need storage capacity for four or more cloudy day sequences once or twice each winter month, or would need back up from some other sources. This means they could not be expected to buffer the intermittency of other components in a fully renewable system.

It seems that troughs suffer a big drop in output in winter, that dish-steam systems cannot operate well enough on stored heat and that hydrogen generating systems are too handicapped by the usual difficulties associated with hydrogen. The prospects for satisfactory winter supply of electricity from solar thermal systems therefore seem to depend on whether or not the dish-ammonia system will be viable on a large scale, and capable of overcoming intermittency problems. The unsatisfactory information available suggests that they will be significant contributors but are not likely to make possible reliable winter electricty supply at a tolerable cost, that they will suffer a significant intermittency problem, and that they cannot be a solution to the integration problems left by other renewables.

GEOTHERMAL ELECTRICITY

Large quantities of energy exist as heat in dry rock masses and it is possible to tap these by pumping water down one bore hole and up another. A 1994 study for the Australian Government's Energy Research and Development Corporation concluded that Australia is probably the only country with extensive hot dry rock resources. (http://www.greenhouse.gov.au/renewable/recp/hotdryrock/two/html)

Much energy will have to be used to drill the holes some 4,000 to 5,000 metres deep, fracture the rock and force water 500 to 1000 metres from one hole to the other. When the water comes up it will only be around 270 degrees C (170 degrees in European locations), meaning rather low generating efficiency.

Uncertainties include the energy needed to fracture the rock between holes to enable water to be pumped from one to the other, the amount of water lost in the rock cracks, and -whether the path the water takes is straight and therefore "mines" little of the rock volume. In other words embodied energy cost, net energy return and generating efficiency are largely unknown at this stage, and are problematic. Scheirmeir et al. 2008 say the global potential is probably in the region of 70 GW. A world of 9 billion living as Australian's expect to by 2050 would need some 15,000 GW.

WAVE POWER

Despite many years of experimentation no commercial wave power plant had been put into operation before 2004. The main problems are to do with storm damage.

According to a source within the industry (personal communication) there are 16,000 km of coast around the world with excellent wave energies, i.e., 30 kW/m, and three times as much energy again if sites down to 20 kW/m are used. Industry sources believe 40% efficiency can be achieved, meaning output of 12 kW/m at the best sites. If 10% of these ideal sites could be used and 40% efficiency achieved, output would be equivalent to 18 power stations. The equivalent of a 1000 MW power station would have to be 80 km long. Hayden (2004, p. 210) derives 130 km from another experimental project assuming 25% efficiency. Adding the estimate for 20 kW/m coasts suggests a total potential roughly equal to 76 power stations. This would be a welcome contribution, but industry sources consulted do not think wave power will exceed 5 – 10% of world demand. This roughly aligns with the estimates for wave and tide potential given by Scheirmeier et al, 2008. World electricity supply at rich world rates of consumption for the present total world population would equate to roughly 9,000 power stations. (Transport will have to be mostly electrical in future, multiplying the electicity supply task by about 3; below.)

GEO-SEQUESTRATION OF CO2.

Might the geo-sequestration of carbon dioxide from coal use (also referred to as Carbon Capture and Storage, CCS) enable sufficient coal use to plug the gaps left by renewables? Two tasks should be considered, the first being to deal with the possible 1100 EJ 2050 world energy supply without exceeding the IPCC emission limits. For an atmospheric limit of 450 ppm the IPCC says 2050 CO2 emissions must be cut by 50 – 80%, i.e., to 5.7 to 13 GT/y. This corresponds to 1.4 – 3.6 GT/y of carbon and 1.98 – 5.1 GT/y of coal. (Coal will be the only fossil fuel available in significant quantity after 2050.) Some argue that the acceptable limit is no more than 350 ppm, which we have already past. (See Hansen et al., 2008.)

Important here is the fact that the IPCC's 2100 target range is much lower than the above estimates for 2050, with a mean close to zero emissions and the lower point in the range less than zero, meaning that a large volume of CO2 would have to be taken from the atmosphere every year. Also important is the fact that atmospheric warming effects are occurring much faster than the IPCC expected so a satisfactory target will surely be under the 450 ppm. underlying the foregoing estimates. It is increasingly accepted that we must almost completely eliminate emissions this century.

Geosequestration can only be applied to stationary sources (so not to vehicles). There seems to be considerable uncertainty about the proportion of CO2 in exhaut gases that it will be possible to extract. The IPCC says it will be possible to extract 80 - 90%. However others say only 71 - 79%. (Barry, 2008.) There is also uncertainty regarding recoverable coal quantities. There could be 15,000 billion tonnes in the crust but the recoverable quantity is generally assumed to be c.1000 billion tonnes. (Some sources state four times as much, without clarifying plausibility of recovery.) The Energy Watch Group (2007) believes the recoverable quantity might be in the region of 500 billion tonnes, and supply might peak within two decades.

These uncertain ranges complicate the scene. Table 2 sets out the approximate values for a) the amount of electricity that could be generated, b) the amount of coal that can be used, and c) the life of coal resources assuming 1000 billion tonnes recoverable, in relation to a CCS rate of 80%, 85% or 90% of CO2e generated and a safe emission rage of 5.7, 9.35 or 13 GT/y of CO2e.

Table 2.

Emissions, coal use and coal life, for different CCS capture rate, and safe emission assumptions.

"Safe" Emission Quantity.	CO2 capture rate. 80%	85%	90%
5.7GT/y	86 EJ/y 9.8 GT/y 104 y	129 EJ/y 14.6 GT/y 79 y	172 EJ/y 20 GT/y 52 y
9.35GT/y	154 EJ/y 17 GT/y 59 y	230 EJ/y 24 GT/y 45 y	308 EJ/y 30 GT/y 32 y
13 GT/y	223 EJ/y	335 EJ/y	446 EJ/y

25 GT/y	35 GT/y	50 GT/y
40 y	30 y	19 y

The table indicates that if it was safe to release 9.35 GT/y of CO_2, the IPCC mid range figure, and if CCS could capture 90% of emissions, then CCS could provide 9 billion people with a little less than the present Australian per capita electricity consumption. At that rate coal would only last about 30 years.

Note that the coal life times given do not take into account the amount that would have been burned between now and 2050. For instance if we increase coal use from the present c. 7 GT/y to 20 GT/y by 2050 then by 2050 we will already have used up 57% of the estimated recoverable amount, and the life time for coal after 2050 would be 20 years.

It could be argued that the most plausible assumptions are a 5.7 GT/y emission and 85% capture and these would enable only 42% as much electricity generation as the above assumption. In either case there would be little or no coal left over to meet non-electricity demand. Also, by 2050 electricity demand could be twice as great as it is now.

It should be stressed that these estimates do not take into account the energy needed to build the geosequestration plant and operate the process, including pumping liquid CO_2 long distances. The operating energy required is estimated at 10 – 30% of energy produced by the coal generating the CO_2. (Barry, 2008 states 30%.)

The next problem concerns the availability for storage sites. The Australian east coast has few possible storage sites close to generation sites (although depleted off shore oil fields might be viable.) It is not likely that storage of very large quantities of CO_2 in the deep ocean would be regarded as acceptable, given that the ecological effects would be uncertain, the CO_2 would return to the surface in time, and global warming will decrease the ocean's capacity to absorb CO_2 and will make ocean currents less predictable. Hendricks, Graus and Van Bergen (2004) say that the best estimate of the land storage capacity is 1700 GT. (The highly speculative upper limit given is 6 times as great.)

The IPCC's medium 2050 permissible emission rate of 9.35 GT/y, along with the assumption that 10 times as much can be generated and 90% of this captured, would mean that 81 GT/y would have to be sequestered. At this rate land storage capacity might last no more than 20 years. Similarly, using coal at the corresponding rate of 30 billion tonnes p.a. would exhaust coal resources in perhaps 3 decades.

THE ENERGY STORAGE PROBLEM.

The intermittent nature of most renewable electricity sources would not be a problem if electricity could be stored in very large quantities. However this is not possible and although potentially valuable technologies are being researched at present there would not seem to be good grounds for expecting this problem to be solved. The very large scale of the problem needs to be kept in mind. Calm conditions can apply across most of a continent for several days in a row in winter. If most of Europe's electricity demand for say four days was to come from stored wind or solar energy then in the order of 50,000 GWh would have to be stored, not taking into account losses in storage. For illustrative purposes, to store this quantity of energy in lead acid batteries would require around 2 billion tonnes of lead some 600 times annual world production (taking into account the fact that lead acid batteries should not be more than 20% discharged, and assuming 90 KJ/kg; Sorenson, 2003.)

Following are brief comments on what seem to be the most promising storage options at present, and their limits.

<u>Pumped water storage.</u>

The gaps left by intermittent sources can be filled to some extent by electricity generated by water that has been pumped up into dams. However the capacity compared with demand is limited. World hydro-electric generation meets only about 15% of electricity demand (6% in Australia) so when wind and sun were meeting little of the demand pumped storage could not take up much of the task even if all he hydro dams were suitable. To increase generating capacity would be to build alternative plant which would sit idle much of the time. The greenhouse problem is likely to reduce hydro electricity capacity significantly in future.

In addition there is the problem of finding low dams that are big enough to hold all the water to be pumped up. The sea can be used but this sets problems to do with seepage of salt into the ground at the high dam sites. This is why a proposal in South Australia was abandoned.

<u>The vanadium battery.</u>

Electrical energy can be stored using vanadium solutions. An 800kWh system is in use on King Island in Bass Straight, Australia. (Skylass-Kazacos, n.d.) However the energy density is quite low and for very large scale storage the materials, energy and dollar costs would be very high. About 70 litres are needed so store 1 kWh. (Personal communication, Cougar energy; see also www.vrbpower.com.) Petrol is about 850 times as energy-dense.

For a PV power station to store energy equivalent to that which a coal-fired station would provide for the 16 hours when the sun is not shining, i.e., 16 million kWh, 1,120 million litres would be needed. This would require 53 tanks of 30 metres diameter and 30 metres high. A renewable energy system would need the capacity to store for many days.

The cost of the 800 kWh King Island system is very high, $4 million, although if mass produced cost per kWh would be much lower. If we assume half of this for the storage part of the system, i.e., $2,500 per kWh, then the cost of the 16 hour storage task for a 1000 MW power station would be $40 billion, and for a four day storage task would be $240 billion…when a $1.2 billion coal-fired plant would do the same job (or $3.7 billion including coal fuel for its lifetime.)

Then there is the cost of the bulky "engine" to produce electricity from the stored solution. According to figures from Cougar Energy, a 1000 MW power station would probably require about 30,000 tonnes of materials.

These numbers are uncertain and costs are likely to fall considerably with development, but it would appear that the extreme dollar and embodied energy costs would prohibit very large scale use of this technology.

Compressed Air storage.

Storage of energy by compressing air is claimed to be between 40% and 70% efficient. Therefore to retrieve the 670 MW x 16 hrs night time output from a 1000 MW power station, i.e., 10,560 MWh, would require storing about 17.6 million kWh. System cost would have to include the cost of the compressors and the turbines for generating electricity from the air (possibly the same devices), and the cost of the storage caverns. This means that for each 1000 MW power station providing the energy to be stored we would have to build another capable of generating 660 MW at night from the compressed air.

Very large storage volumes would be required to store significant quantities of energy. Sorensen (2000) says 15 MJ can be stored per cubic metre, i.e., 4.16 kWh. Therefore to deliver 10,560 MWh to meet night time demand from a 1000 MW plant via a 0.5 efficient system would require a storage volume of approximately 8,460 million cubic metres, i.e., a mine shaft around 8,460 km long. There would probably be too few caverns or old mines large enough for this form of storage to enable bulk electricity supply via intermittent sources. Excavation is economically feasible for heat storage in water but much less so for the larger volumes required for compressed air storage.

The biggest problem would seem to be the fact that high efficiency requires the addition of heat via gas burning at the regeneration stage. In a wholly renewable energy world this will not be possible. Solar heat could be used, but this would mean solar plant would have to be added to collect energy in the form of heat equivalent to a large fraction of the energy collected as wind, and the plant to store it would also have to be built. Heat availability would be at its lowest in winter when wind energy for storage was at its highest.

Ammonia.

Within the above discussion of solar thermal reference has been made to the possibility of storing large quantities of heat via chemical reactions such as the dissociation of ammonia. This would seem to be quite promising for solar thermal systems. However it would seem to involve very high plant embodied energy costs for heavy pressure containers, for 12 hour storage, let alone 4 day storage. It is also shown in Trainer 2008 that solar thermal's energy storage capacity could not overcome the much greater general gap problem set by renewables .

Use the batteries of electric vehicles?

It is sometimes claimed that if we had a large number of electric vehicles then their batteries could be used to organise large scale storage of electricity, by plugging into the mains for several hours a day. There is not much scope for this. The car would need a fully-charged battery when it is to be used so its battery could only be of use for other purposes if it could be plugged in when low, charged up and then run down powering the general electricity system and recharged fully again, all before the car was needed again. It is not likely that this could be organised effectively, that is making sure that each of the millions of cars in a system stored ands delivered energy and thenwas fully recharged when it was to be used. Even if car users could set the time when they intended to drive again, would there be a need for storage in that period? Storage would be most needed on a cloudy or calm day and how could this be provided for in advance. If surplus storage capacity was to be available in the car all the time, then why not locate this independently of cars?

CONVERSION LOSSES

Advocates of renewable energy often fail to take into account the fact that energy is needed in particular forms and this sets the problem of converting it from other forms and the problem of the associated losses. (Stern's Fig. 9.4. fails to deal with this issue.) This is most obvious with respect to transport. If biomass is used to produce ethanol about 2/3 of the primary energy is lost, and if coal is used to produce liquids the energy efficiency is around .6. More significantly, if electricity is to provide liquid fuel for transport in the form of hydrogen, four times as much electrical energy has to be generated compared with the amount of energy to go through the wheels of vehicles. (Bossell, 2004.)

If we assume that Australia's transport fleet operates at 40% efficiency (petrol to wheels) then some 500 PJ would be needed at the wheels of vehicles (ignoring the fact that electricity cannot power air or sea transport.) To provide this via the hydrogen path would require generation of 2 EJ and when this is combined with the .7 EJ of direct electricity demand, 4 times Australia's present electricity generation would have to be produced.

Thus the quantities of renewable energy required when conversion losses involved in providing needed energy forms are taken into account will be much greater than it might appear if the various amounts of "service" or "final" energy, (e.g, transport) are simply added. Note also that transport energy accounts for only about half Australia's total oil plus gas consumption, so after meeting Australia's transport demand it would be necessary to provide as much liquid energy again through the conversion of other primary forms, again at a high energy cost.

THE SYSTEM INTEGRATION PROBLEM.

Within the above discussion of wind energy reference was made to the difficulties involved in combining a significant amount of wind energy with coal, gas or nuclear contributions. This problem exists in a more complex and large scale form when the task is the integration of a number of different renewable sources into the one supply system.

Figure 1 makes the magnitude of the problem evident. Imagine a system in which demand is X GW. Figure 1 represents the typical output from a wind system of X GW capacity and the typical output from a PV system of X GW capacity, on a very sunny and very windy day. Figure 2 represents the output from these wind and solar systems on a cloudy day with little wind (and there would be times when cloud and calm affected whole regions and output would be almost zero for days on end.)

(Diagrams to be inserted here.)

Figures 3 and 4 represent the combined wind plus PV output for each of these days. Daily demand is also represented in diagrams 3 and 4. It can be seen that on day 2 renewables would provide much less energy than is demanded and the hatched area represents the proportion that would have to be provided by coal or nuclear sources. However on day 1 the combined solar and wind output would exceed demand greatly and about half of the electricity generated would have to be dumped, or stored inefficiently as hydrogen.

Over time the X GW of peak wind capacity would generate .23 GW (the world wind system average, (IPCC 2007, Section 4.3.3.2) and the X GW peak PV system would contribute about .2 (…in Australia, but much less in Europe), meaning that coal or nuclear sources would have to provide about 60% of electricity. Thus to reduce this amount the renewable components of the system would have to add to more than 2X GW capacity, and even more electricity would have to be dumped on good days. Even if renewable capacity was increased to

4 GW about X GW of coal or nuclear generation would still be needed on the days when there was no sun or wind.

Thus it is evident how the extreme variability of the renewable sources sets very difficult problems, and leads in the direction of “over sizing” and dumping, yet cannot eliminate significant use of coal or nuclear sources, because there will always be some probability of zero input from renewables regardless of how oversized their capacity is. Again cloudy and calm periods can dominate continental areas for days on end. The capacity of solar thermal systems to store heat will make a significant contribution to reducing the problem, but as was explained above (and detailed in Trainer, 2008) this cannot solve the total renewable system problem set by sequences of cloudy and/or calm days.

How big might the gap left by combined renewbles be? This is difficult to estimate without detailed study but the following considerations indicate the nature of the problem. As is apparent from above the lower we want to make the gap (and therefore the need for coal or nuclear power) the more we will have to over-size the renewable components of the system, with significant consequences for embodied and capital costs. We saw that a system with X GW of coal/nuclear, wind, PV and solar thermal respectively might only meet 60% of demand (if problems of integration, ramping, storage, cloudy and calm days are ignored.) We also saw that if we double the amount of each renewable component there would still be times when there was little sun or wind for days and therefore there would still be a gap of some considerable magnitude.

A system in which we had,

1 X GW of coal powered generating capacity,

2 X GW of wind (with a cost per kWh <u>delivered</u>, not peak, that is 3 times that for coal, because wind capacity is ..23 and for coal it is .8+),

2X GW of PV (…maybe 5 – 7 times coal …),

2X GW of solar thermal (…maybe by 5 -7 again…)

would have a total capital cost that is in the region of 33 times that of an X GW coal/nuclear capacity that could do the whole job. The example is exaggerated but indicates the way total system costs would tend to multiply.

<u>**RENEWABLES ARE ALTERNATIVE NOT ADDITIVE**</u>.

Renewable energy sources are usually thought of as additive, that is, as if building X GW of wind capacity and X GW of PV capacity would give us 2X GW of generating capacity. However on calm nights these two sources would give us no generating capacity at all. Thus they are best thought of as sources which at times can be alternated with or substituted for coal fired power, but not as sources which can always be added to each other. This means that we might have three or more very expensive systems each capable of more or less meeting demand while the others sit idle, and in addition we must retain a coal or nuclear system capable of meeting most or all demand when most or all the renewables are down.

HYROGEN

Chapter 6 of Trainer 2007 outlines the reasons why we are not likely to have a hydrogen economy. Firstly the hydrogen would have to be produced from some renewable source. Present industrial production of hydrogen from electricity is around 65% energy efficient. Bossell concludes that if the hydrogen is then compressed, pumped, stored and re-used, the energy losses at each of these steps will result in something like only 25% of the energy generated being available for use to drive the wheels of a fuel-cell powered car. (Bossell, 2003, 2004, and undated.) That this plausible can be seen if we assume .7 efficiency for production of hydrogen from electricity, an optimistic .8 for storage and distribution by compression, pumping or tanking, fuel tank filling, and .4 for fuel-cell operation, which would combine to yield an overall mill to wheels efficiency of 22%. In fact plausible assumptions can make the final figure closer to 10%. (North, 2005.) It is by no means generally assumed that fuel cell efficiency will rise to c. .5 - .6. In addition, platinum resources are insufficient for large scale use of PEM fuel cells (Gordon, Bertram and Graedel, 2006), although other forms of fuel cell might become viable. Because the hydrogen atom is very small and light it leaks through vales and seals easily. It also reacts with other elements, making metals brittle. How often would pipes etc. have to be replaced? How much petroleum would it take to put in a plastic pipe distribution system (inside steel pipes to take the pressure) Consider the extent of the existing gas supply infrastructure; another more expensive system about as big would have to be put in for a hydrogen distribution system (if only because the gas system will still be in use.)

Bossell details these and other difficulties. For instance he points out that a standard tanker can deliver 20 tonnes of petrol, but it would only deliver 320 kg of compressed hydrogen. To pump hydrogen to Europe from the Sahara would take 65% of the energy going into the pipe line at the start. It is therefore not likely that energy-intensive societies could be run on hydrogen shipped around the world in tankers from sites such as the Antarctic where winds are very strong.

Lovins (2003) argues that for these reasons the best strategy would be to distribute electricity to many small hydrogen generating outlets for storage and vehicle refuelling. This would reduce the distribution losses, but it would probably still involve a considerable (e.g., 10 – 15%) loss in transmission of electricity from distant renewable electricity sources such as wind farms in Siberia (Czisch, 2004), a lowered hydrogen generation and storage efficiency because of the need for many small units, and it would still involve compression losses in filling vehicle tanks, and the need for considerable storage. Pressurised tanks in vehicles would add weight, reducing the efficiency of vehicles, and constitute a much greater explosive crash risk. The overall mill to wheels efficiency would therefore probably remain around .25. Lovins' optimistic assumptions are questioned (Crea, 2004. Wilson, 2002) and he does not seem to take into account the considerably greater embodied energy costs in the kinds of super-efficient vehicles he assumes. (Matejda, 2000, documents surprising embodied energy costs of this kind.)

Consider the capital and embodied energy costs of a system to deliver 1000 MW. This would have to include the capital cost of the windmills, the transmission lines, the hydrogen generating plant, the compressing, pumping and storage equipment capable of handling very large volumes of gas, and the cost of the "power station" required to produce electricity from the stored hydrogen. The last item would be equivalent to the 1000 MW coal or nuclear power plant that would have avoided the need for all this plant on the hydrogen path. To deliver the initial 1000 MW electricity we would need 3,000 MW of wind capacity, even at an ideal wind site, and 4340 MW at the world average site where capacity is .23 (IPCC, 2007. Section 4.3.3.2.)

In Australia transport takes almost twice as much energy as there is electrical energy consumed. In view of the above losses, the c. 40% petrol to wheels efficiency of the present system, to run transport on hydrogen generated from wind electricity would require generation of <u>4 times</u> as much electricity (700 + 2000 PJ) as would be needed just to meet electrical demand (700 PJ). Use of electric vehicles might halve the task according to Bossel, although electricity cannot run ships or aircraft. Average vehicle energy efficiency can be expected to increase markedly, possibly trebling, but some important factors counter-balance this. The embodied energy costs of the new light vehicles are quite high, and especially important, electricity and transport energy demand in Australia are increasing at 2- 3% p.a.

The hydrogen optimist's best strategy might be to have wind and solar to meet say one-third (or one-half) of system electricity demand directly and to meet the rest via much additional capacity storing hydrogen for use at c. .25 efficiency. In other words to meet the remaining two-thirds (or one-half) of the target 8 times (or 4 times) as much electricity would have to be generated as would meet that first one-third (or one-half) of demand. Thus contending with variability greatly multiplies the need for plant, with associated embodied energy costs, e.g., for hydrogen production and storage and regeneration equipment. Adding the transmission task from distant wind fields, would seem to imply an impossibly costly system…just to meet the 20+% of total energy demand that takes the form of electricity. To also run transport this way would be to add a task that is almost twice as big. (Australia's present electricity consumption is 700 PJ and transport use is 1200 PJ.)

NUCLEAR ENERGY?

It is often assumed that the difficulties set by renewables means that nuclear energy must be adopted. Chapter 9 of Trainer 2007 presents several reasons why nuclear energy cannot solve the general energy problem, if only because there is likely to be far too little fuel. If reactors were to provide 9 billion people with the present Australian per capita electricity use nuclear generating capacity would have to be around 40 times as large as it is now, (and Australian electricity demand might double by 2050). The commonly stated 3 – 4 million tonne estimated Uranium resource figure (Leeuwin and Smith, 2005, Zittel, 2006) could not make a significant difference to the global energy situation, (unless fusion or breeder technology is assumed.) Taking the highest speculative estimates (c. 13 million tonnes) and adding thorium would not alter the outlook significantly. A 4 million tonne fuel resource would generate perhaps a total of 700 EJ, corresponding to less than 12 years of present world electricity demand. It would provide Australia's present per capita electricity consumption to 9 billion for about 2 years. There are large quantities of Uranium in very low grade sources such as sea water, but Leeuwin and Smith argue that the energy cost of retrieving useful concentrations would be greater than the energy required to do this.

GENERAL CONCLUSIONS ON ELECTRICITY

The foregoing evidence seems to at leave much doubt as to how much electricity from renewable sources we are likely to be able to afford or integrate into the supply system. It seems to show that it is unlikely that demand could be met in winter. It is much more unlikely that renewables will be able to generate sufficient electricity to fuel all of our transport via electric or hydrogen vehicles.

To this we must add the fact that electricity demand is rising all the time, and fast. In recent years Australian peak demand has increased at more than 3% p.a. At this rate it would be more than 4 times as great as it is now by 2050, although The Australian Bureau of Agricultural and Resource Economics (2006) expects the rate of energy growth to have fallen to 1.9% p.a. by 2030. However energy consumption growth in the Third World and for the world as a whole is increasing much faster than in the rich countries. Garnaut's Figs. 2 and 4 (2008), taken from IPCC sources, indicate that continuation of business as usual growth in energy use would see CO_2 emissions 4 -5 times as great by 2050.

CAN IMPROVED ENERGY CONSERVATION AND EFFICENCY SOLVE THE PROBLEM?

It is commonly assumed that technical advance and greater conservation effort can greatly reduce the need for energy. Lovins and von Weisacher (1997) have argued that a “Factor Four “ reduction is achievable, i.e., halving resource and environmental loads while doubling GDP. Most of Lovins’ (valuable) analyses of particular instances indicate 50 – 75% reductions. But it is easily shown that these would be far from sufficient.

Let us assume that rich world energy use and other resource and environmental impacts must be halved (…although solving greenhouse and footprint problems would require around factor 10 reductions.) If by 2070 there are 9+ billion people on the “living standards” Australians would have by then given 3% growth, total world economic output would be 60 times as great as it is now. If by that point in time we have reduced present environmental impacts by 50%, we would have made a Factor 120 reduction in the rate of impact per unit of economic output or consumption, as distinct from a Factor 4 reduction. This is far beyond the realm of credibility.

ATTEMPTING A GLOBAL ENERGY BUDGET

The situation (and the unsatisfactory nature of the IPCC and Stern analyses) can be made clear by attempting to explain how future world energy budgets might be composed.

For 2050.

The assumptions will be;

- 9 billion people.
- The common expectation of a world energy demand of 1100 EJ corresponding to 2+ times present consumption.
- Energy conservation and savings reduce consumption by 25% meaning 825 EJ is to be provided.
- Low temperature space and water heating, 25% of demand, and would be easily supplied by solar sources (which is not valid for mid to high latitudes).
- Geosequestration as in Table 2 above. The first assumption here will at first be 90% capture and 5.7 GT/y “safe” emission.
- Electricity 25% or 206 EJ.
- Transport 35% or 290 EJ. This is the energy value of the fossil fuel. Assuming 40% efficiency within the vehicle tank-to-wheels system, energy needed to drive wheels would be 116 EJ.

Electricity (206 EJ.): If we follow Stern and assume 110 EJ of biomass primary energy providing 35 EJ of ethanol this might provide 5 EJ of electricity from lignin waste (this might not be possible.) Let us assume that wind, PV and Solar thermal each provide 60 EJ, but their combined intermittency leaves a 10% gap to be plugged, requiring 20 EJ. If geosequestration is drawn on for this purpose 150 EJ from this source would be left. We would need about 120 times the early 2000s wind capacity, and this would have to be located a very long way from users (again the limit of European capacity might be 4 EJ.) Almost 80 billion square metres of PV panels would be needed (at the Sydney level of radiation), almost 9 metres per person (to provide 7% of total energy). This does not take into account the immense/insurmountable problems of integration and storage, but let us assume electricity has been accounted for.

Transport (290 EJ): If we take Stern's assumed 110 EJ of biomass primary energy this would provide 35 EJ of ethanol. (This is an implausibly high assumption because it corresponds to about 850 million ha of plantations.) Thus most of the transport energy would have to be electrical. Let us assume that present vehicles have a 40% efficiency between tank and wheels, meaning that the 290 EJ stated in the above list of assumptions as the primary fuel amount corresponds to 116 EJ driving wheels. Subtracting the ethanol leaves 81 EJ to be provided, and if there is as Bossell says a 50% efficiency on the electrical path from wind etc. to wheels, then 162 EJ must be found. If we allocate the remaining 150 EJ above from geosequestration we would still need another 12 EJ. (We will ignore the fact that air and sea transport cannot be run on electricity.)

The remainder (125 EJ): We would at this point have explained low temperature heat, electricity and transport, but there would still be 15% of demand to supply, 125 EJ. None of this would be in the form of electricity and much of it would be in the form of liquid fuel (only half liquid fuel used goes to transport). Therefore large conversion losses would be involved, e.g., 75% for hydrogen from electricity. If we assume a 50% conversion efficiency the need would be for another 250 EJ. Adding the 12 EJ transport deficiency would make the total needed 262 EJ. If this is added to the wind, PV and solar thermal accounts each would have to generate almost 150 EJ. In other words wind would have to provide maybe 300 times as much as it provided in the early 2000s.

Let's try different assumptions.

If we assume CCS at the maximum rate in Table 2, corresponding to 13 GT/y CO_2 emissions and a 90% capture rate, then 36 GT/y of coal would be used, generating 446 EJ/y of electricity.

The tasks for wind, PV and solar thermal would each have been reduced by 90 EJ, but it would still be 60 EJ each, equivalent to present total world electricity generation. However we could not go on at these rates for any length of time because if we rose to them there would probably be no coal left by 2050.

Note that these two attempts target the supply of 1100 EJ, but this would provide 9 billion with only 122 GJ/person, which is half the present Australian consumption, and probably one-quarter of the consumption we are heading for by 2050.

The 2100 situation.

For 2100 it is not likely that we could assume any coal use, on the grounds that no CO2 emissions will be permissible. If 9 billion people had the per capita average energy consumption Australians are likely to have by 2050, i.e., c. 500 GJ/person the gross target would be 4,500 EJ. If energy saving and conservation advance reduced this to 3375 EJ, and if low temperature heat could easily be derived from solar sources (again not a valid assumption for Europe and US in winter), the energy "service" target for renewables would become 2,530 EJ.

If the 844 EJ of electricity was to come equally from wind, PV and solar thermal, wind capacity would have to be about 560 times as great as it was in the early 2000s. We would need 72 PV panels per person, at Sydney insolation, and therefore many more in Europe.

The 464 EJ for transport (i.e., the amount driving wheels) would require generation of 928 EJ of electricity (or twice as much again if via hydrogen) making the total electricity task 1,172 EJ, and therefore requiring a wind capacity some 1,180 times as great as in the early 2000s (assuming the task is divided equally between wind, PV and solar thermal), again ignoring intermittency and integration problems.

There should be no need to continue. Clearly if the 2050 budget is impossible then one that is 4 times as big and unable to use geosequestration will be far more so. Note that the never-questioned business as usual expectation of 3% p.a. economic growth from here to 2100 would see a global economy churning out more than 16 times as many goods and services in that year as is produced and consumed each year now.

These accounts only deal with annual aggregate quantities and do not take in the fact that in winter solar sources would be much lower than average in most of the regions where rich countries are to be found. Nor does it deal at all with the problems of integrating into the system very large quantities from highly variable sources. However a somewhat more favourable budget might be drawn up if solar thermal sources were given a large proportion of the electricity load.

IMPRESSIVE ADVANCES IN THE NEAR FUTURE WILL CONFUSE THE SCENE.

In the next ten to twenty years there will certainly be major advances in the development of renewable technologies and in carbon emission abatement. In the past abundant and cheap fossil fuels led to the neglect of renewables and to the development of wasteful ways. Now that more attention is being given to these tasks spectacular achievements are likely to be made. Unfortunately however these will reinforce the belief that technical developments can solve the problems – all we have to do is keep up this impressive progress. The argument in this paper has been that the rapid initial progress, made by "picking the low hanging fruit", will increasingly run into difficulties and limits long before it could become possible for renewables to sustain consumer societies.

An example is the fact that putting PV panels on house roofs is effective while the capacity is small in relation to the coal or nuclear capacity that must also be there to take over when the sun is not shining, but there is a limit to the amount of energy that could come from such a source.

THE GROWTH COMMITMENT

The above references have been to the difficulty or impossibility of meeting present energy demand from renewables. That is not the focal problem. The crucial question is whether renewables can meet the future demand for energy in a society that is committed to limitless increases in "living standards" and economic output. The magnitude of the implications of this commitment are evident if we consider 9 billion people rising to the "living standards" we in rich countries will have in 2070 given 3% p.a. economic growth. Total world economic output would be 60 times as great as it is now, and doubling every 23 years thereafter.

The projections given by the Australian Bureau of Agricultural Economics (2006) anticipates a 71% increase in national energy use by 2030, indicating that Australian per capita energy use might be more than 500 GJ by 2050 (alt hough they expect the growth rate to decline to 1.9% p.a. by 2030.). As has been noted above, if all the world's expected 9 billion people were to rise to that level of energy use then world energy production would probably have to be 4500 EJ, about 9 times as great as it is now.

The argument in this paper has been that present levels of energy use are seriously unsustainable and cannot be provided by renewable sources, yet in consumer society there is a strong tendency to assume that there is no need to consider the commitment to limitless growth in production and consumption, and that renewables can provide all the energy this would require.

It is very likely that in coming decades rich countries will run into increasingly serious problems of energy supply, ecological destruction, resource scarcity, resulting geopolitical difficulties, and therefore economic and financial problems. Resources, energy, materials and construction costs are already rising rapidly. Thus the conditions in which renewable energy technologies will have to be researched, developed, financed and built on a massive scale are very likely to be far more difficult than at present, imposing significantly higher energy and dollar costs. Energy, materials and dollar costs estimated at today's values are therefore likely to be significantly misleading.

THE ANSWER?

The energy and greenhouse problems are only two of the increasingly serious problems consumer society is running into. In Chapter 10 of Trainer 2007 it is argued that it will not be possible to solve these unless the commitment to affluence and growth is abandoned. (A much earlier statement of the case was given in Trainer, 1985.) Consumer-capitalist society is described as irredeemably unsustainable and unjust. It involves rates of resource use and environmental impact that are far beyond sustainable levels and could never be extended to all the world's people. Present affluent "living standards" would not be possible for the rich countries if these countries were not taking most of the world's resource output, thereby condemning the Third World majority to far less than their fair share. In other word it is not just that consumer society is unsustainable -- it cannot be made sustainable.

It is argued that the commitment to affluent "living standards" and limitless growth is the predominant cause of the multi-faceted global predicament. This inevitably generates problems of ecological destruction, resource depletion, Third World deprivation and geopolitical conflict and war. In addition it is argued that the obsession with growth and affluence is damaging the quality of life and social cohesion in even the richest societies. The present levels of production and consumption are the basic cause of these many alarming problems, yet the top priority is economic growth, and therefore the magnitude of the problems will inevitably be multiplied in coming decades.

Chapter 10 argues that huge and radical system change is clearly needed. The problems cannot be solved by technical advance or more conservation effort on the part of individuals, firms and governments within a consumer-capitalist society. They are being caused by an overshoot that is far too great for that, and they are being caused by the fundamental structures and commitments in consumer-capitalist society. The necessary vast reductions in energy and resource use and environmental impact cannot be made without dramatically reducing the volume of production and consumption and therefore without changing from a society in which the top priority is increasing hem without limit.

Chapter 11 of Trainer 2007 argues that the solution must be thought of in terms of a transition to some kind of Simpler Way (detailed in Trainer, 2006.). This must involve non-affluent (but sufficient) material living standards, mostly small and highly self-sufficient local economies (and therefore localization as distinct from globalization), zero-growth economic systems under social control and driven by need and not by market forces or the profit motive (although there might be a place for markets and private firms), and highly cooperative and participatory systems. Obviously such radical system transition could not be made without profound change in values and world view, away from competitive, acquisitive individualism.

There are good reasons for thinking that changes of this magnitude will not be made, especially given that the need for them is not on the agenda of official or public discussion. A major factor that has kept them off the agenda has been the strength of the assumption that renewable energy sources can substitute for fossil fuels.

Augenstein, D. and J. Benemann, (2007), The Cellulosic Ethanol Delusion, http://www.aiche-norcal.org/.Symposium/Symposium2006/pdfs/EnergySolutions.pdf

Australian Bureau of Agricultural Economics, (ABARE), (2006), Technological Development and Economic Growth, Jan. 12.

Australian Solar Radiation Data Handbook, (2006), ANZ Solar Energy Society, April. Energy Partners, 6260 6173.

Baer, P, and M. Mastrandrea, (2006), High Stakes; Designing Emissions Pathways to Reduce the Risk of Dangerous Climate Change, Institute of Public Policy Research, Nov. www.ippr.olrg. See Rising Tide Australia; 2007, http://risingtide.org.au/cleancoal

Barker, T., et al.,(2007), Working group 111 Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report, Climate Change 2007: Mitigation of Climate Change, Summary for Policy Makers.

P. Barry, (2008), “Carbon sequestration frustration”, Science News, Aug. 13th.

Black, R., (2006), “Sea energy could help power UK”. http://news.bbc.co.uk/2/hi/science/nature/4645452.stm

Bossel, U., (2003), “Efficiency of hydrogen fuel cell, diesel-SOFC-hybrid and battery electric vehicles”, European Fuel Cell Forum, Morgenazvcherstrasse2F, CH-5452 Oberrohrdorf.

Bossel, U., (2004) “The hydrogen illusion; why electrons are a better energy carrier,” Cogeneration and On-Site Power Production, March – April, 55 – 59.

Bossel, U., (Undated), “Towards a sustainable energy future”, www.efcf.com

Coelingh, J. P., 1999, Geographical dispersion of wind power output in Ireland, Ecofys, P.O. Box 8408, NL – 3503 RK Utrecht, The Netherlands. www.ecofys.com.

Crea, D., 2004, “Twenty hydrogen myths; a Physicist’s Review”, http://www.theraht.info/archive/001289.html

Czisch, G., (2001), Global Renewable energy potential; approaches to its use, http://www.iset.uni-kassel.de/abt/w3-w/folien/magdeb0030901/

Czisch, G., (2004), Least-cost European/Transeuropean electricity supply entirely with renewable energies”, www.iset.uni-kassel.de/abt/w3-w/project/Eur-Transeur-El-Sup.pdf

Czisch, G. and B. Ernst, (2003),"High wind power penetration by the systematic use of smoothing effects within huge catchment areas shown in a European example", gazisch@iset.uni-kasel.de

Davy, R. and P. Coppin, (2003), South East Australian Wind Power Study, Wind Energy Research Unit, CSIRO, Australia.

Energy Watch Group, (2007), Coal Resources and Future Production, April. www.enegywatchgroup.org/files/Coalreport.pdf

E.On Netz, (2004), Wind Report 2004, http://www.eon-netz.com http://www.nowhinashwindfarm.co.uk/EON_Netz_Windreport_e_eng.pdf or www.members.aol.com/optjournal4/eon04pdf.pdf

E.On Netz, (2005), Wind Report 2005, http://www.eon-netz.com

Fulton, L., (2004), Biofuels For Transport; An International Perspective, International Energy Agency. (No source.)

Gale, J., 2002), “Overview of CO2 emission sources, potential, transport and geographical distribution of storage possibilities”, IEA Greenhouse Gas R and D Programme, Stoke Orchard, Cheltenham, Glos. GL52 4RZ, UK.

Garnaut, R., (2008), The Garnaut Climate Change Review; Interim Report.

Gordon, R. B., M. Bertram and T. E. Graedel, (2006), “Metal stocks and sustainability”, Proceedings of the National Academy of Science, Jan, 31, 1209-1214.

Hansen, J., et al., (2008), “Target atmospheric CO2; Where Should humanity aim?”, Climate Progress, http://climateprogress.org/2008/03/17/hansen-et-al-must-read-back-to-350-ppm-or-risk-an-ice-free-planet/

Hayden, H. C., (2004), The Solar Fraud, (Second Edition), Vales Lake, Pueblo West.

Heinberg, R., (2003), The Party's Over, Gabriola Island,New Society.

Hendricks, C., W. Graus, and F. van Bergen, (2004), "Global carbon sioxide storage potential and costs, Ecofys", Utrecht. www.ecofys.nl.

Hoehne, N., 2006, What is Next After the Kyoto Protrocol? Assessment of Options for International Climate Policy Post 2012. TechnePress, Amsterdam, May.

Hohenstein, W. G., and L. L. Wright, (1994), "Biomass energy production in the United States; An overview," Biomass and Energy, 6, 3., 161-173.

Intergovernmental Panel on Climate Change, (2001), Climate Change 2001; Impacts, Adaptations and Vulnerability, Report of Working Group II, Geneva, Switzerland, Feb.

Leeuwen, J. W., and Smith, P., (2005), Nuclear Energy; The Energy Balance, Sixth Revision, Ch. 2.

Lenzen, M., 1999, "Greenhouse gas analysis of solar-thermal electricity generation", Solar Energy, 65, 6, pp. 353 – 368.

Lovins, A. M., E. K. Datta, O. J. Bustnes, G. Kooey and N.J. Glasgow, (2005), Winning the Oil End Game, Colorado, Rocky Mountains Institute.

Lovins, A and E. Von Weisacher, (1997), Factor Four : Doubling Wealth - Halving Resource Use : A New Report to the Club of Rome, St Leondards, Allen & Unwin.

Lovins, A, Twenty Hydrogen Myths, http://www.rmi.org/images/other/Energy/E03-05_20HydrogenMyths.pdf

Mateja, D., (2000),"Hybrids aren't so green after all", www.usnews.com/usnews/biztech/articles/060331/31hybrids.htm

Metz, B, O. Davidson, H. de Coninch, M. Loos and L. Meyer, (Undated), Carbon Dioxide Capture and Storage, IPCC Special Report, Summary for Policy Makers, Working Group III.

Mills D. R., P. Le Lievre, and G. L. Morrison, (2003), "Solar Prehating of the Liddell Coal-fired Powerplant", ANZSES Annual Conference Melbourne 600-604.

Mills, D. R., G. L. Morrison, and P. Le Lievre, (2006), "Multi-tower line focus Fresnell array project", Journal of Solar Energy Engineering, Feb., 128, 118 120.

North, P., (2005), (Tanker designer), Personal Communications.

Odeh, S. D., M. Behnia and G. L. Morrison, (2003), "Performance evaluation of solar thermal electricity generation systems." http://www.sciencedirect.com/science4?_ob=Artricle URL&_udi=B6V2P-47YH2W7

Oswald Consulting, (2006), 25GW of distributed wind on the UK electricity system, An engineering assessment carried out for the Renewable Energy Foundation, London. http://www.ref.org.uk/images/pdfs/ref.wind.smoothing.08.12.06.pdf

RREDC, undated, (http://rredc.nrel/gov/solar/old_data/nsrdb/redbook/atlas/serve.cgi)

SANDIA, (undated), "An Overview of Solar Thermal Technologies", http://www.hcs.harvard.edu/~hejc/papers/Solar%20Jan07/solar_thermal_overview.pdf

Sargent and Lundy (Consulting Group), (2003), Assessment of Parabolic Trough and Power Tower Solar Technology Cost nd Performance Forecasts, NREL.

Scheirmeier, Q., J. Tolleffson, T. Scully, A. Witze and O. Morton, (2008), "Energy alternatives. Electricity without carbon", News Feature, Nature, (Published Online), 13th Aug., 454, 816 – 213.

Sharman, H.,(2005a), "The dash for wind; West Denmark's experience and UK energy aspirations", www.glebemountaingroup.org/Articles/DanishLessons.pdf

Skylass-Kazacos: n.d., "The Vanadium redox battery and fuel cell for large scale energy storage", Manuscript from Chemical Engineering and Industrial Chemistry, Univ. of NSW, Australia.

Sorensen, B., (2003), Renewable Energy: Its Physics, Engineering, Use, Environmental Impacts, Economy, and Planning Aspects. Elsevier, Amsterdam.

Stern, N., (2006), Review on the Economics of Climate Change, H.M.Treasury, UK, Oct., . http://www.sternreview.org.uk

Trainer, F. E. (T.), (1985), Abandon Affluence, London, Zed Books.

Trainer, F. E. (T.), (2006), The Simpler Way website, **http://ssis.arts.unsw.edu.au/tsw/**

Trainer, F. E., (T.), (2007a), Renewable Energy Cannot Sustain A Consumer Society, Springer, Dordrecht.

Trainer, T., (2007b), "The Stern Review; A critical assessment of its mitigation optimism," http://ssis.arts.unsw.edu.au/tsw/Stern.18.12.07.html

Trainer, T., (2007c), "A critical discussion of the IPCC analyses of carbon emission mitigation possibilities and costs", http://ssis.arts.unsw.edu.au/tsw/IPCCcrit.html

Trainer, T., (2008), Estimating the potential of solar thermal power, http://ssis.arts.unsw.edu.au/tsw/solarthermal.html

Trieb, F., (undated), Trans-Mediterranean Interconnection for Concentrating Solar Power; Final Report.

Wilson, E., (2002), "Twenty Myths Challenged", EV World. Duplicated manuscript.